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RESEARCH ARTICLE

Simulating climate change in a coastal watershed with an integrated suite of airshed, watershed, and estuary models

Lewis C. Linker[1] | **Gary W. Shenk**[2] | **Gopal Bhatt**[3] | **Richard Tian**[4] | **Carl F. Cerco**[5] | **Isabella Bertani**[4]

[1]U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland, USA

[2]U.S. Geological Survey, Virginia/West Virginia Water Science Center, Richmond, Virginia, USA

[3]Penn State University, Chesapeake Bay Program Office, Annapolis, Maryland, USA

[4]University of Maryland Center for Environmental Science, University of Maryland, Annapolis, Maryland, USA

[5]Attain Inc., Chesapeake Bay Program Office, Annapolis, Maryland, USA

Correspondence
Lewis C. Linker, U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, MD, USA.
Email: linker.lewis@epa.gov

Abstract

In 2020, the Chesapeake Bay Program moved to offset impacts from climate change for the 30-year period from 1995 through 2025 by having its seven watershed jurisdictions (Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia) apply additional nutrient pollutant reduction practices. The climate change assessment was performed with integrated models of the Chesapeake watershed, airshed, and estuary. Scenarios run for the years 2025, 2035, 2045, and 2055 estimated effects from the different future climatic conditions. This article presents the results of that assessment and is intended to provide a guide to assist other modeling practitioners in assessing climate change impacts in coastal watersheds. Major influences of climate change that were quantified include increases in precipitation volume, potential evapotranspiration, watershed nutrient loads, tidal water temperature, and sea level. Minor influences quantified in the climate change analysis include changes in nutrient speciation and increases in wet deposition of nitrogen, CO_2, rainfall intensity, tidal wetland loss, up-estuary salt intrusion, and phytoplankton biomass. To offset climate change impacts from 1995 to 2025 on water quality, the scenarios indicate an additional 2.3 million and 0.3 million kg of nitrogen and phosphorus per annum, respectively, will need to be reduced beyond what is called for in the Chesapeake Total Maximum Daily Load.

KEYWORDS

climate change, Chesapeake Bay, sea level rise, integrated environmental models, water quality standards, watershed management, Total Maximum Daily Load (TMDL), eutrophication

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Research Impact Statement

A comprehensive analysis supporting the United States' largest TMDL in offsetting current and future climate impacts by quantifying its impairments to water quality in the Chesapeake is described.

1 | INTRODUCTION

The Chesapeake Bay is the largest estuary in North America and is eutrophic (Boynton et al., 1995; Boynton & Kemp, 2008). To address the restoration of Chesapeake water quality and habitat, the Chesapeake Bay Program (CBP) a State and Federal Program has been working since 1983 (Gillelan et al., 1983). At the 40-year anniversary of the CBP, the program has found that climate change has made Chesapeake watershed and tidal Bay restoration more difficult, but by no means unachievable. The CBP is now organized to meet the goals of the 2010 Chesapeake Total Maximum Daily Load (TMDL; see the next section) and the Chesapeake Bay Watershed Agreement which is a formal agreement to achieve the restoration and protection of the Chesapeake Bay (Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013; USEPA, 2010a). In 2020, the CBP decided to offset impacts from climate change for the 30-year period from 1995 through 2025 by asking the seven Chesapeake watershed jurisdictions (Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia) to have additional nitrogen and phosphorus pollutant reduction practices in place across the watershed (PSC, 2020). Future 2035 climate change impacts will be addressed by further updated nutrient pollution targets to be developed in 2027 using a refined suite (Phase 7) of CBP land-use, airshed-, watershed-, estuarine-, and living resource models (PSC, 2020).

1.1 | Chesapeake Bay TMDL

The Chesapeake TMDL is the largest, most complex TMDL in the United States and is aimed at restoring the ecological health of a eutrophic Chesapeake watershed and tidal Bay (Boynton et al., 1995; Boynton & Kemp, 2008; Gillelan et al., 1983; Kemp et al., 1992, 2004, 2005; Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013; Madden & Kemp, 1996; Paolisso et al., 2015; USEPA, 2010a). The TMDL covers a 166,000 km^2 watershed across the states that form the State and Federal partnership of the CBP (Figure 1). Established in 2010, the Chesapeake TMDL allocates loadings of nitrogen, phosphorus, and sediment to sources and areas of the watershed contributing those pollutants, thereby reducing the nutrient and sediment loads to reduce hypoxia and remove impairments for aquatic life uses in the Bay's tidal tributaries and embayments (Hernandez-Cordero et al., 2020; USEPA, 2010b, 2010e). Development of the Chesapeake TMDL was documented in the Journal of the American Water Resources Association's Featured Collection titled Chesapeake Bay Total Maximum Daily Load Development and Application.

1.2 | Chesapeake Midpoint Assessment

The 2010 Chesapeake Bay TMDL document (USEPA, 2010a) called for a 2017 Midpoint Assessment between the 2010 initiation of the TMDL and 2025, when all management actions, practices, and controls were to be implemented to achieve water quality standards of dissolved oxygen (DO), water clarity/submerged aquatic vegetation, and chlorophyll-*a*. The purpose of the 2017 Midpoint Assessment was to review progress toward meeting the nutrient and sediment pollutant load reductions necessary for Bay restoration including setting new nutrient and sediment targets (in 2019) for the TMDL to address growth of human and animal populations and associated land use change in the watershed (Claggett et al., 2023 this featured collection) and account for load changes from reservoir infill (Cerco, 2016; Cerco & Noel, 2016; Langland, 2015; Linker, Batiuk, et al., 2016; Linker, Hirsch, et al., 2016; Palinkas et al., 2019). A third component of the Midpoint Assessment was the review of the latest science, data, modeling, and decision support tools assessing climate change impacts on Chesapeake Bay water quality. In 2020, additional nutrient reduction targets were set to offset impacts from climate change over the 1995 to 2025 period (PSC, 2020).

1.3 | Addressing climate change risk in the Chesapeake

Climate change was recognized in the 2010 TMDL as an influence on Chesapeake water quality but was excluded from the 2010 target loads because of insufficient information to quantify its impact on nutrient and sediment loads and water quality standards (Pyke et al., 2008; USEPA, 2010a). Since then, additional research, modeling, and analyses have been carried out to estimate how climate change has increased

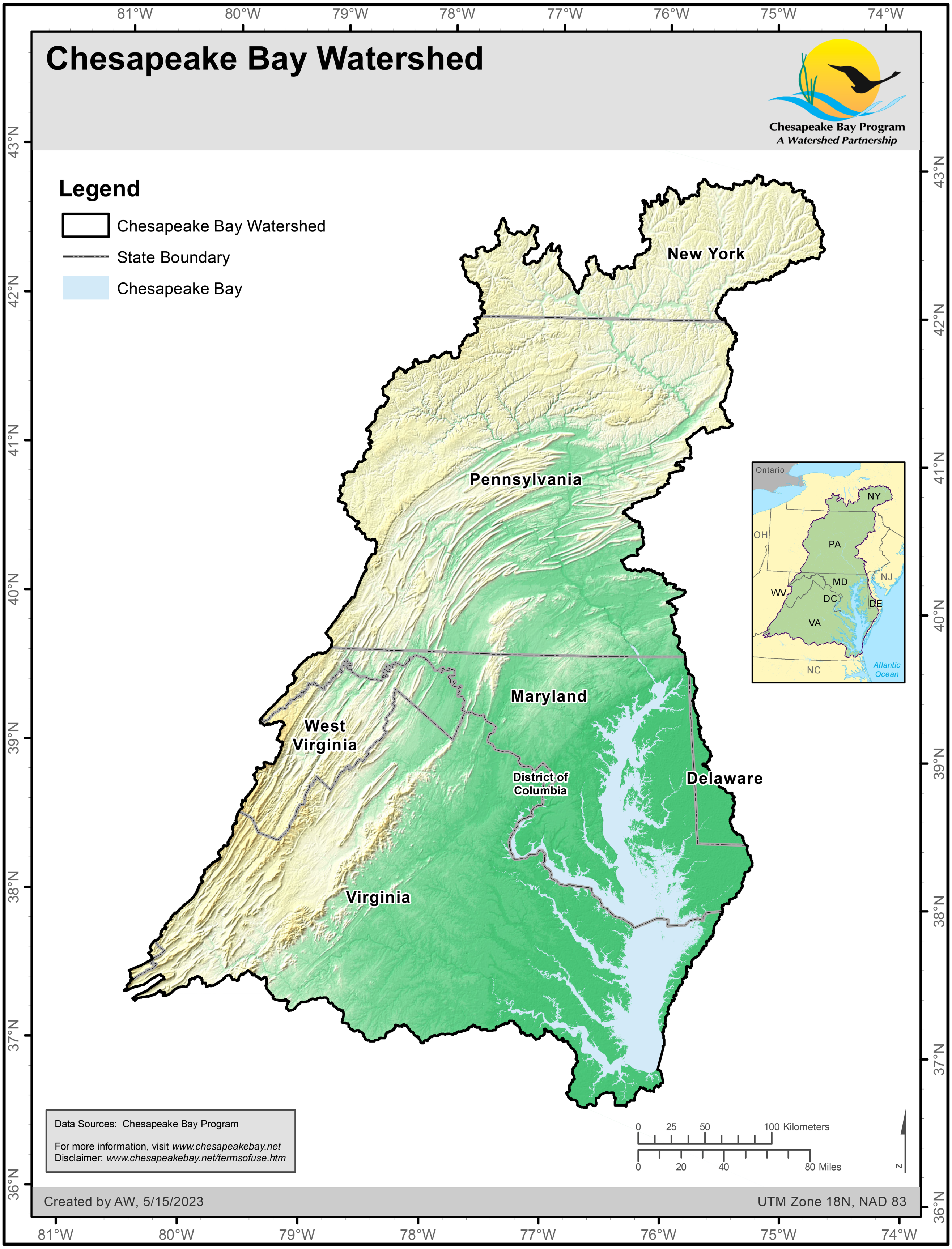


FIGURE 1 The Chesapeake watershed and tidal waters, showing New York, Pennsylvania, Maryland, District of Columbia, Delaware, Virginia, and West Virginia jurisdictions of the Chesapeake Bay Program (CBP) Partnership.

estuarine water column temperatures, rainfall volume, and intensity (Bhatt et al., 2023 this featured collection; Melillo et al., 2014; Najjar et al., 2010; Romero-Lankao et al., 2014), tidal wetland erosion Cerco & Tian, 2021 this featured collection; (Cornwell et al., 2021 this featured collection), sea level rise (Cai, Shen, et al., 2022; Cai, Zhang, et al., 2022 this featured collection; Irby et al., 2018; St-Laurent et al., 2019; Tian et al., 2022 this featured collection), and other factors affecting pollutant loads to the Bay. The findings are that the overall effect of climate change on the Chesapeake will be to exacerbate hypoxia in the Bay through an increase in watershed runoff, river flow, and nutrient loads (Bhatt et al., 2023 this featured collection; Karl & Knight, 1998; Rice et al., 2017; Shenk, Bhatt, et al., 2021). In tidal waters, increased temperatures will reduce DO solubility and increase respiration and stratification (Cai, Shen, et al., 2022 this featured collection; Irby et al., 2018; Tian et al., 2022 this featured collection), adding to hypoxia problems in the Chesapeake.

In 2020, the CBP updated the nutrient targets to account for *further* reductions in nitrogen and phosphorus loads necessary to offset the estimated impacts of 2025 climate change conditions to the Chesapeake living resource-based water quality standards. In the assessment of the changes in nutrient and sediment loads brought about by 2025 climate change, key aspects of climate change effects were considered, including changes in precipitation volume and intensity, evapotranspiration, atmospheric carbon dioxide (CO_2) concentrations, streamflow, and nutrient and sediment load (Bertani et al., 2021 this featured collection; Bhatt et al., 2023 this featured collection). The estuarine changes of water-column warming, sea level rise, tidal wetland loss brought about by climate change and phenological changes in nutrient loading were also examined (Basenback et al., 2023 this featured collection; Cai, Shen, et al., 2022 this featured collection; Cerco & Tian, 2021 this featured collection; Cornwell et al., 2021 this featured collection; Hinson et al., 2021 this featured collection; Testa et al., 2021 this featured collection; Tian et al., 2022 this featured collection).

In the watershed and airshed, the primary influence of climate change is to increase the nutrient loads to the tidal waters of the Chesapeake through increases in precipitation volume. In the tidal waters, the primary influence is from the physical conditions of increased water-column temperature and sea level rise. Overall, the Chesapeake Bay 2010 TMDL allocations (USEPA, 2010f) and subsequent updated 2017 and 2020 target loads become the objectives of comprehensive watershed implementation plans (WIPs), which include rigorous accountability measures, to restore water quality and living resources in the Chesapeake Bay (PSC, 2020).

The overall intention of this article is to examine the Chesapeake climate change analysis as a case study to provide a guide to modeling practitioners and resource managers in the assessment of climate change impacts in eutrophic coastal watersheds. In Section 2 key elements of the climate change simulation are identified with an overview of how they are simulated in the Chesapeake watershed, airshed, and estuary models. In Section 3 the key elements are sorted into major and minor influences on the water quality standards of the Chesapeake TMDL and key model scenarios are described. Finally, Sections 4 and 5 examine their relevance to modeling practitioners and policy makers.

2 | METHODS

2.1 | Overview of CBP Phase 6 models and their application to assess climate change impacts

The suite of models developed by the CBP to quantify watershed and estuarine responses to management actions has gone through several iterations and major updates (referred to as “Phases”) over the years, with the most recent version being finalized in 2017 and referred to as “Phase 6” (Hood et al., 2021). The Phase 6 suite of integrated models includes a model of the airshed (the Community Multiscale Air Quality Model, or CMAQ, coupled with a regression model of wet nitrogen deposition), a watershed model (Phase 6 Chesapeake Bay Watershed Model), a land-use model (Chesapeake Bay Land Change Model or CBLCM), and a tidal Bay water-quality model (2017 Chesapeake Bay Water Quality and Sediment Transport Model or 2017 Chesapeake Bay WQSTM). The term *integrated models* is used because the separate models of Phase 6 are brought together and unified into a linked and coordinated whole with the output of one model being used as the input of another. The Phase 6 models were applied to the assessment of climate change in the Chesapeake as detailed in the section titled “Climate Change Analysis Elements” (Bhatt et al., 2023 this featured collection; Campbell et al., 2019; CBPO, 2020; Cerco & Noel, 2019; Cerco & Tian, 2021 this featured collection; Claggett et al., 2023 this featured collection; Shenk, Bhatt, et al., 2021; Tian et al., 2022 this featured collection). The airshed, watershed, land use, and tidal water quality models have undergone continuous cycles of development and application for more than 30 years, are extensively documented and were used to establish the 2010 Chesapeake TMDL (Cerco et al., 2010; Cerco & Noel, 2004, 2013, 2019; Cerco, Kim, et al., 2013; Cerco, Noel, et al., 2013; Dennis et al., 2007; Grimm & Lynch, 2000, 2005; Hameedi et al., 2007; Bash et al., 2010; Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013; Linker et al., 2000, 2008; Shenk & Linker, 2013; USEPA, 2017). Figure 2 shows the relationships and interactions among the CBP Phase 6 Models.

The CBP Phase 6 airshed, land use, watershed, and tidal water quality models were used to predict changes in water quality conditions brought about by 2025 climate change. The future climate change conditions of 2035, 2045, and 2055 were also examined. It was necessary to compare the climate change scenario results with the applicable water quality standards to determine compliance with the standards (Linker, Batiuk, et al., 2013; USEPA, 2010a). To determine management scenarios that achieved water quality standards, model scenarios were run with the Phase 6 Watershed Model representing 2025, 2035, 2045, and 2055 climate change conditions using the delta method (Anandhi et al., 2011;

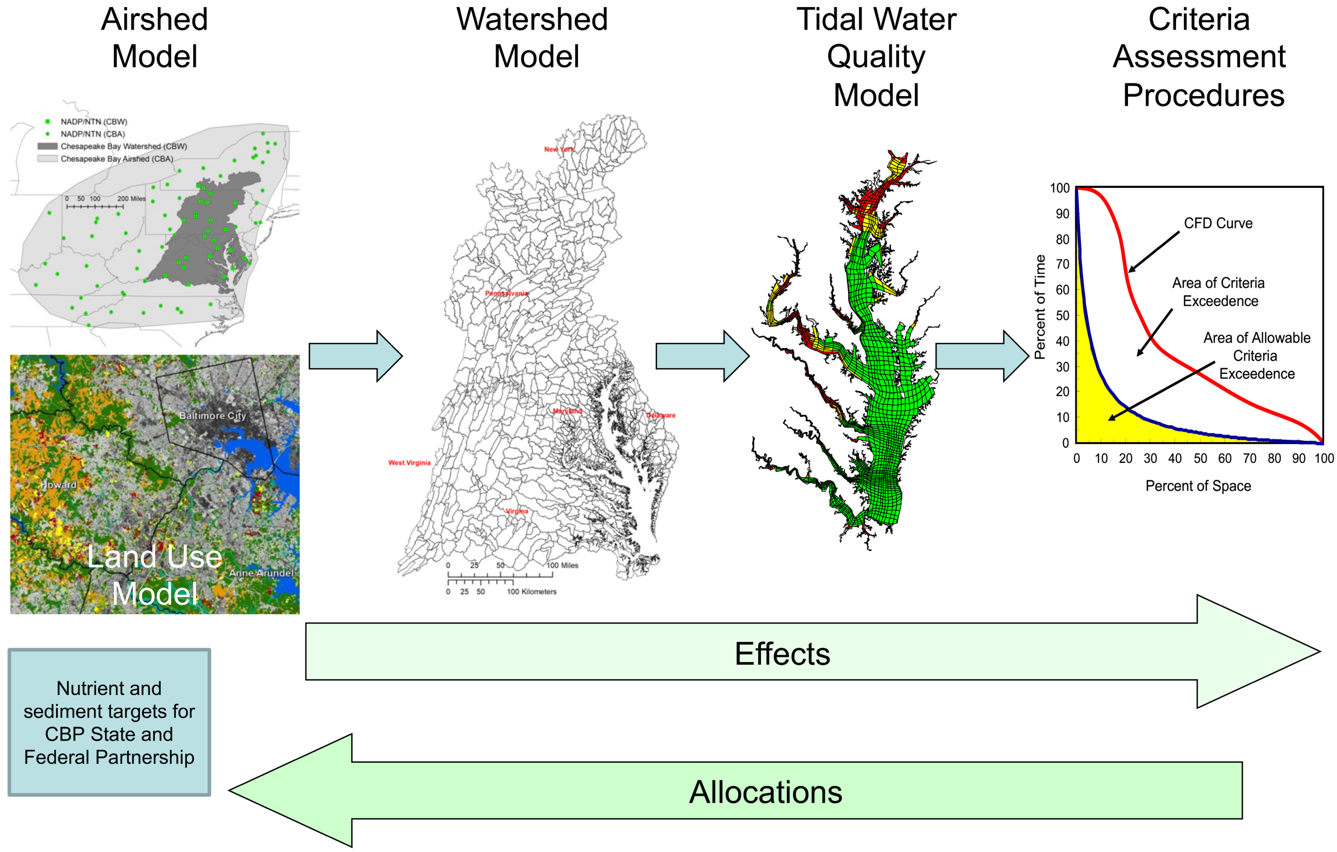


FIGURE 2 The Phase 6 CBP models of the climate change analysis including the main models of the airshed, future land use change, watershed, tidal Bay, and assessment procedures. The flow and sequence of the analyses is from left to right. The results of the analysis support policy decisions resulting in target loads needed to respond to climate change represented as the flow from right to left.

Ramirez Villejas & Jarvis, 2010; Shenk, Bhatt, et al., 2021) to quantify the degree of water quality standard nonattainment brought about by climate change. The resultant Watershed Model-simulated nitrogen, phosphorus, and sediment loadings (Bhatt et al., 2023 this featured collection) were used as input into the 2017 Chesapeake Bay WQSTM to evaluate the response of critical water quality parameters, specifically the deep water DO and deep channel DO water quality standards (Cerco & Tian, 2021 this featured collection; Shenk, Bhatt, et al., 2021; Tian et al., 2022 this featured collection). The deep water DO water quality standard is set at 3 mg/L to provide fish habitat below the surface mixed layer. The deep channel DO water quality standard is set at 1 mg/L to provide benthos habitat in the deepest waters of the Chesapeake (USEPA, 2010b).

The development of the Chesapeake climate change assessment can be broken down into four separate but integrated groups of analysis elements, which are six *Climate Change Forcing Elements*, nine *Watershed Model Elements*, seven *Tidal Bay Model Elements*, and one *Management Decision Element* as shown in Figure 3.

2.2 | Climate change forcing elements

The 2010 Chesapeake TMDL is based on two key time periods. The critical period of 1993–1995 is the span of hydrologic years used to determine the Chesapeake's nutrient load carrying capacity (USEPA, 2010g). The Chesapeake's nutrient load carrying capacity is the nutrient load that allows all water quality standards to be achieved. For the TMDL, impacts of all estimated nutrient-load change scenarios in the estuary are estimated relative to water quality standard achievement during the critical period.

The nutrient load carrying capacity becomes nitrogen and phosphorus load targets that are distributed among the major Chesapeake basins. The 10-year *hydrologic averaging period* from January 1, 1991 to December 31, 2000 provides long-term average load conditions for each basin of the Bay's watershed and a representative mix of point and nonpoint loads under a wide range of high- to low-river flows used to distribute nutrient load reductions required to reach the nitrogen and phosphorus nutrient load targets. Loading targets for the six state and District of Columbia jurisdictions are expressed as the adjusted 1991–2000 long-term average loads that, when combined, would not exceed the nutrient load carrying capacity and result in the achievement of water quality standards (Linker, Batiuk, et al., 2013; USEPA, 2010a, 2010c).

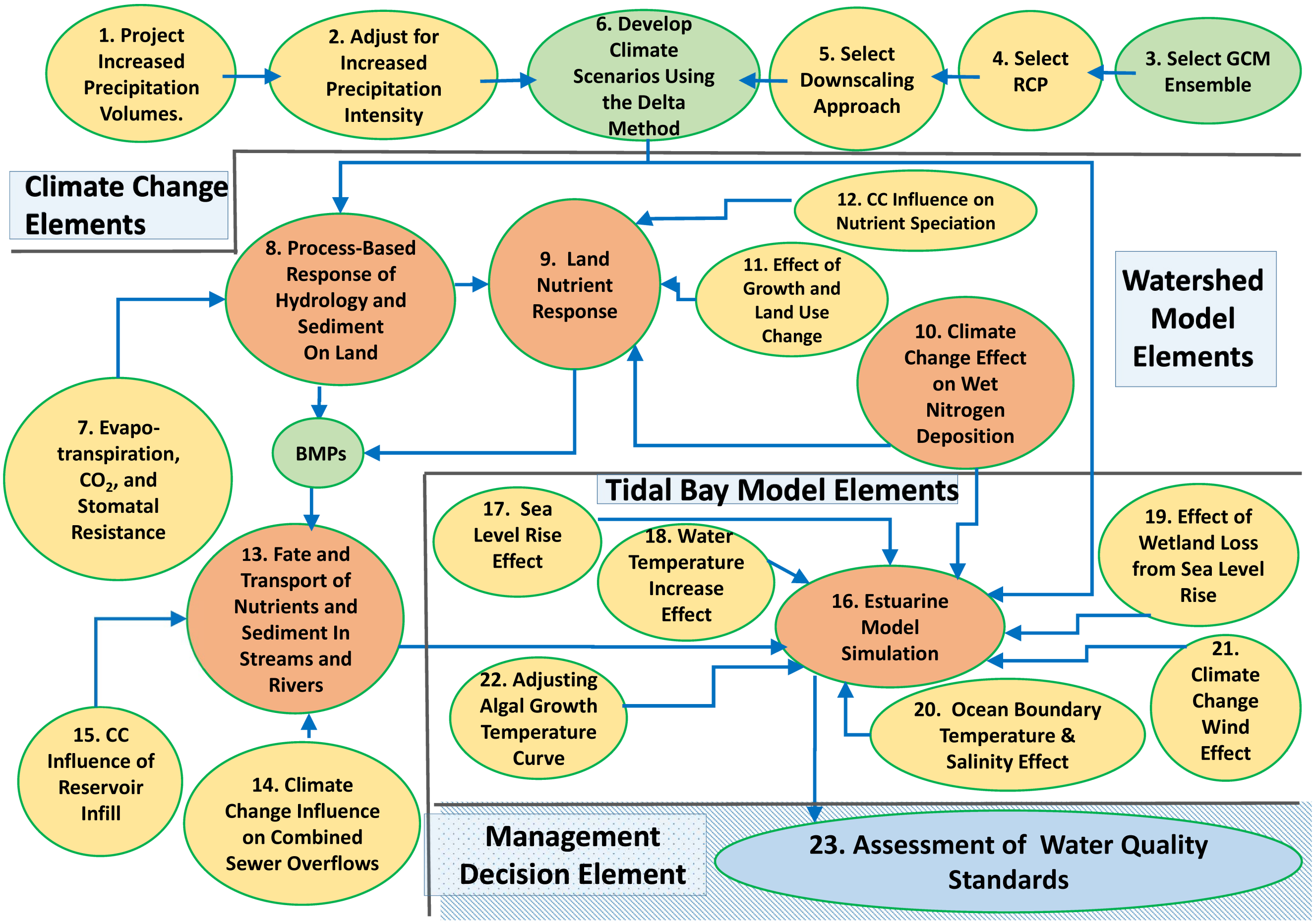


FIGURE 3 Flow chart of model tasks and decisions for a comprehensive assessment of climate change influence on Chesapeake Bay water quality. Green, data set: orange, model component; yellow, project task or decision; and blue, management endpoints.

Given the set TMDL management baselines of the critical and hydrologic averaging periods, the CBP selected the delta method approach (Anandhi et al., 2011; Bhatt et al., 2023; de Castro et al., 2007) to project 30 years of estimated climate change from the baseline year of 1995 (middle of the 1991–2000 hydrologic reference period and end of the 1993–1995 critical period) to 2025. The delta method applies change factors that quantify the expected influence of climate change to historical meteorological time series. This was done for 2025 by applying the change in precipitation and air temperature for a 30-year period centered around 2025 and 1995 to the 1991–2000 hydrologic reference period with the delta method (Anandhi et al., 2011; Bhatt et al., 2023 this featured collection). The 2025 year was chosen because the CBP determined it to be the year that it would begin to track climate change nutrient and sediment reduction targets needed to achieve and maintain the TMDL water quality standards. Further revisions to the climate change reduction targets were envisioned every 10 years. Accordingly climate change conditions for 2035, 2045, and 2055 were estimated in the same way as done for 2025 (Bhatt et al., 2023). For each of these future scenario years, changes in climate conditions with respect to the baseline were estimated as the difference between climate model predictions for a 30-, 40-, 50-, and 60-year difference centered around the 2025, 2035, 2045, and 2055 climate scenario year, respectively and 1995 in the reference hydrology year.

The estimation of 2025 Chesapeake climate change had six elements, which were: (1) project precipitation volumes; (2) adjust for increased precipitation intensity; (3) select global climate model (GCM) ensemble; (4) select the representative concentration pathway (RCP); (5) select the GCM downscaling approach; and (6) develop the climate scenarios using the delta method (see Figure 3 for numbers in parentheses). A flow chart outlining model tasks and decisions to accomplish these elements is shown in Figure 3 and additional details for these elements are provided below.

2.2.1 | Project increased precipitation volume (see Element 1 in Figure 3)

Both the extrapolation of long-term precipitation observations and the application of the ensemble of GCMs were used to estimate change in precipitation volumes for 2025, 2035, 2045, and 2055 as compared to 1995. Scientific and technical advice and guidance on the development of the CBP climate change assessment was provided by the CBP's Scientific and Technical Advisory Committee (STAC) (Herrmann et al., 2018; Hood et al., 2019, 2021; Johnson et al., 2016; Shenk, Bennett, et al., 2021; STAC, 2011). A specific STAC recommendation was to use long-term observed precipitation trends for 2025 projections of near-term change in precipitation volumes. This is because the application of the CBP climate change analysis in 2020 was only 5 years from the assessment year of 2025 and there was more confidence in the direct extrapolation of long-term observed precipitation than in the application of the ensemble of GCMs for short-range projections (Bhatt et al., 2023 this featured collection; Johnson et al., 2016). Interestingly, the 2025 short-range GCM ensemble was ultimately found to be entirely consistent with the long-term extrapolation of observed precipitation providing additional confidence in the 2025 climate estimates (Bhatt et al., 2023 this featured collection).

The 2055 projections were based on projections from an ensemble of climate models. The precipitation volumes for 2035 and 2045 were a combination of projections from long-term observations and climate model projections as described in Bhatt et al. (2023 this featured collection) where 2035 and 2045 were given a weighted average of the long-term observations relative to climate model ensemble of 2/3 and 1/3 in 2035 and 2045, respectively.

A long-term trend in observed precipitation volume was estimated through linear regression for each of the Phase 6 Watershed Model land segments, which are model land simulation units typically representing counties within the watershed (CBPO, 2020; Shenk & Linker, 2013). Precipitation trends for model land segments were estimated using the Parameter-elevation Relationship on Independent Slope Model (PRISM) precipitation data (Daly et al., 2008). The PRISM dataset is a reanalysis product that uses point data measurements at rain gauges and incorporates a conceptual framework to address spatial variability in precipitation due to orographic and other processes. The annual PRISM dataset for the years 1927 to 2014, that is, 88 years, was used in the linear regression trend analysis. Gridded PRISM data were first spatially aggregated to each Phase 6 land segment (Bhatt et al., 2023 this featured collection), then for each land segment, a linear trend line was fitted to the annual precipitation data and the estimated trend was extrapolated out to 2025 (Shenk, Bhatt, et al., 2021).

2.2.2 | Adjust for increased precipitation intensity (see Element 2 in Figure 3)

The capability to change simulated precipitation intensity consistent with long-term observations was incorporated into the analysis. Changes in precipitation volume were divided among intensity deciles based on documented changes in intensity and frequency of precipitation events using a century of observations in the northeastern United States (Gordon et al., 1992; Groisman et al., 2001, 2004; Karl & Knight, 1998). The observed increases in larger precipitation events (Groisman et al., 2004) were the basis for assigning the total change in precipitation volume disproportionately to the highest intensity deciles. Following Groisman et al. (2004), most of the increase in estimated precipitation volume due to climate change was placed in the highest intensity decile, with 64% in the upper most and 82% in the upper three deciles (Bhatt et al., 2023 this featured collection).

2.2.3 | Select GCMs ensemble (see Element 3 in Figure 3)

For 2055 precipitation volume estimates, the Coupled Model Intercomparison Project Phase 5 (CMIP5) set of 31 GCMs as described in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5; IPCC, 2013) was used.

An ensemble analysis is a widely used technique in climate change assessments where projections from multiple climate models are combined in an ensemble of predictions. The approach allows increasing the sampling of both initial conditions and model properties in the subsequent climate change assessment. Furthermore, it has been shown that multi-model ensemble means generally exhibit higher skill, for example, in capturing Atlantic Multi-decadal Variability, as compared to a single-model projection as described in Bhatt et al. (2023). For each climate change scenario, we calculated the monthly median changes in precipitation projected by the 31-model ensemble and applied those to the reference 1991–2000 period as described in the section “Developing Climate Inputs using the Delta Method” and in more detail in Bhatt et al., 2023 (this featured collection). The monthly median changes in air temperature projected by the CMIP5 GCM ensemble also provided the estimated temperatures for all land segments for the 2025 scenario as well as for the 2035, 2045, and 2055 climate-change scenarios as suggested by Johnson et al. (2016; Bhatt et al., 2023 this featured collection; Shenk, Bhatt, et al., 2021).

2.2.4 | Select the RCP (see Element 4 in Figure 3)

The GCM projections of precipitation and air temperature changes used in the 2025, 2035, 2045, and 2055 assessments were based on the RCP 4.5 (IPCC, 2013, 2014). Other RCPs (RCP 2.6, RCP 6.0, and RCP 8.5) adopted by the IPCC AR5 to represent future trajectories of greenhouse-gas concentrations were unexamined due to computational and analysis constraints. The CBP management community adopted the application of the RCP 4.5 as a conservative, low-emissions "middle of the road" scenario that would provide decision-makers with a reasonable representation of future climate challenges in meeting the TMDL.

2.2.5 | Selecting the downscaling approach (see Element 5 in Figure 3)

Based on STAC recommendations (Johnson et al., 2016), it was decided to use an existent downscaled dataset rather than either developing or applying a tailored statistical or dynamic climate downscaling process.

The bias corrected spatial disaggregation (BCSD) downscaling methodology was selected because of its commonality among numerous datasets including the U.S. Climate Resilience Toolkit and the NASA Earth Exchange (NEX) Downscaled Climate Projections (NEX-DCP30), its extensive review in peer-reviewed literature in comparison with other downscaling methodologies and its relative ease of access and flexibility in choosing models and realizations to be incorporated into analyses. The downscaled dataset was among the ones recommended by the data.gov climate data catalog (https://data.gov/climate/portals/ accessed May 2, 2023).

The BCSD statistically downscaled CMIP5 climate projections were downloaded from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ and accessed through the U.S. Geological Survey's (USGS) Geo Data Portal at https://cida.usgs.gov/gdp/.

2.2.6 | Developing climate scenarios using the delta method (see Element 6 in Figure 3)

The impacts of 2025, 2035, 2045, and 2055 climate change conditions were estimated with respect to the 1991–2000 hydrologic averaging period by adopting a delta method approach, which developed future 2025, 2035, 2045, and 2055 meteorological time series by applying appropriate monthly delta change (delta factors change for rainfall and delta difference for air temperature) to the 1991–2000 reference period (Anandhi et al., 2011; Bhatt et al., 2023 this featured collection). The Phase 6 Watershed Model used estimated changes in 2025 precipitation relative to 1995 precipitation based on historical observed trends within the watershed. On the other hand, the CMIP5 climate models were used to estimate changes in precipitation between 1995 and the climate scenario year of 2055. For the estimated decades of 2035 and 2045, an interpolation between the two approaches was used to generate delta-change factors (Shenk, Bhatt, et al., 2021). For the expected changes in 2025, 2035, 2045, and 2055 air temperatures, the consistency of temperature estimates of the CMIP5 ensemble models allowed them to be used as the sole method and were applied as monthly delta differences.

2.3 | Watershed model elements

The estimation of climate change effects in the Chesapeake watershed had nine main elements which were: (7) Evapotranspiration, CO_2, and stomatal resistance; (8) process-based response of hydrology and sediment on land; (9) land nutrient response; (10) climate change influence on wet nitrogen deposition; (11) effect of growth and land use change; (12) climate change influence on nutrient speciation; (13) fate and transport of nutrients and sediment in streams and rivers; (14) climate change influence on combined sewer overflows (CSOs); and (15) climate change influence on reservoir infill (see Figure 3 for numbered elements in parentheses).

2.3.1 | Evapotranspiration, CO_2, and stomatal resistance (see Element 7 in Figure 3)

In the Mid-Atlantic region, streamflow under climate change conditions is largely determined by a balance between increased precipitation volumes and increased temperature, which drives an increase in evapotranspiration (Johnson et al., 2016). Therefore, getting good estimates of a watershed's potential evapotranspiration (PET) is a key aspect of a climate change assessment.

The Hargreaves-Samani approach (Hargreaves & Samani, 1985), which uses readily available meteorological variables, provided an estimated relationship of PET change with temperature similar to that obtained using the Penman-Monteith method, which is more input data intensive (Bhatt et al., 2023 this featured collection; Shenk, Bhatt, et al., 2021). For that reason, the Hargreaves-Samani method was used for estimating the change in PET under climate change conditions. The estimated daily change in PET was added as a factor to the hourly reference period (1991–2000) PET dataset. The Phase 6 Watershed Model simulations showed improved simulation results (Bhatt et al., 2023 this featured collection) that were consistent with observed streamflow trends (USEPA, 2016; Rice et al., 2017) when the change in PET was estimated using the Hargreaves-Samani method (Johnson et al., 2016; Shenk, Bhatt, et al., 2021).

The increase in global CO_2 levels results in a change in plant physiology by reducing the time leaf stomata are needed to remain open to capture and ultimately fix CO_2. Termed stomatal resistance, it has the effect of decreasing transpiration by enhancing plant water use efficiency for photosynthesis (Guerrieri et al., 2019). Anticipated values of CO_2 concentrations were compiled from the IPCC's 5th Assessment Report for different emission scenarios (Shenk, Bhatt, et al., 2021). Carbon dioxide concentration levels of approximately 427, 448, 474, and 498 ppm were obtained for the RCP 4.5 for 2025, 2035, 2045, and 2055, respectively (IPCC, 2013). This is compared to an average concentration of 363 ppm for the reference period 1991–2000. The expected change in PET due to stomatal resistance was estimated using the Penman-Monteith estimate of the CO_2 concentration's effect on PET (Shenk, Bhatt, et al., 2021).

2.3.2 | Process-based response of hydrology and sediment on land (see Element 8 in Figure 3)

Simulation of hydrology and sediment on land was by the deterministic process-based hydrologic simulation program—FORTRAN (HSPF) model as described by Shenk and Linker (2013) and Shenk, Bhatt, et al. (2021). The sediment loads simulated from the process-based response of hydrology and sediment on land (8) were mediated by sediment best management practices (BMPs) before being passed to the fate and transport of nutrients and sediment in streams and rivers (13).

2.3.3 | Land nutrient response (see Element 9 in Figure 3)

Simulation of nutrients on land under conditions of increased precipitation volumes, intensities, and air temperature was performed by a multiple model approach described in Shenk, Bhatt, et al. (2021). Based on a multiple model analysis, nitrogen concentrations are assumed to remain constant under climate change, although with speciation changes as described below. As a result, changes in total nitrogen are proportional to changes in total flow from the land. More details on the simulation of Land Nutrient Response (9) can be found in sections 2 and 7 of the Phase 6 model documentation (CBPO, 2020) as well as in Shenk, Bhatt, et al. (2021) and Bhatt et al. (2023 this featured collection). Phosphorus sensitivities to sediment production and overland flow in the Phase 6 model were used to estimate changes to phosphorus loads relative to climate change. Future soil phosphorus concentration under climate change was calculated to decrease more rapidly as more runoff and infiltration depletes the storage. Details can be found in section 3 of CBPO (2020) and in Shenk, Bhatt, et al. (2021). The nutrient loads simulated from the land nutrient response (9) were mediated by BMPs before being passed to the fate and transport of nutrients and sediment in streams and rivers (13).

2.3.4 | Climate change influence on wet nitrogen deposition (see Element 10 in Figure 3)

The estimates of atmospheric nitrogen deposition in the climate change analysis were a combination of a statistical regression model of wet nitrogen deposition (Grimm & Lynch, 2000, 2005) and a continental-scale application of the CMAQ model for estimates of dry nitrogen deposition (Bash et al., 2013; Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013).

Linear regressions in each of the 235 land segments of the Phase 6 watershed model were used for developing relationships or sensitivities for how atmospheric nitrogen deposition loads from the land varied with changes in rainfall. Linear regressions of percent change in wet oxidized nitrogen (NOx), percent change in wet reduced nitrogen (ammonium or NH_4^+), percent change in dry NOx, and percent change in dry NH_3 against percent change in rainfall were developed from three separate data sources. The first dataset was a set of monthly estimates of nitrogen deposition and rainfall from a dry, wet, and moderate future year simulated by the CMAQ model over the Bay watershed by Campbell et al. (2019). The other two datasets were a set of annual wet atmospheric nitrogen deposition estimates generated by the Phase 6 airshed model for the 235 land segments in the Watershed model for the range of precipitation from 1991 to 2000 and a set of rainfall and precipitation chemistry data from 79 National Atmospheric Deposition Program monitoring stations in the Chesapeake Bay airshed (Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013) for the years 1978–2011. In each of the sets of regressions from the three data sources, the land segments had a similar linear positive slope for both wet NOx and wet NH_4^+ deposition with rainfall. As described in more detail in Section 3, the influence of climate change was primarily due to the increased volume of rain. Moreover, dry NOx and NH_3 deposition failed to have any sensitivity to changes in rainfall or temperature, suggesting that climate alone had little impact on dry deposition. The slopes of the wet NOx and NH_4^+ deposition were then applied to the estimated increase in rainfall for the 2025, 2035, 2045, and 2055 years to account for the effects of rainfall volume changes in climate change scenarios (Shenk, Bhatt, et al., 2021).

2.3.5 | Effect of growth and land use change (see Element 11 in Figure 3)

An effective assessment of future climate change loads in the Chesapeake watershed requires estimates of the expected future growth of human and animal populations and associated land-use change. Tracking estimated future land use is also important because developed and urban areas increase the temperature and hydrologic flashiness of runoff and streamflow in a way that is similar and synergistic to climate change effects (Rosburg et al., 2017).

The CBLCM was used to estimate land use in the years 2025, 2035, 2045, and 2055 (Claggett et al., 2023 this featured collection). The CBLCM uses county-level projections of population and employment to develop estimated residential and commercial development while keeping track of allowable infill, redevelopment, and expansion of developed land on to either agricultural or forested/natural lands. The four future land use estimates for 2025, 2035, 2045, and 2055 from CBLCM projections were input into the Phase 6 Watershed Model for those projected years of climate and land use change. The four CBLCM projected years were static. For example, land use for a particular climate change scenario year, such as 2055, would have the same 2055 land use applied as the land use for each of the 10 years in the 1991–2000 reference hydrology period (Bhatt et al., 2023 this featured collection).

2.3.6 | Climate change influence on nutrient speciation (see Element 12 in Figure 3)

Total nitrogen is formed from the dissolved nitrogen fractions of nitrate, ammonia, and dissolved organic nitrogen as well as the particulate nitrogen fraction which is organic nitrogen and particulate ammonia. To track changes in nitrogen speciation brought about by climate change Bertani et al. (2022 this featured collection) developed an empirical hierarchical model to estimate changes in the fraction of nitrate to total nitrogen load as a function of changes in total nitrogen loads. The hierarchical model results indicated that when considering a long-term dataset of nitrogen loads from over 100 river stations across the Bay watershed, a negative relationship existed between changes in total nitrogen loads driven by increased streamflow and corresponding expected changes in the fraction of nitrate (Bertani et al., 2022). This empirical negative relationship was applied to the nitrogen speciation of Watershed model loads (Bhatt et al., 2023 this featured collection) in response to the increased flows from the climate-driven changes in hydrology estimated for 2025, 2035, 2045, and 2055.

2.3.7 | Fate and transport of nutrients and sediment in streams and rivers (see Element 13 in Figure 3)

Development and application of the stream-to-river delivery factor is described in section 9 of CBPO (2020) as well as in Shenk, Bhatt, et al. (2021) and were applied in reference as well as climate change scenarios. The Watershed model simulation of rivers under increased flow from climate change was by the deterministic process-based HSPF model as described by Shenk and Linker (2013) and Shenk, Bhatt, et al. (2021). The linked airshed model, watershed model, and WQSTM were run sequentially and then linked with output from one as the input to the other (Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013; Shenk & Linker, 2013). The Airshed model inputs to the Watershed Model were hourly loads of atmospheric wet deposition of nitrogen, combined with daily aliquots of seasonally estimated dry fall nitrogen deposition, which were input to the Watershed model's land-river segments, its smallest spatial computational units (CBPO, 2020). The calibration and verification of the Watershed model was extensive and applied at 253 monitoring stations for streamflow, 215 stations for water temperature, 212 stations for DO, 221 stations for nitrate, 216 stations for ammonia, 188 stations for total nitrogen, 176 stations for dissolved orthophosphate, 215 stations for total phosphorus, and 39 stations for chlorophyll over the 30-year period of 1985–2014 (Bhatt et al., 2023; CBPO, 2020; Shenk & Linker, 2013).

2.3.8 | Climate change influence on CSOs (see Element 14 in Figure 3)

Changes in CSO volumes were obtained by first estimating the expected changes in rainfall volume and intensity under the 2025, 2035, 2045, and 2055 climate scenarios and then using an empirical regression between observed rainfall and daily CSO volumes (CBPO, 2020).

After generating new time series (1991–2000) of daily precipitation events for each CSO service area and for each climate change scenario, an empirical regression between CSO volume and rainfall was applied to obtain projected daily CSO volumes under each climate change scenario. Loads of constituents were calculated by multiplying CSO volumes by event mean concentrations derived from observations or literature as described in section 8.5 of the Phase 6 CAST and watershed model documentation (CBPO, 2020).

2.3.9 | Climate change influence on reservoir infill (see Element 15 in Figure 3)

The Chesapeake watershed has reservoirs for drinking water, power supply, flood control, and recreation. Like reservoirs everywhere (Fan & Morris, 1992; Gunatilake & Gopalakrishnan, 1999; Labadz et al., 1995; Molisani et al., 2006; Palmieri et al., 2001; Podolak & Doyle, 2015), the reservoirs in the watershed are filling with sediment and particulate organic and inorganic nutrients (Linker, Batiuk, et al., 2016; Morris et al., 2008; USCOE, 2016). One reservoir in particular, the Conowingo on the Susquehanna River, has reached a level of infill called dynamic equilibrium (Hirsch, 2012; Langland, 2015; Linker, Hirsch, et al., 2016; Zhang et al., 2013). Dynamic equilibrium is a condition where a long-term equilibrium is achieved between the reservoir's deposition and erosion events (CBPO, 2020; Cerco, 2016; Cerco & Noel, 2016; Shenk, Bhatt, et al., 2021).

To examine the impact of the infill in the Conowingo Reservoir, the behavior of reservoir, which exhibited an absence of storage capacity by 2025, was simulated by the Weighted Regressions of Concentrations on Time, Discharge, and Season (WRTDS) Model (Zhang, Ball, et al., 2016; Zhang, Hirsch, et al., 2016). The critical shear stress of Phase 6 scour and deposition rates were adjusted to achieve the nutrient and sediment loads exported from the Conowingo Reservoir estimated by the WRTDS Model.

Different sets of model parameters were estimated for changing reservoir infill states and net trapping capacity. Estimated changes in scour and deposition parameters between early 1990s and early 2010s were obtained by matching model response to loads estimated by WRTDS for the same period (Zhang, Ball, et al., 2016; Zhang, Hirsch, et al., 2016). For sediment, changes in erodibility and settling velocity parameters for silt and clay were estimated, and for nitrogen and phosphorus changes in refractory settling rate parameters were estimated (CBPO, 2020). In addition, the bioavailability of organic material decreased linearly with flows greater than 6500 m^3/s. The estimated reservoir erosional, depositional, and biochemical changes were applied to the climate change scenarios.

2.4 | Tidal Chesapeake Bay water quality and sediment transport model elements

The estuarine simulation of climate change had seven main elements: (16) estuarine model simulation; (17) sea level rise effect; (18) water temperature increase effect; (19) effect of wetland loss from sea level rise; (20) ocean boundary temperature and salinity effect; (21) climate change wind effect; and (22) adjusting algal growth temperature curve (see Figure 3 for numbers in parentheses).

2.4.1 | Estuarine model simulation (see Element 16 in Figure 3)

The development, calibration, and application of the 2017 Chesapeake Bay WQSTM is documented in Cerco and Noel (2019) and elsewhere (Cerco et al., 2010; Cerco & Noel, 2004, 2013; Cerco, Kim, et al., 2013; Cerco, Noel, et al., 2013). The WQSTM has a high fidelity to observed Chesapeake data. The calibration and verification of the WQSTM are extensively documented in Cerco and Noel (2019) in Appendices A and B—time series comparisons of observed and simulated data; Appendices C and D—longitudinal comparisons of observed and simulated data; Appendix E—comparisons of observed and simulated nutrient limitation; and Appendix F—comparisons of observed and simulated hypoxic volume. The linkage of the Phase 6 Watershed Model to the WQSTM was sequential. Once a scenario was completed on the Watershed Model it provided daily flows and loads inputs to tributaries and peripheral surface cells of the WQSTM (Cerco & Noel, 2019, section 6.1). Loads from the Airshed Model were daily loads of atmospheric deposition, primarily daily wet fall nitrogen deposition and seasonal dry fall nitrogen deposition, delivered to WQSTM surface cells (Cerco & Noel, 2019, section 6.4).

2.4.2 | Sea level rise effect (see Element 17 in Figure 3)

Sea level rise is a major influence on water quality in the Chesapeake because it influences estuarine circulation, stratification, and saltwater intrusion. Sea level rise was specified as a scenario boundary condition at the mouth of the Chesapeake for the 2025, 2035, 2045, and 2055 climate change scenarios. The actual forcing functions of sea level rise including thermal expansion, glacial rebound, local subsidence from groundwater pumping, Gulf Stream effects, and so forth were not simulated. Two methods were used to estimate sea level rise boundary conditions under climate change: the quadratic function (Boon & Mitchell, 2015) and the probabilistic projection (Kopp et al., 2014).

The Boon and Mitchell (2015) approach of fitting a quadratic function to tidal gauge data and estimating future sea level up to the year 2055 at numerous North America tidal gauge sites was applied to the Sewells Point tidal gauge. The tidal gauge site of Sewells Point is located at the entrance of the Chesapeake Bay and has sea-surface-level data for over 50 years, from 1969 to the present, providing the basis for model fitting and projection. The fitted sea-level-rise rate was estimated to be 5.2 mm/year with an acceleration rate of 0.12 mm/$year^2$. The observed sea level rise rate at Sewells Point is more than double the global ocean surface level rise of about 2 mm/year because of land subsidence, groundwater withdrawals, and other factors.

The other approach of estimating future sea level rise was the probabilistic method, known as the K14 method (Kopp et al., 2014), which combines the IPCC projection of global seal level rise based on projections from GCMs with local tidal gauge data through a Gaussian process model for prediction at the local scale. Glacier and ice cap melt, oceanographic processes, local land water storage, and local non-climatic background were included in the sea level rise estimate at the Sewells Point tide gauge.

The sea level rise estimates at Sewells Point from the two methods are consistent (Figure S1). Using 1995 as the reference point, or the central year of the 1991–2000 reference hydrology period used by the CBP, the sea surface level rise estimate is 22 cm by 2025 based on the quadratic function projection and 23 cm based on the K14 projection. The differences between the quadratic and probabilistic method were within 5% for the sea level rise estimates for 2035, 2045, and 2055. Ultimately the average of the two estimates was used in the Chesapeake Bay climate change analysis as shown in Figure S1.

2.4.3 | Water temperature increase effect (see Element 18 in Figure 3)

Air temperature data from the Patuxent Naval Air Station (Menne et al., 2012) were used to provide daily temperatures for the estuary model calibration. Temperatures for the 2025, 2035, 2045, and 2055 climate conditions were from projections from the downscaled GCMs. For the 2025 climate condition, the daily temperature data were adjusted from the 1995 calibration condition using the delta method, which resulted in an average increase of 1.06°C for the 30-year difference from 1995 to 2025. The monthly delta increase in air temperature applied to the 1991–2000 reference period was used for the daily temperature inputs for the watershed and the estuary model for the 2025 climate scenario (Bhatt et al., 2023; Tian et al., 2022). Similar delta method adjustments were made for the 2035, 2045, and 2055 scenarios.

2.4.4 | Effect of wetland loss from sea level rise (see Element 19 in Figure 3)

Sea level rise causes tidal wetland erosion with the eroded wetland adding nutrient loads to the Bay. To quantify the tidal wetland erosion's addition to nutrient loads to the Chesapeake, a study of the potential system-wide nutrient additions was conducted (Cerco & Tian, 2021 this featured collection). Tidal wetlands in the 2017 Chesapeake Bay WQSTM are simulated with a continual exchange of nutrients and particulates between tidal waters and wetlands. Tidal wetland nutrient uptake, denitrification, and particulate nutrient and sediment settling are simulated along with wetland oxygen consumption through respiration and export of dissolved organic carbon.

Sea level rise from 1995 base conditions for the years 2025, 2035, 2045, and 2055 were respectively, 0.22, 0.31, 0.42, and 0.53 m as described under the header Estimating Sea Level Rise and in Figure S1. The sea level affecting marshes model (SLAMM) provided estimates of eroded wetland area based on the sea level rise of 2025, 2035, 2045, and 2055 (Cerco & Tian, 2021 this featured collection; Warren Pinnacle Consulting, 2018).

In addition, observed measurements of the nutrient content of tidal wetland areas that could be mobilized by tidal shoreline erosion were obtained (Cornwell et al., 2021 this featured collection) and used to convert the SLAMM estimates of eroded wetland material to estimates of corresponding nutrient loads. The estimated mobilized nutrients from tidal wetland erosion in 2025, 2035, 2045, and 2055 were added to cells of the 2017 Chesapeake Bay WQSTM adjacent to the eroded tidal wetland area.

2.4.5 | Ocean boundary temperature and salinity effect (see Element 20 in Figure 3)

An assessment of historical changes in sea surface temperature and modeled air temperature changes provided the relation between air and ocean temperatures that was then applied across seasons and depths at the ocean boundary. The results of a modeling study relating salinity to sea level rise also were applied to the ocean boundary conditions. Approaches to adjusting both the temperature and salinity ocean boundary conditions under 2025, 2035, 2045, and 2055 sea level rise conditions are described in Tian et al. (2021 this featured collection).

2.4.6 | Climate change wind effect (see Element 21 in Figure 3)

The influence of wind direction and velocity is an important episodic control on Chesapeake hypoxia. The 2017 Chesapeake Bay WQSTM provides a good representation of wind effects on estuarine circulation and water quality including the high wind velocity that is effective in mixing the water column and reducing hypoxia (Scully, 2010; Wang et al., 2015; Wang, Wang, Linker, & Hinson, 2016; Wang, Wang, Linker, & Tian, 2016). Changes in wind velocity predicted by the GCM ensemble were assessed for potential inclusion in climate change simulations.

2.4.7 | Adjusting algal growth temperature curve. (see Element 22 in Figure 3)

Tidal water temperature increases are one of the key projected impacts of climate change on the Chesapeake tidal waters, resulting in lower DO saturation, increased deep water and deep channel respiration, greater stratification, and increased phytoplankton production. Therefore, an adequate simulated response of phytoplankton growth and respiration to temperature increase is important for a robust assessment of the climate change impact on water quality in the Bay.

The response of the phytoplankton growth rate to temperature increase is typically expressed as the Q10 coefficient, which is the growth rate increase over a 10°C temperature increase. Lomas et al. (2002) carried out an extensive study of the temperature effect on phytoplankton growth rate and microbial processes in the Chesapeake Bay and found values of Q10 ranging from 1.7 to 3.4. A Q10 of 2, which means that the phytoplankton growth rate will double over a 10°C increase in water temperature, is commonly used in the modeling community (Eppley, 1972; Tian et al., 2014).

The CBP partnership's 2017 Chesapeake Bay WQSTM was calibrated for the period 1991 to 2000, which is the standard hydrology period used in the 2010 Chesapeake Bay TMDL (USEPA, 2010a). Although the phytoplankton growth curves used in the calibration were appropriate for temperatures observed in the Bay during that period, the temperature-related coefficients for phytoplankton growth and respiration need to adequately reflect the characteristics of the phytoplankton assemblage over the range of water temperatures expected in the Bay due to climate change.

There are three generalized groups of phytoplankton in the model: cyanobacteria, diatoms, and green algae. The cyanobacteria group represents a freshwater, nitrogen-fixing algal group limited to the tidal fresh zone of the tributaries. Diatoms represent a cold-water group present in the winter and spring, and green algae represent all other species predominant in the summer and fall. Initially, the optimal temperatures for growth (Topt) were set to 29, 25, and 16°C for cyanobacteria, green algae, and diatoms, respectively. Water temperatures exceeding Topt would either decrease algal biomass for the cyanobacteria algal group, all other things being equal, or result in a static algal biomass for the green algal group (Figure 4, orange or "original" algal growth curve).

The optimal temperatures for cyanobacteria and green algae were both revised to 37°C, a value unlikely for tidal water temperatures to fully reach in the Chesapeake even under climate change conditions but sufficient to cover the few degrees of temperature increase and associated increase in algal growth in the WQSTM climate change scenarios. The optimal temperature for diatoms was unchanged because it is a cold-water transitional group present in the winter and in spring and succeeded by green algae in the summer. Figure 4 shows the adjusted growth rates and optimal temperatures for cyanobacteria (Phytoplankton Group 1 or P1) and green algae (Phytoplankton Group 3 or P3), which provided an algal response to temperature consistent with observations. Additional details on the approach taken for algal growth and respiration adjustments to future increases in temperature can be found in Cerco and Noel (2019 Appendix G) and Tian et al. (2022 this featured collection).

2.5 | Management decision element

2.5.1 | Assessment of water quality standards (see Element 23 in Figure 3)

The Chesapeake TMDL water quality standards are biologically based and designed to be protective of Chesapeake living resource habitat using seasonal-based criteria for DO, chlorophyll-*a*, and water clarity to protect major habitat regions of the Bay (Keisman & Shenk, 2013; Linker, Batiuk, et al., 2013; Tango & Batiuk, 2013; USEPA, 2010a, 2010e). To determine whether the climate change scenarios met the Bay DO

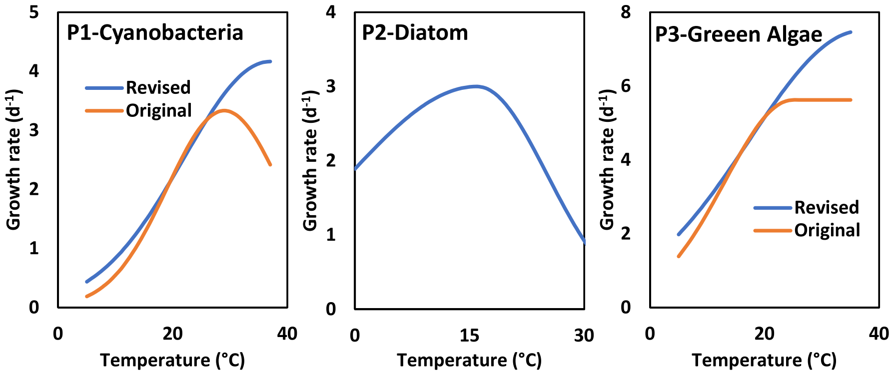


FIGURE 4 Phytoplankton growth curve as a function of water temperature for cyanobacteria (Phytoplankton Group 1 or P1), diatoms (Phytoplankton Group 2 or P2), and green algae (Phytoplankton Group 3 or P3). Orange line = original calibration curve. Blue line = revised curve for climate change assessment. Cold water adapted diatom group (P2) was unadjusted.

water quality standards, the 2017 Chesapeake Bay WQSTM-simulated tidal water quality responses for DO under future climate conditions were compared to the corresponding simulated values during the 1993–1995 critical period. The predicted changes were then applied to observed monitoring values collected during the same 3-year critical period as described in Keisman and Shenk (2013).

2.6 | Examination of climate change impacts on watershed loads under 2025 and 2055 Phase 3 WIP and No-Action conditions

To examine the prospect of a Chesapeake Bay without a CBP Federal-State partnership and the associated state, local, and national impetus to spur point-source and nonpoint-source controls to restore the Chesapeake, a No-Action Scenario was developed. The No-Action Scenario uses 1985 implementation rates of point-source and nonpoint-source nutrient controls. The year 1985 was chosen because it was just before the start of accelerated implementation of management actions and BMPs brought about by the CBP. The 1985 No-Action levels of point-source controls were limited to secondary treatment only (TN effluent = 18 mg/L and TP effluent = 3 mg/L) for all wastewater treatment plants and to an equivalent level for industrial dischargers (CBPO, 2020, section 12). Nonpoint-source controls for agricultural, forested, and developed land uses were also set to 1985 which were at their lowest levels of implementation in the last four decades. The No-Action Scenario was run for the years and estimated climate conditions of 2025 and 2055 and compared to the full application of CBP management actions in point source and nonpoint source controls under the CBP Phase 3 WIPs (USEPA, 2021a) for 2025 and 2055. The WIPs are implementation plan documents developed by the seven Bay jurisdictions to map out the management actions that each jurisdiction plans to take to meet TMDL goals. The jurisdictions developed WIPs in three phases over the course of the years, with the most recent Phase 3 WIPs being finalized in 2019.

The Phase 3 WIP scenarios of 2025 and 2055 atmospheric nitrogen deposition concentrations were at the estimated levels of emission controls based on national Clean Air Act (CAA) emission regulations for 2025 and 2030, respectively, but wet deposition of nitrogen was adjusted for the increased precipitation volume estimated for the 2025 and 2055 climate change years. The Phase 3 WIP and No-Action Scenarios had the same level of management controls on nitrogen deposition to the watershed and Bay because the reductions in nitrogen deposition were brought about by the national emission controls and regulations of the CAA that were implemented for human health concerns such as the ground level ozone and 2.5-µm particulate matter (PM2.5) air quality regulations and consequently were not a part of the regional and State CBP management actions. The estimated total nitrogen loads from atmospheric deposition to the Chesapeake watershed in the Phase 3 WIP and No Action scenarios (for the year 2030) was 121 million kg which was a 50% reduction in loads from the 1985 zenith.

3 | RESULTS

3.1 | Major climate change impacts in the watershed

An overall summary of the influence of climate change on the Chesapeake is provided in Figure 5. Estimated changes in watershed inputs to the tidal waters brought about by the 30-year estimated change in climate conditions from 1995 to 2025 are summarized by an overall watershed wide estimated flow increase of 2.4% which, through increased precipitation volume (3.1%) and intensity, increased the nitrogen, phosphorus, and sediment load delivered to the Bay by 2.6%, 4.5%, and 3.8%, respectively. For 2035 climate conditions the estimated precipitation, flow, and nitrogen, phosphorus, and sediment loads increased relative to the 1991–2000 reference period by 4.2%, 3.7%, 4.7%, 9.9%, and 8.5%, respectively (Figure S2). Estimated load changes for 2025, 2035, 2045, and 2055 are in Table 1. Increases in temperature of the air and open boundary condition at the Bay mouth as well as sea level rise are also shown in Figure 5.

Major watershed influences are the combined influence of increased precipitation volume and the estimated climate change influence on PET. Watershed wide, the estimated PET is 58% of all precipitation (rain, snow, etc.). The choice of which PET method to use is a key consideration in the simulation of climate change in watersheds and the simulation of climate change is highly sensitive to the choice of the method to calculate PET (Bhatt et al., 2023 this featured collection; Bormann, 2011; Butcher et al., 2014; Kingston et al., 2009; McKenney & Rosenberg, 1993; Hamon, 1961).

Figure 6 shows the relative estimated effects of precipitation and PET under 2025 and 2055 climate change conditions on flow (Figure 6a) and nitrogen loads (Figure 6b). The increased PET brought about by higher air temperatures reduces flows and loads of nutrients and sediment (Butcher et al., 2014). Histograms for precipitation, temperature, and CO_2 fail to sum to all together for nitrogen delivery (Figure 6b) because of nonlinearities of temperature adjusted denitrification, ammonification, nitrification, and other process rates in the model as well as differences in nonlinear rates of transport of particulate nutrients under different flow conditions. Overall, for nitrogen loads (Figure 6b) the estimated increase in precipitation volume had more than twice the influence on loads than PET.

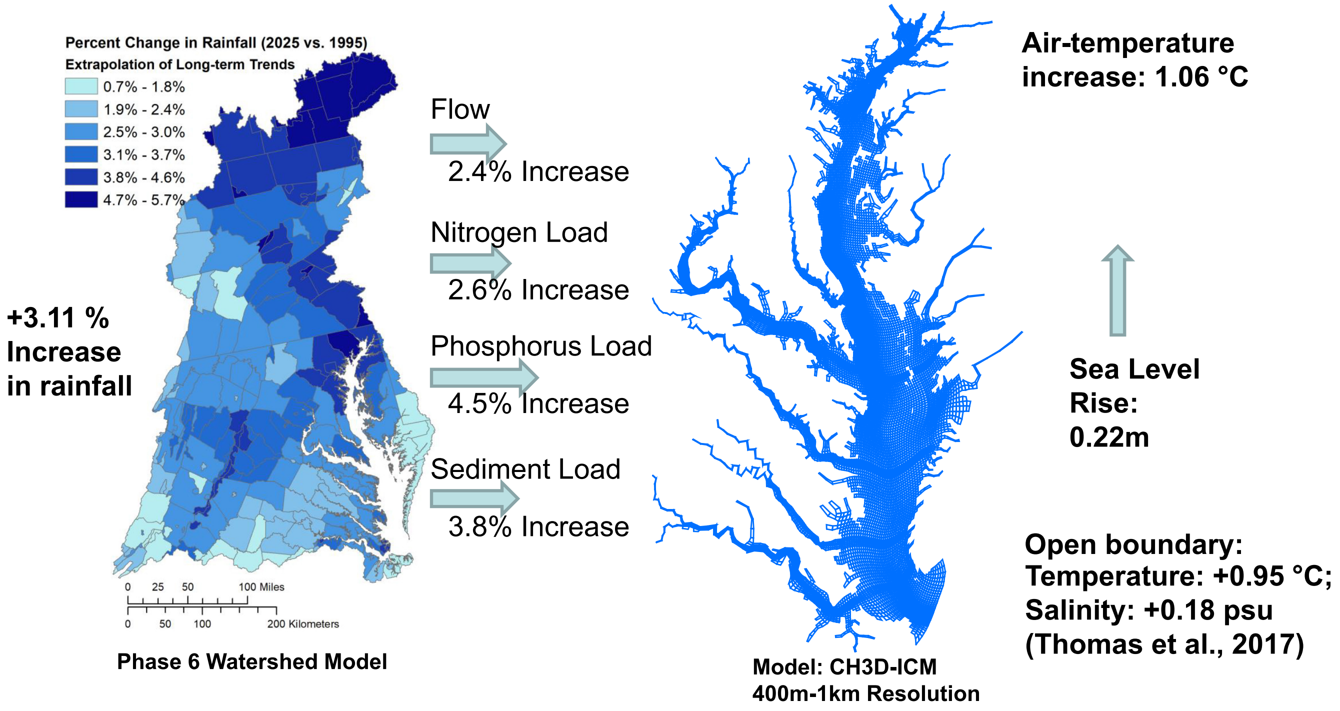


FIGURE 5 Overall summary of the estimated 30-year change of climate conditions from 1995 to 2025 in the watershed and tidal waters. The spatial differences in the average annual precipitation change across Phase 6 Watershed model land segments show relatively higher increases in precipitation in the northern and western portions of the watershed as well as in a narrow north to south band as a result of orographic effects of windward mountain sides.

TABLE 1 Watershed-wide estimated average change in precipitation, flow, and nitrogen (N), phosphorus (P), and sediment (S) loads delivered to the tidal Chesapeake from climate change conditions of 2025, 2035, 2045, and 2055 compared to 1995 climate conditions. A 1991–2000 base hydrology and conditions[a] were used for all scenarios which had average estimated precipitation of 105.6 cm, flow (44.8 cm), nitrogen load (90.3 million kg), phosphorus load (6.09 million kg), and sediment load (8.43 billion kg).

Climate change conditions	Rainfall (%)	Rainfall (cm)	Air temp. (°C)	Flow (%)	Flow (cm)	N load (%)	N load (millions of kg)	P load (%)	P load (millions of kg)	S load (%)	S load (billions of kg)
2025	3.1	108.9	1.12	2.4	45.8	2.6	92.7	4.5	6.35	3.8	8.75
2035	4.2	110.1	1.45	3.7	46.4	4.7	94.5	9.9	6.64	8.5	9.14
2045	5.2	111.1	1.84	4.5	46.8	6.5	96.1	14.9	6.99	12.4	9.48
2055	6.4	112.4	2.12	6.2	47.5	10.4	99.7	24.0	7.55	18.4	9.99

[a] The 1991–2000 *Planning Target Level of Effort Scenario* (PT-LOE) was used as a base condition in all scenarios with the only change being the climate change conditions of 2025, 2035, 2045, or 2055. The PT-LOE conditions represent the loads required to achieve water quality standards under the Chesapeake total maximum daily load (TMDL) and closely approximate the final Watershed Implementation Plan—Phase 3 loads that were put forward by the CBP partnership (USEPA, 2021a).

3.2 | Minor climate change impacts in the watershed and airshed

Minor climate change influences on watershed loads and Chesapeake hypoxia include changes in CO_2 and stomatal resistance, nutrient speciation, CSOs, wet deposition of atmospheric nitrogen, and land use change. A minor change impact is defined as less than 3% change of total nitrogen load when comparing the 2055 climate change load estimates to the 1995 base conditions load.

3.2.1 | Estimated climate change influence from increased CO_2 and stomatal resistance

Figure 6 shows the relative estimated effect of stomatal resistance from increased CO_2 atmospheric concentrations under 2025 and 2055 climate change conditions on flow (Figure 6a) and nitrogen loads (Figure 6b). The increase in CO_2 concentrations causes plant stomata to be closed more

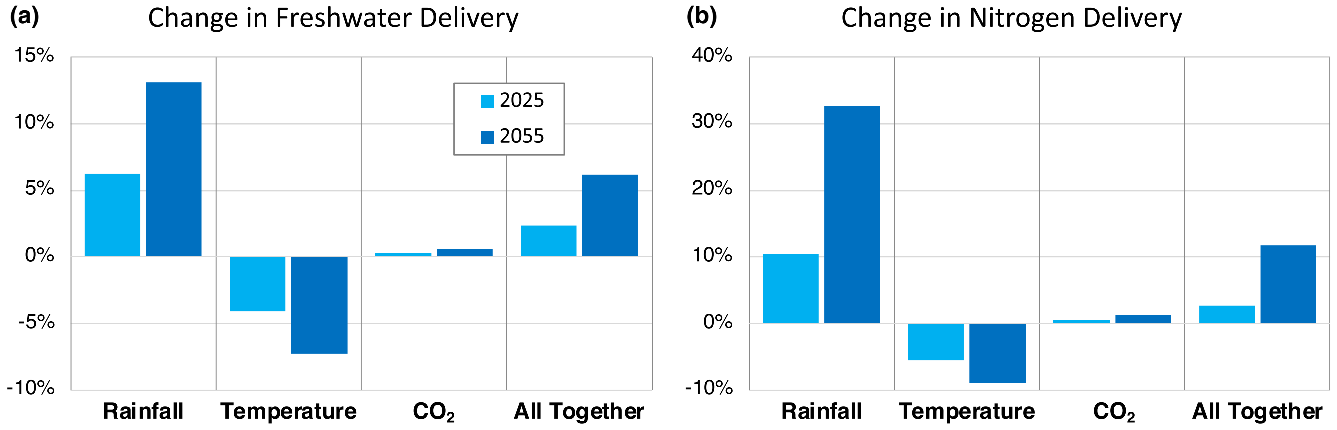


FIGURE 6 The relative estimated change in flow (a) and nitrogen load (b) for 2025 and 2055 compared to the 1991–2000 ten-year average Chesapeake TMDL hydrology baseline. Phosphorus and sediment loads were consistent with the relative changes in nitrogen loads but had greater magnitude.

often with the higher CO_2 levels being available for photosynthetic fixation (Butcher et al., 2014). The change in flows or nitrogen loads from future climate stomatal resistance is an order of magnitude less than the major influences of increased precipitation volume and PET.

3.2.2 | Estimated climate change influence on nutrient speciation

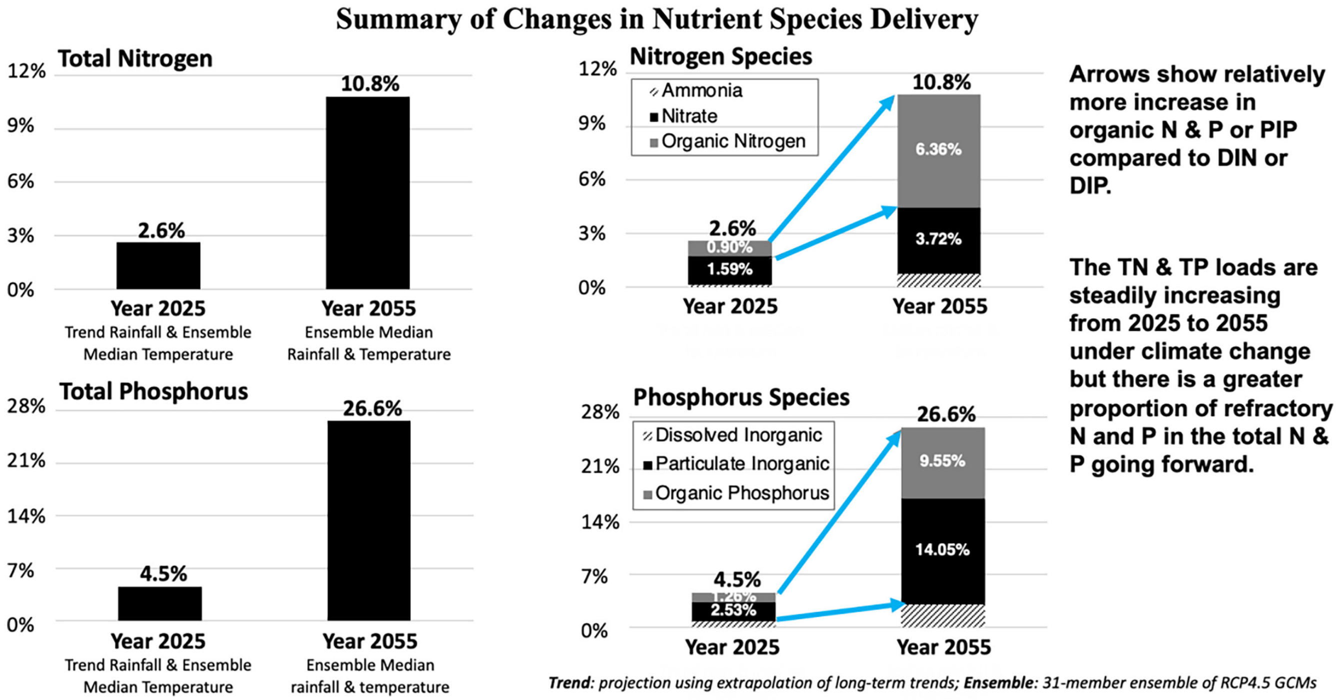
The empirical hierarchical model used to estimate changes in the fraction of nitrate to total nitrogen load occurring at different scales (Bertani et al., 2022 this featured collection) estimated that increases in total nitrogen loads resulting from changes in anthropogenic inputs, such as increased fertilization of cropland, lead to an increase in the nitrate/total nitrogen ratio. However, a decrease in the nitrate/total nitrogen ratio was estimated when increases in total nitrogen loads are driven by increased flow such as with climate change. In the model simulation as well as on the actual landscape, land use changes that increased anthropogenic nitrogen inputs, which also increased the nitrate/total nitrogen ratio in the Watershed Model simulations, were comingled with increased flows due to climate change, which tended to decrease the nitrate/total nitrogen ratio (Figure 7). The relative influence of the two separate forcing functions was quantified by the empirical hierarchical model. In addition, the simulation of additional eroded load from higher river flow resulted in an increase in organic nitrogen and phosphorus loads. Overall, climate change simulations resulted in a higher overall delivery to the tidal Bay of nutrient loads but with nutrient speciation mixes that were relatively less biologically reactive, for example, a higher proportion of organic nitrogen and organic and particulate inorganic phosphorus than dissolved inorganic nitrogen and dissolved inorganic phosphorus, respectively.

3.2.3 | Climate change influence on CSO loads

Increased CSO volumes due to increased precipitation volume and intensity exhibited only a minor influence on nutrient loads. The 2025 climate change influence on CSO nutrient loads was an estimated 5000 kg of nitrogen and 650 kg of phosphorus, which is 0.005% and 0.011%, respectively, of the total Phase 3 WIP loads (Phase 3 WIP target load not to exceed 91.4 million kg nitrogen and 6.4 million kg phosphorus delivered to the tidal Bay). The two cities in the Chesapeake watershed with the largest CSO loads subject to increases due to climate change are the District of Columbia and Richmond, Virginia.

3.2.4 | Estimated climate change influence on atmospheric deposition of nitrogen

Atmospheric deposition was one of the largest nitrogen input loads to the watershed and tidal Bay at the start of the Chesapeake TMDL in 2010. Due to CAA emission reductions by 2025, however, the atmospheric deposition load of nitrogen is now equivalent to nitrogen loads from fertilizers or manure (Linker, Batiuk, et al., 2013; Linker, Dennis, et al., 2013). The estimated 2025 atmospheric deposition, fertilizer, and manure loads to the watershed was 127, 137, and 120 million kg, respectively. The estimated 1985 atmospheric deposition loads were 243 million kg. With the widespread decreases in NOx emissions from power plants, mobile sources, and other combustion sources brought about by the CAA (Dennis et al., 2007), NOx deposition was estimated to continue to the year 2050 due to ongoing reductions in NOx emissions



Trend: projection using extrapolation of long-term trends; *Ensemble:* 31-member ensemble of RCP4.5 GCMs

FIGURE 7 Estimated changes in total nitrogen (TN) and total phosphorus (TP) loads for 2025 and 2055 under climate change conditions compared to the 1991–2000 base scenario hydrology of the Chesapeake TMDL. Estimated changes in nutrient speciation for 2055 relative to 2025 show higher estimated particulate organic and inorganic loads and relatively less dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). This is a result of the higher flow and scour conditions of the 2025 and 2055 hydrologies as represented in Bertani et al. (2021). In this figure organic phosphorus and particulate inorganic phosphorus (PIP) are combined and differentiated from DIP.

(Campbell et al., 2019). The NH_4^+ depositions, having emissions that are uncontrolled by the CAA, were estimated to increase by 10% in the Chesapeake Bay watershed over the same period.

Against the backdrop of ongoing reductions in NOx emissions and NOx atmospheric concentrations, climate change is causing a slight long-term upward trend in wet deposition nitrogen loads due to the increasing volume of precipitation in the Chesapeake watershed and tidal Bay as estimated by Campbell et al. (2019). The overall increase in atmospheric wet deposition of nitrogen due to climate change alone is estimated by 2055 to be 3.11 and 0.21 million kg of total nitrogen for the watershed and tidal waters of the estuary, respectively. The difference between the 2025 and 2035 atmospheric deposition loads is slight, about 0.5 million kg/year nitrogen.

The trend of increasing wet deposition of nitrogen with climate change is more than offset by continued reductions in national nitrogen emissions. Nevertheless, the combined effects of the estimated greater nitrogen wet deposition in the future and the reductions in nitrogen deposition due to the CAA and associated management actions reducing NOx emissions were two adjustments to the atmospheric nitrogen loads made for the 2025, 2035, 2045, and 2055 climate change scenarios.

3.2.5 | Comparison of influences of climate and land use change

At the entire watershed scale, climate change has an estimated impact of seven-fold more than land-use change in terms of attainment of the deep water DO water quality standard (Figure 8). This is because climate change has a greater influence on increasing watershed nutrient loads but also higher water temperatures due to climate change in the tidal Bay directly decrease the solubility of oxygen in water, increase bottom water respiration, and increase stratification (Irby et al., 2018; Tian et al., 2021 this featured collection; Hinson et al., 2021 this featured collection), as described in more detail in Section 3.3.

The deep channel DO water quality standard has a criterion requiring DO to be equal to or greater than 1.0 mg/L which provides habitat of benthos for foraging fish, crabs, and other living resources (Tango & Batiuk, 2013; USEPA, 2010a). In addition, a bottom DO ≤1.0 mg/L reduces the flux of ammonium and phosphate out of bottom sediments (Di Toro, 2001; Kemp et al., 1992, 2005; Testa et al., 2013). To assess the attainment of the deep channel DO standard, a time and space method of non-attainability is applied (USEPA, 2010a).

The two deep channel DO water quality standards that went into nonattainment under 2025 and 2035 climate conditions were in the middle mainstem Bay (Chesapeake Bay segment CB4 Mesohaline—CB4MH) and the Chester River (Chesapeake Bay segment Chester

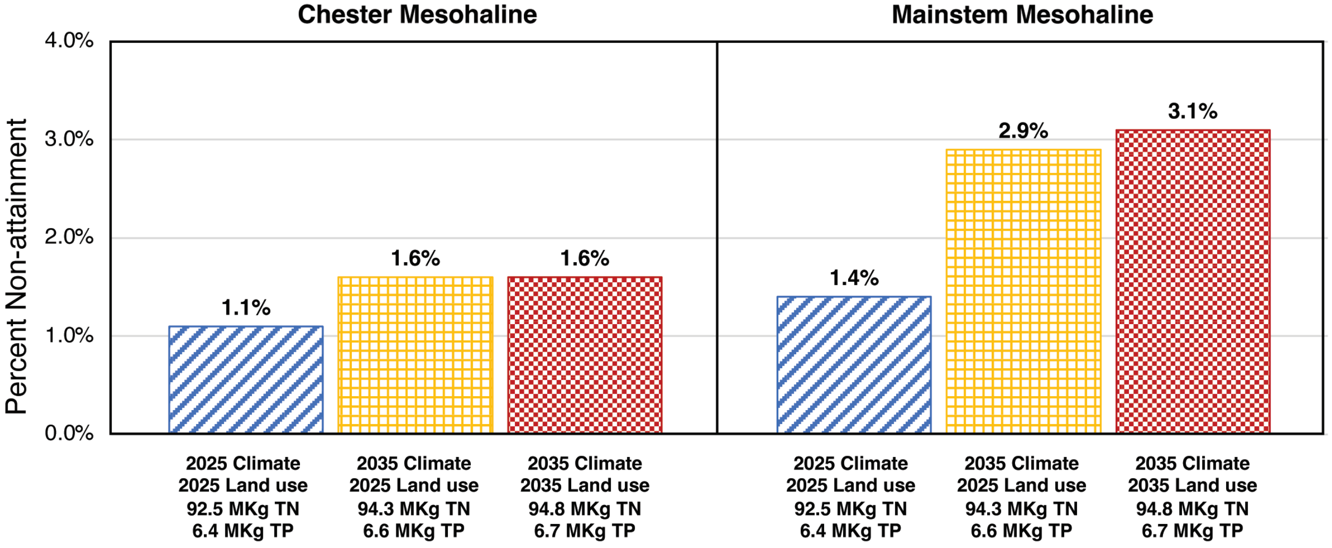


FIGURE 8 Two Chesapeake Bay designated uses where deep channel dissolved oxygen (DO) water quality standards went into nonattainment under various conditions of 2025 and 2035 climate or land use conditions compared to 2025 Phase 3 watershed implementation plan (WIP3) climate and land use conditions. Mesohaline regions in the Chesapeake are defined as zones with salinity typically between 5 and 18 parts per thousand.

Mesohaline—CSHMH). The Chesapeake TMDL allows for no increase in water quality nonattainment due to climate change above the 2025 WIP3 condition (blue striped bar). Compared to the 2025 WIP3 condition of climate change and land use in the CB4 Mesohaline segment, when the 2035 climate change and 2025 land use conditions were applied the level of TMDL nonattainment increased by 1.5% (Figure 8). In contrast, when the 2035 land use condition was also applied to the 2035 climate change condition the increase in nonattainment was a further increase of only 0.2%. The impact of the 2035 climate condition had more than a seven-fold impact compared to the 2035 land use condition. Likewise, in the Chester Mesohaline the increase in nonattainment of the 2035 climate change and 2025 land use condition relative to the 2025 land use and climate change condition was 0.5%. The addition of the 2035 land use to the 2035 climate change condition failed to increase nonattainment. Figure 9 provides additional credence based on the watershed loads under climate change and climate change plus land use change scenarios. In the 2035, 2045, and 2055 scenarios, climate change causes greater estimated nitrogen, phosphorus, and sediment load than land use change (Figure 9). This finding is expanded on in Section 4.

3.3 | Major climate change impacts in the tidal waters

In the estuary, the two major influences are the warming of the estuary, generating more hypoxia in tidal waters because of decreased DO solubility, increased deep-water respiration, and greater stratification (Figure 10) combined with higher nutrient and sediment loads delivered to the Bay from the watershed. Countering this somewhat are the influence of increased estuarine circulation, due to sea level rise as well as higher flows from the watershed which decrease hypoxia (Figure S3) (Tian et al., 2022 this featured collection).

3.3.1 | Influence from estuarine warming

In the estuary, warming as a result of climate change is a major influence on hypoxia (Hinson et al., 2021 this featured collection; Wang et al., 2017; Irby et al., 2018; Tian et al., 2022 this featured collection; Frankel et al., 2022). Under climate change conditions the average annual temperature is estimated to increase by 1°C over the three-decade period between the reference hydrology period used for the Chesapeake TMDL (1991–2000) and the year 2025. By 2055 the average temperature is estimated to increase by 2°C compared to 1995 (CBPO, 2020).

DO solubility in water is sensitive to temperature. Higher water temperatures also increase the consumption of oxygen by increased respiration and strengthened stratification. Figure 10 isolates the various physical conditions affecting Chesapeake Bay hypoxia under climate change. Physical conditions include estimated increased water-column temperature, sea level rise, and watershed flows (flows in this case isolated from associated nutrient and sediment loads) for 2025 Phase 3 WIP conditions compared to 1995 Phase 3 WIP conditions (base scenario of 1991–2000 reference hydrology). Under the estimated 2025 Phase 3 WIP loads and conditions, solely from a 1 °C temperature increase, the increase in average summer (June–September) Chesapeake hypoxic water volume (<1 mg/L) is estimated to be in part due to

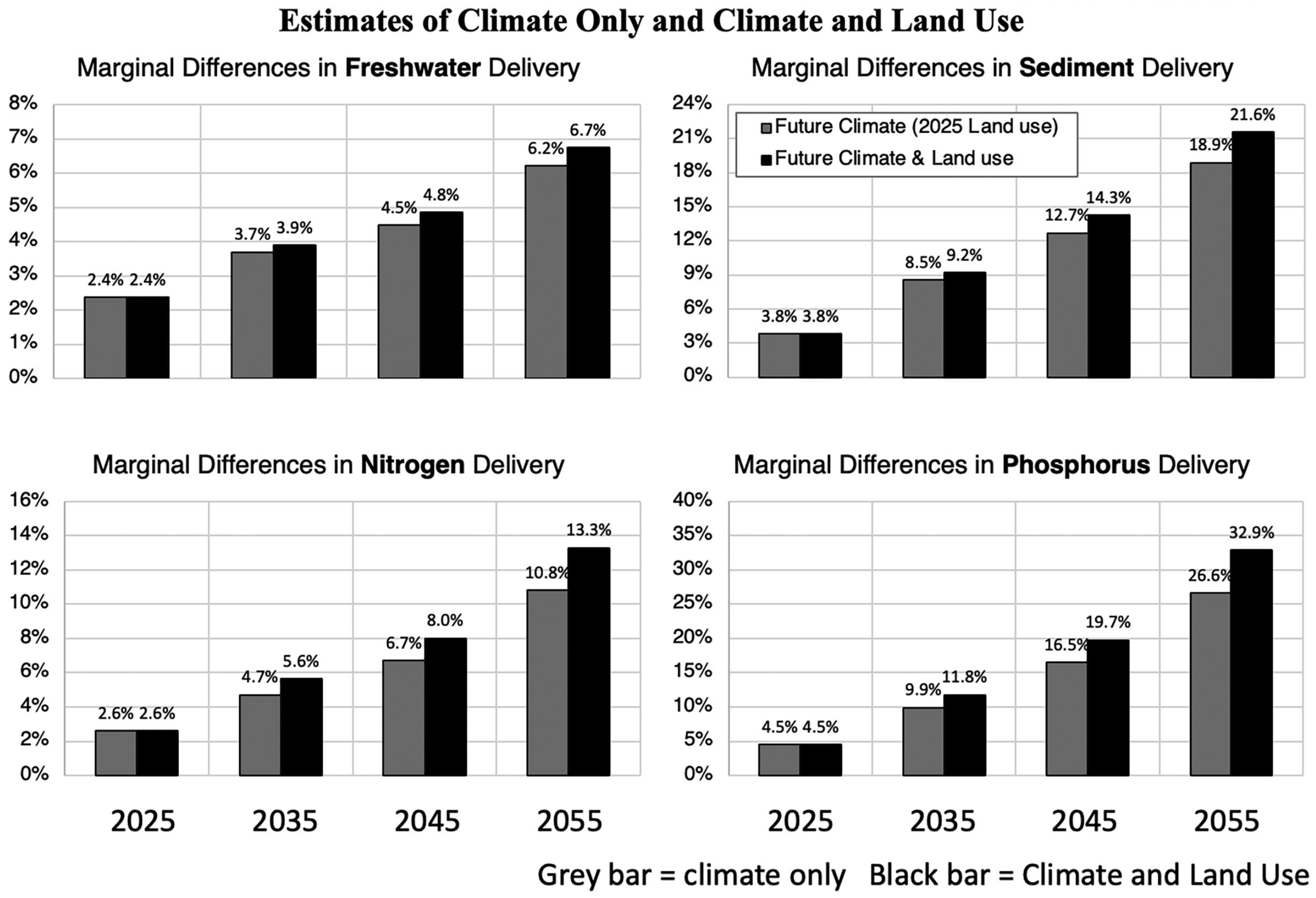


FIGURE 9 Estimated changes due to climate change (gray bar) and the combination of climate change and land use (black bar) for the years 2025, 2035, 2045, and 2055 relative to the 1991–2000 hydrologic averaging period.

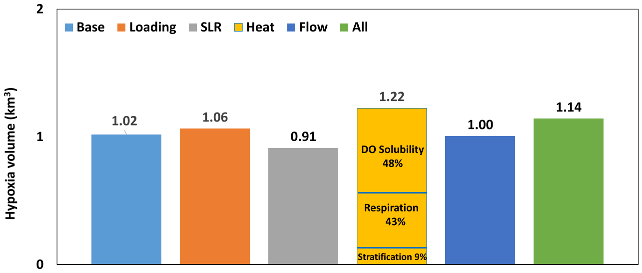


FIGURE 10 Estimated hypoxia effects under 2025 Phase 3 WIP conditions with no climate change effects (light blue bar), with the addition of climate change watershed loads (orange bar) with the addition of 2025 sea level rise (SLR, gray bar), with the addition of 2025 tidal water temperature increases (yellow bar), with the addition of watershed flows (dark blue bar), and with all four factors combined (green bar). Units of km^3 for summer (June–September) hypoxia volume (<1 mg/L) average for 1991–2000 in the whole Bay.

decreased solubility of oxygen (48%), in part from increased respiration (43%), and also from increased stratification (9%) (Figure 10—yellow stacked bar). Individual physical conditions of warmer tidal waters (yellow stacked bar) and sea level rise (gray bar) both had a greater influence on Chesapeake hypoxia than the increased loading from the watershed and airshed (orange bar) (Figure 10).

3.3.2 | Influence of sea level rise and greater watershed inflows on water quality

Sea level rise and greater watershed inflows have a major influence on Chesapeake water quality (Cai et al., 2021 this featured collection; Irby et al., 2018; St-Laurent et al., 2019, 2021; Tian et al., 2022 this featured collection). Both are physical conditions that increase the physical process of gravitational circulation which in turn increases the inflow of coastal ocean water to bottom waters and reduces average annual hypoxia in the Chesapeake (Figure 10). Compared to the sole influence of the increase in watershed and airshed nutrient loads brought about by climate change (orange bar), sea level rise (gray bar) was almost three times more effective at reducing summer average hypoxia.

Likewise, the sole influence of the higher watershed flows (Figures 5 and 10) brought about by climate change (dark blue bar) were half as effective at reducing hypoxia than the sole influence of increased loads from the watershed and airshed brought about by climate change. The essential distinction here is that in this sensitivity scenario only the increased freshwater flows from the watershed brought about by climate change are assessed. The model allows the separate assessment of watershed inflows and watershed loads. If the nutrients associated with the higher flows were included then hypoxia would increase.

The case that sea level rise and greater watershed inflows reduce hypoxia is further demonstrated in Figure S3, which shows a spatial view of the single contribution of increased sea level rise, watershed inflow, tidal water temperature, and all factors combined. The physical conditions of increased sea level rise and watershed inflow under climate change conditions are estimated to reduce hypoxia. However, the influence of increased temperature in increasing hypoxia to a greater extent than sea level rise and watershed flows in alleviating it can be seen in the final two panels of Figure S3.

3.4 | Minor climate change impacts in the estuary

Minor climate change influences in the estuary on Chesapeake hypoxia include up-estuary salt intrusion, adjustments of algal growth sensitivity to temperature, wind effects, and at least until midcentury, tidal wetland loss from sea level rise.

3.4.1 | Increased up-estuary salt intrusion

Increased up-estuary salt intrusion can have deleterious effects particularly for tidal fresh water-supply intakes, but in Chesapeake Bay few tidal fresh water public water-supply intakes are of immediate concern. In addition, the 2017 Chesapeake Bay WQSTM was unable to discern a difference in up-estuary salt intrusion as a result of climate change, perhaps because of insufficient spatial resolution.

3.4.2 | Influence from temperature increases on phytoplankton biomass

Algal production increases with temperature. Chlorophyll concentration, a surrogate for algal biomass, is a numeric water quality standard in the tidal James River and in the District of Columbia waters of the Potomac, two major tributaries to the Bay. In the James River there was an increase in chlorophyll concentrations and nonattainment in the water-quality assessment of chlorophyll when the higher temperatures of 2025 climate change were compared to the base calibration year of 2005 for the James Chlorophyll model (Cerco & Noel, 2019; Shenk, Bhatt, et al., 2021; Wang et al., 2019).

No more than a 2°C temperature increase was simulated under climate change conditions. Over that temperature increase, algal production rose under the assumption of algal community succession as algal communities become better adapted to higher temperatures over time (Dutkiewicz et al., 2013; Thomas et al., 2012). At temperatures higher than the mid-30s °C the algal production response to further temperature increases is unknown. Although algal parameterization for the fresh water algal group (Group 1) had an agal growth temperature optimum of 37°C in the WQSTM the temperatures simulated in the model were always several degrees less than the parametrized optimum. This allowed algal production to increase for the few degrees above 30°C simulated under climate change conditions while allowing the model to remain effectively and operationally silent on the unknown question of what happens to algal production above 35°C. As a point of comparison, an examination of latitudinal variation in marine algal community optimum temperature found that communities at low latitudes had high optimum temperatures but rarely exceeded 35°C (Thomas et al., 2012). Likewise, a modeling study examined global warming in marine phytoplankton communities using optimum temperatures that reached values of 35°C and found that ecological shifts toward higher optimal temperatures were likely (Dutkiewicz et al., 2013). A model simulation of an adjacent coastal estuary to the south of the Chesapeake, the Neuse River, had an algal optimal growth temperature of 35°C (Bales & Robbins, 1999).

Although the chlorophyll concentrations increased by a few μg/L with the additional 1°C in the tidal water column under 2025 climate change conditions, the effects of increasing algal biomass on the DO and water clarity standards were small but meaningful in the James River chlorophyll assessment. Although small in effect, the adjustment of algal growth curves to represent future higher tidal water temperatures is necessary for proper chlorophyll assessment under climate change conditions.

3.4.3 | Influence from changes in wind speed or direction

Changes in mean wind velocity predicted by the GCM ensemble were slight, on the order of only 0.1 m/s, for the 2035, 2045, and 2055 future climate scenarios. The 0.1 m/s change in wind velocity was insufficient to have an effect on water quality and hypoxia in the Chesapeake and was therefore not included in climate change simulations (Shenk, Bhatt, et al., 2021; Wang et al., 2013, 2015).

3.4.4 | Influence from loss of tidal wetlands

Loss of tidal wetlands results in a loss of nutrient attenuation (Cerco & Tian, 2021 this featured collection) as well as an increase in nutrient loading from eroded material (Cornwell et al., 2021 this featured collection). Tidal wetland loss from sea level rise is estimated to be relatively minor for the 30-year period of 1995 to 2025. Chesapeake tidal wetland area is estimated to remain at a relatively constant area of about 130,000 ha until 2035. However, Cerco and Tian (2021 this featured collection) estimate the area of Chesapeake tidal wetlands to decrease by 27% between 2025 (0.22 m of sea level rise) and 2055 (0.53 m of sea level rise). The result will be a considerable loss of tidal wetland denitrification and other nutrient attenuation processes, from an estimated 8.46 million kg nitrogen attenuation per annum in 2025 to 6.8 million kg per annum in 2055 (Figure S4). Having an estimate of the tidal wetland loss over time and its implications for water quality as well as for critical living-resource habitat in the Bay helps water quality managers to address near-term and far-term problems in Bay restoration and the risk associated with the failure to address tidal wetland loss, particularly in the long term (Cerco & Tian, 2021; Cornwell et al., 2021 this featured collection).

3.5 | Climate change impacts on watershed loads under 2025 and 2055 Phase 3 WIP and No-Action conditions

The reduction of nitrogen loads under the 2025 Phase 3 WIP Scenario was 48.5 million kg or a 33-percent reduction compared to the 1991–2000 base scenario (Table S1). For phosphorus, the estimated reduction of loads from the 1991–2000 base scenario to the Phase 3 WIP scenario condition was 3.5 million kg, or a 35% reduction. The reduction of nutrient loads from the base scenario to the Phase 3 WIP scenario reduced hypoxia (DO <1 mg/L) from 2.82 to 1.08 km^3, a 62% reduction and a level that meets Chesapeake habitat requirements of the water quality standards (Figure 11). If the additional load reductions needed due to Conowingo Reservoir infill and 2025 climate change were added to the Phase 3 WIP load reductions, the nitrogen reduction would be even more, increasing to 54.0 million kg nitrogen and 4.2 million kg phosphorus resulting in even further hypoxia reductions (not shown).

In contrast, if no nutrient controls had been implemented, the loads from the No-Action Scenario compared to the Phase 3 WIP Scenario would essentially double for nitrogen and increase by a factor of three for phosphorus (Table S1), which would lead to an estimated hypoxia volume of 3.87 km^3 of DO <1 mg/L compared to the 2025 Phase 3 WIP Scenario of 1.08 km^3, a 258% increase of hypoxic volume (Figure 11). By 2055, under No-Action Scenario conditions, the nitrogen and phosphorus loads relative to the 2025 Phase 3 WIP loads further increase due to climate change and growth with an estimated 294% increase in hypoxic volume for DO <1 mg/L and a 109% increase in DO <3 mg/L (Figure 11).

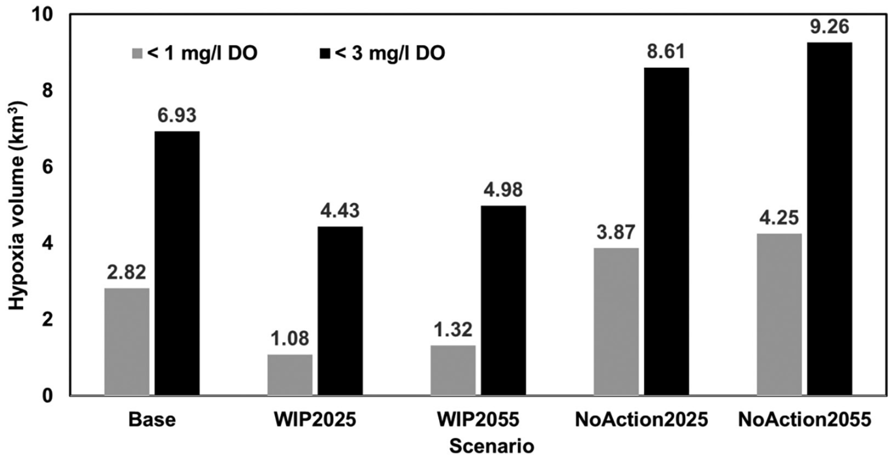


FIGURE 11 The 2025 and 2055 No-Action Scenario compared to the Phase 3 WIP scenario in 2025 and 2055. Summer hypoxia volume averaged over 10 years in all tidal waters of the Bay from the June to September period and showing the critical values of 1 mg/L DO for the deep channel DO water quality standard and 3 mg/L DO for the deep water DO water quality standard. Units in cubic kilometers.

4 | DISCUSSION

4.1 | Assessment of nitrogen, phosphorus, and sediment loads under different land use and climate change scenarios

There is a synergistic influence of climate change and growth at the local scale (Claggett et al., 2023 this featured collection) with both contributing to higher flows, water temperatures, and hydrologic flashiness. Alamdari et al. (2022) demonstrated that on the local scale of rapidly developing watersheds, land use may have a greater influence than climate change on nutrient and sediment load export. However, although growth and other land-use change can have dominant impacts at a local scale, climate change influences all land uses everywhere in the watershed and has a more global influence on nutrient loads delivered to the Chesapeake and their impact on tidal waters. Therefore, climate change influences the loads from the entire watershed to a greater degree than does land-use change.

The scenarios of 2035, 2045, and 2055 for climate change alone (gray bars, Figure 9) have an annual average load increase of nitrogen, phosphorus, and sediment relative to the 2025 climate change and land use. When 2035, 2045, and 2055 land use were also added (black bars, Figure 9) the land use change was always comparatively less effective at increasing load than climate change. The increased precipitation volumes and intensities influence all land uses in the entire watershed, whereas land-use change from population growth occurs only on a fraction of the landscape.

For example, the estimated nitrogen loads from the 2055 climate change scenario (2055 gray bar in the nitrogen delivery panel, Figure 9) increased 8.2% compared to the 2025 climate change (2025 gray bar in the nitrogen delivery panel, Figure 9). However, when 2055 land use was introduced in the scenario along with 2055 climate change the nitrogen loads only increased another 2.5% over the case of climate change alone (2055 gray and black bars in the nitrogen delivery panel, Figure 9). The greater influence of climate change relative to land-use change is seen in estimated flows and in loads from phosphorus and sediment as well for the 2035 and 2045 scenario estimates.

The effect of land-use change on nutrient and sediment loads principally tracks the expansion of developed land. In some cases, if development is on row crop land, the net overall loads could diminish. If natural land uses like forest become developed land, then net nutrient and sediment loads increase. Nevertheless, while the influence of land-use change is less than climate change overall in the Chesapeake watershed loads, there are local streams and basins where land-use change has a dominant influence in nutrient and sediment loads and stream health (Abdelnour et al., 2010; Alamdari et al., 2022).

4.2 | Climate change in perspective to other major load reductions

To offset current climate change impacts from 1995 to 2025 on water quality, the scenarios indicate an additional 2.3 million kg of nitrogen and 0.3 million kg of phosphorus per annum will need to be reduced beyond what is called for in the Chesapeake Bay TMDL (2010 allocations updated to 2017 nutrient targets, also called the Phase 3 WIP loads). For climate change between 2025 and 2035, this amount is estimated to increase by a further 2.4 and 0.4 million kg of nitrogen and phosphorus, respectively, to maintain living resource-based water quality standards.

The State and Federal CBP partnership has been reducing nutrient and sediment loads to the watershed and tidal Bay from 1985 to the present. To put the climate change nutrient load reductions in context, the record of CBP nutrient load reductions can be divided into separate periods. The first period is from 1985 to 2009, immediately prior to when the historic 2010 Chesapeake Bay TMDL was established. The second was the period of 2010 to 2019, under the TMDL Phase 1 WIP and Phase 2 WIP. The third period covers 2020 to 2025 under the Phase 3 WIP implementation plan. Additional load reduction components are for reservoir infill and for 2025 to 2035 estimated climate change (Figure 12).

4.2.1 | Estimated load reductions from 1985 to 2009

The load reductions during this period were principally undertaken through tributary strategies, which were established in watersheds of Pennsylvania, Maryland, Virginia, and District of Columbia (USEPA, 2021b). The tributary strategies and other efforts are estimated to have reduced nitrogen and phosphorus loads by 28.1 and 5.6 million kg per annum, respectively, as shown in Figure 12.

4.2.2 | Estimated load reductions from 2009 to 2019

Nutrient and sediment reductions from 2009 to the present were undertaken under the WIPs of Phase 1 and Phase 2 WIPs. By 2010 the WIPs were inclusive of the entire Chesapeake watershed including New York, West Virginia, and Delaware. The Phase 1 and Phase 2 WIP efforts reduced nitrogen and phosphorus by a further 8.8 and 0.9 million kg per annum, respectively, during the 2009 to 2019 decade (Figure 12).

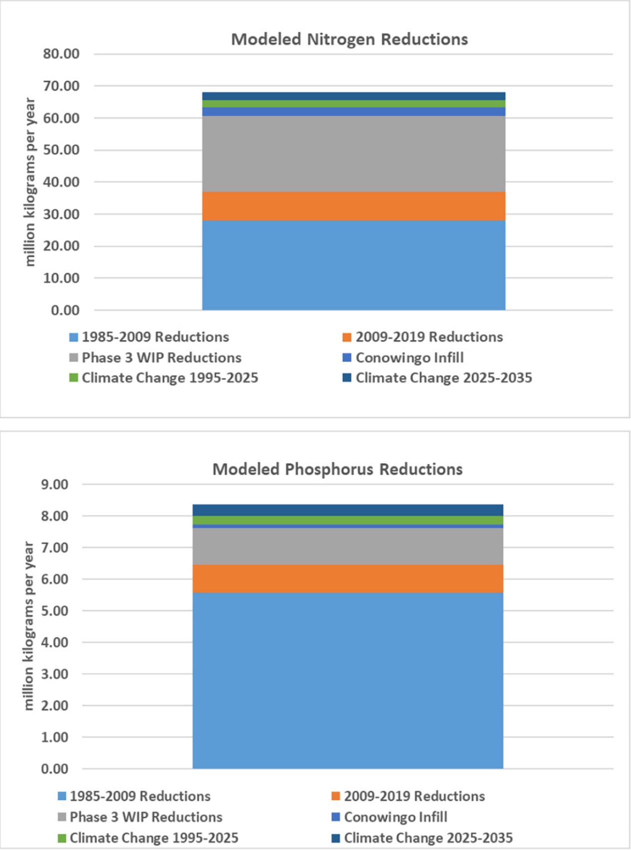


FIGURE 12 Climate change nutrient load reductions in perspective showing estimated Chesapeake nitrogen and phosphorus load reductions from 1985 to 2009 (blue), estimated load reductions from 2009 to 2019 (orange), load targets of the Phase 3 WIP (gray), load targets from reservoir infill (light blue), load targets for 1985 to 2025 climate change (green), and estimated load targets for 2025 to 2035 climate change (dark blue).

4.2.3 | Load targets of the Phase 3 WIPs

The Phase 3 WIP nutrient reduction targets, to be implemented between 2020 and 2025, covered growth in the watershed from 2010 to 2025 as well as the nutrient loads remaining to be reduced from previous WIPs (Figure 12). The Phase 3 WIPs, once implemented, will reduce nitrogen and phosphorus loads by an additional 23.8 and 1.1 million kg per annum, respectively.

4.2.4 | Load targets from reservoir infill

A major finding during the assessment of growth and climate change in the Chesapeake was that decreased reservoir storage between the 1990s and 2025 in the Conowingo Reservoir increased nutrient and sediment loads to the Bay. The Conowingo Reservoir is in a dynamic steady-state equilibrium condition of reservoir infill, with the mass of nutrients and sediment into and out of the reservoir in balance over the long term, but not in the short term. In fact, the reservoir is always moving toward, but never quite achieving equilibrium, in which one hydrology period of extreme flows could scour out years of deposition only to be followed by a more quiescent hydrology period of refilling. As shown in Figure 12, the CBP agreed that additional nitrogen and phosphorus reductions of 2.8 and 0.1 million kg per annum, respectively, would offset the impact of reservoir infill (Cerco, 2016; Cerco & Noel, 2016; Linker, Batiuk, et al., 2016; Linker, Hirsch, et al., 2016). Ultimately, the greater precipitation volumes and intensities under climate change conditions and the estimated increase in flow will result in a new dynamic equilibrium, one with different bioavailability and greater variability in storage between scour and refill, and therefore increase the long-term export of material (Cerco, 2016; Cerco & Noel, 2016).

4.2.5 | Load targets for 1995 to 2025 climate change

Compared to the three other periods of nutrient-load reduction from 1985 to 2025 implementation of the Phase 3 WIPs, the nutrient targets to offset climate change are small. Estimated nutrient load reductions needed to address climate change for the three-decade period from

1995 to 2025 are 2.3 million and 0.3 million kg per annum for nitrogen and phosphorus, respectively. In comparison, the estimated nutrient load reductions from 1985 to full implementation of the Phase 3 WIPs are 60.7 and 7.6 million kg per annum for nitrogen and phosphorus, respectively (Figure 12).

4.2.6 | Estimated load targets for 2025 to 2035 climate change

Likewise, the further load reductions to address climate change between 2025 and 2035 are currently estimated to be 2.4 and 0.4 million kg per annum for nitrogen and phosphorus, respectively (Figure 12).

4.3 | Climate change assessments in other coastal systems

Climate change has been extensively studied in the Chesapeake Bay and other coastal estuaries. An early and extensive study of the different effects of climate change in the Chesapeake was by Pyke et al. (2008). The current study is in agreement with Pyke et al. as well as with Sinha et al. (2017) who found that increased storm intensity and precipitation lead to increased nitrogen loads, particularly in northeastern U.S. estuaries. Newton et al. (2020) in a study of 15 tidal wetlands on five continents described sea level rise as a major cause of tidal wetland loss with attendant loss in ecosystem services of nutrient attenuation and habitat. Nelson and Zavaleta (2012) also found a loss of tidal wetland nutrient attenuation with sea level rise.

Several studies examined increased watershed flow and nutrient loads with future climate change as well as with land use change. In an examination of effects of climate and land use changes on water quantity and quality in the coastal watersheds of Narragansett Bay, Ross and Randhir (2022) concluded that climate impacts were much more significant than land-use effects. Others have had similar findings. Piniewski et al. (2014) in a Polish watershed draining to the Baltic Sea found that future climate change was estimated to have more impact on increased flows and loads to tidal waters than urban growth. Qi et al. (2009) also found that the influence of future climate change was greater than that of land use change in a North Carolina estuary.

4.4 | Limitations and uncertainty in the analysis

Limitations of the CBP analysis of climate change are described in Supporting Information. However, a major limitation of this study was that only deep water and deep channel DO water quality standards of hypoxia were examined. Although the open water attainment of DO in shallow waters was unavailable because of insufficient model spatial scale of the WQSTM, many living resource benefits are dependent upon conditions in the shallow water habitat and therefore this was a limited assessment of climate change impacts. This is being addressed in a new assessment of 2035 climate change impacts to the Chesapeake TMDL with an estuarine model spatial scale several times higher resolution than the WQSTM (Cai, Zhang, et al., 2022 this featured collection).

There is an additional potential compounding of uncertainty associated with integrating several models with their attendant assumptions. To a large extent this is mitigated by the extensive calibration and model peer reviews of the Phase 6 land use, watershed, airshed, and estuarine models as documented in the Methods. Moreover, because the CBP plans to revisit and renew the climate change assessment on a decadal basis there is in place a self-correcting, adaptive management approach that adjusts the course of management as needed for climate change nutrient reductions in the Chesapeake Bay going forward.

5 | CONCLUSIONS

5.1 | Estimated load targets for 2025 and 2035 climate change

At the initiation of any modeling assessment, practitioners want to know, “What are the Big Problems and what are the Little Problems.” The big problems need to be carefully tracked and addressed but the little problems much less so. This article provides a guide to the assessment of nutrient loads and eutrophication under climate change conditions in coastal estuaries, particularly those experiencing future hotter and wetter conditions. However, because of the need for ongoing corrections and adjustments to climate change over time the assessment of climate change in the Chesapeake is an ongoing process.

Estimated nutrient load reductions needed to address climate change for the three-decade period from 1995 to 2025 are 2.3 million and 0.3 million kg for nitrogen and phosphorus per annum, respectively. Load reductions to address climate change between 2026 and 2035 are currently estimated to be 2.4 and 0.4 million kg per annum for nitrogen and phosphorus as shown in Figure 12. That estimate is being revisited and work is underway in the next phase of the CBP integrated land-use, airshed-, watershed-, tidal-water, and living-resource models to refine the 2035 nutrient load-reduction estimates as well as providing nutrient load estimates for 2045, 2055, 2075, and 2100 climate change conditions.

5.2 | Lessons learned

I current study provides decision makers with a tool to quantify the various aspects of climate change impacts and to weigh the trade-offs in costs and benefits of addressing, for example, CSO improvements compared to tidal wetland protection/restoration under future climate conditions. In addition, despite the many impacts of climate change in the Chesapeake, decision makers found that future climate conditions are manageable and that any retrenchment from continued commitment to maintaining water quality standards under climate conditions is unwarranted (PSC, 2020).

Climate change has a major influence on Chesapeake water quality standards. It is the global influence of climate change on watershed nutrient and sediment loads along with the additional physical influence of climate change on tidal Bay water-column temperature that causes the effect of climate change to have more influence on attainment of the DO deep channel water quality standards than land use change.

The difference in the estimated increase in loads from three decades of climate change compared to land-use change is notable because conventional wisdom was that the increase in loads from land-use change was the predominant headwind in the required nutrient and sediment reductions being brought about by the Chesapeake TMDL and the tributary strategies (Linker et al., 2000) that preceded it. However, this does not diminish the importance of managing for land use change at all scales and particularly at the local scale where land use change has high impacts.

6 | SUMMARY

The influence of climate change on increasing Chesapeake nutrient and sediment loads and associated water quality standard nonattainment has only been recognized in the last two decades and has now been quantified in detail for major and minor climate change influences on the Chesapeake TMDL. Understanding the overall influence of climate change in the Chesapeake was obscured by consistent application of the 1991–2000 CBP reference hydrology and 1995–1997 critical period hydrology, which imposed the condition of stationarity on hydrology and associated loads of nutrients and sediment. Nevertheless, by 2020, the risk of climate change to the Chesapeake TMDL was widely recognized and the CBP State and Federal partnership addressed climate change as a numeric management target.

The CBP climate change analysis looked at 22 different influences on Chesapeake water quality standards, principally on the living resource-based oxygen concentration criteria in the deep waters of the Chesapeake. The major and minor influences of climate change were identified and quantified allowing decision makers to choose appropriate levers of watershed or estuarine management to respond to its challenge for the Chesapeake TMDL.

In the Chesapeake watershed, the major influences are greater precipitation volumes and to a lesser extent intensities, which increase flows and consequently nitrogen, phosphorus, and sediment loads. On the other hand, increased evapotranspiration from higher watershed temperatures reduces and ameliorates higher future flows and loads.

In the Chesapeake tidal waters, the estimated key impacts on water quality standards were higher water temperatures, which decrease DO saturation rates and increase stratification, and deep-water respiration causing an amplification of hypoxia in the Chesapeake. However, sea level rise and freshwater inflows (in the absence of their associated higher nutrient loads) from the watershed are estimated to increase estuarine circulation and ameliorate somewhat the estimated increase in hypoxia.

There is now broad recognition that climate change is a multi-generational challenge for Chesapeake Bay restoration. The impacts of climate change on Chesapeake water quality are inevitable over the next half century regardless of future paths of higher or lower CO_2 emission reductions because of slow rates of global processing and clearing of CO_2. Flow, nutrient, and sediment loads from the watershed and tidal Bay hypoxia are estimated to continue to increase from 1995 to 2055 from climate change. In response, the CBP is developing better management tools combined with an ongoing multi-decadal plan of adaptation to climate change to maintain the Chesapeake TMDL and restoration objectives for the Chesapeake. The assessment of climate change impacts on the Chesapeake TMDL is an iterative process and reassessments each decade are currently planned.

AUTHOR CONTRIBUTIONS

Lewis C. Linker: Conceptualization; formal analysis; investigation; methodology; project administration; resources; supervision; writing – original draft; writing – review and editing. **Gary W. Shenk:** Formal analysis; investigation; methodology; writing – review and editing. **Gopal Bhatt:** Formal analysis; investigation; methodology; writing – review and editing. **Richard Tian:** Formal analysis; investigation; methodology; writing

– review and editing. **Carl F. Cerco:** Formal analysis; investigation; methodology; writing – review and editing. **Isabella Bertani:** Formal analysis; investigation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors delare no conflict of interest.

DATA AVAILABILITY STATEMENT

At the time of publication, data that support the findings of this study were not available from the Chesapeake Bay Program Office. However, the data are available upon request from the corresponding author.

ORCID

Gary W. Shenk https://orcid.org/0000-0001-6451-2513

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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