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INTRODUCTION

Featured Collection introduction: Climate change in Chesapeake Bay

1 | BACKGROUND

Mathematical modeling has provided guidance to environmental management of Chesapeake Bay for more than 30 years. The need for model support became obvious as management response was required to resolve complex problems including bottom-water hypoxia, submerged aquatic vegetation (SAV) die-off, and living-resource depletion. The first application of the current, modern modeling framework was to provide support for a 1991 re-evaluation of a 1987 nutrient reduction goal. The framework included a three-dimensional, time-varying, hydrodynamic model, a eutrophication model linked to the hydrodynamic model, and a predictive sediment diagenesis model. Volumetric flows and nutrient loads to the Bay were provided by an independent watershed model.

The models have been repeatedly revised and upgraded as new management needs reveal themselves. The initial modeling phase was followed by a Tributary Strategy management effort. This phase refined the Bay model computational grid in the major western tributaries and introduced direct computation of living resources, including SAV and benthos, into the model framework. Model refinements and re-calibrations have continued into the present in response to the need evaluate progress toward management goals. Initial management commitments to reduce nutrient and sediment loads to the Bay were largely voluntary on the part of watershed states and the District of Columbia. In 2010, however, the requirement for a statutory Total Maximum Daily Load (TMDL) placed new demands for management support on the management models. Most recently, the models provided guidance for a 2017 Mid-Point Reassessment of the 2010 TMDL.

Now, climate change presents a new challenge to management plans for Bay restoration. Challenges include alterations to hydrology in the watershed caused by changing precipitation, alterations to circulation in the Bay caused by increasing sea level, and alterations to eutrophication processes induced by increasing temperature. A new generation of modeling is taking place to provide insights into climate change effects in the Bay and to provide guidance to accommodate the projected changes. This Featured Collection presents an assembly of publications which describe a wide range of recent model activities.

2 | OVERVIEW OF THE FEATURED COLLECTION

2.1 | Climate change in the watershed

Predictions of nutrient and sediment loads from the watershed under various climate change scenarios are crucial to projecting climate change impacts on Bay water quality. Nitrogen loading from the watershed is a key factor contributing to eutrophication of Chesapeake Bay. Nitrogen fuels primary production of organic matter, a portion of which settles to the bottom of the Bay. Subsequent respiration, supported by this organic matter, consumes dissolved oxygen (DO), resulting in bottom-water hypoxia. Nitrogen enters the Bay in multiple particulate and dissolved forms. Of these, dissolved inorganic nitrogen, primarily nitrate (NO_3), is most readily available to primary producers of organic matter. Consequently, knowledge of the NO_3 fraction in the total nitrogen (TN) load is crucial to predicting the impact of variations in TN loading on eutrophication processes.

Bertani et al. (2022) employ a hierarchical statistical model to investigate how the NO_3 fraction varies as a function of the TN load. The model is based on observations at more than 100 stations within the Chesapeake Bay watershed, collected over the period 1985–2016. They investigate the response of the NO_3 fraction across river stations, where TN loads vary largely due to anthropogenic loading to the watershed, versus within river stations, where TN loads vary largely due to hydrology. Results indicate that increases in TN loads resulting from changes in anthropogenic inputs lead to an increase in the NO_3 fraction, while a decrease in the NO_3 fraction occurs when increases in TN loads are driven by increased streamflow.

Precipitation and streamflow are anticipated to increase as a result of climate change in the Chesapeake Bay watershed. The results of this study suggest that the increased streamflow will be accompanied by a decrease in the NO_3 fraction of TN loads. The authors caution that this inference is not conclusive, however, since the increased streamflow will be accompanied by numerous other factors which are not considered in the statistical model.

2.2 | Temperature effects on Chesapeake Bay

The most obvious indicator of climate change is temperature. Hinson et al. (2022) employ observations and a hydrodynamic model to examine temperature trends and the processes affecting the trends in Bay waters. They find that since 1985, the mainstem Bay is warming at a rate of 0.02 ± 0.02°C/year. The warming rate in summer, 0.04 ± 0.01°C/year, is greater than the rate in winter, 0.01 ± 0.01°C/year. The preponderance of the warming is driven by atmospheric effects, temperature and radiation. Near the Bay mouth, however, ocean warming accounts for half the summer temperature increase in Bay bottom waters.

St. Laurent et al. (2022) present a historical, data-driven assessment of climate variability and extremes in near-shore regions of the Bay. Their work is a cautionary tale of the difficulty of discerning climate trends in the presence of natural variability and cyclic climate modes. They focus on "centennial" trends and emphasize the need for records at least 60 years in length to avoid confusing cyclic climate modes for trends. They also note that local analyses can differ from coarser regional-level and state-level analyses. Among the trends they detect are annual and seasonal declines in the percentage of cold days and increases in precipitation intensity. They also note annual and seasonal increases in the percentage of warm days. These trends in warm days are present throughout the year in the northern Bay but are present only in spring and summer in the southern Bay.

Tian et al. (2022) provide a first look at the effects of temperature increase on eutrophication processes in the Bay. The investigations indicate that response to warming is influenced by physical features of the Bay and by the timing and details of the climate-induced changes imposed in their model scenario analyses. They investigate the impact of a uniform increase in water temperature. They employ the CH3D hydrodynamic and ICM eutrophication models, largely as configured for the investigation of Bay TMDLs (Cerco & Noel, 2019; Cerco et al., 2010). Temperature change is induced by altering air temperature and oceanic boundary conditions. The alterations are based on projected (air temperature) and observed (boundary conditions) 30-year trends. An increase in water temperature of 0.85–0.9°C results. The emphasis of their study is on DO. They find that the volume of hypoxic water (DO $<2\ \mathrm{g/m^3}$) increases by 9% and the duration of hypoxia increases by 6.6%. Reduction in DO saturation concentration is responsible for 56% of the change in hypoxic volume. Alterations in biological processes account for 33% of the change in volume. The remaining 11% is attributable to increased vertical stratification.

The investigation concurs with a previous study (Scully, 2016) that the DO response is greatly influenced by the presence of a shoal roughly 25 km upstream from the Bay mouth. The shoal introduces convergence of upstream and downstream flowing water and forces downwelling and vertical mixing. The downwelling brings water of surface temperature and DO concentration to the bottom, upstream of the shoal. This water then propagates upstream, driven by classic gravitational circulation. Owing to the temperature increase, the DO saturation concentration of the surface water is reduced as is the amount of oxygen supplied to the bottom. The reduction in oxygen supply to the bottom is responsible for the predominant influence of DO saturation concentration on total increase in hypoxic volume. The Rappahannock Shoal is a distinct feature of Chesapeake Bay. The outstanding influence of this feature indicates caution is necessary in any attempt to generalize results of climate change among different estuaries.

Testa et al. (2022) shift the investigation of climate change impact on DO from the mainstem of Chesapeake Bay to a shallow tributary, the Chester River, located on the eastern shore of the Bay. Shallow estuarine systems have several unique characteristics compared to larger, deeper systems. In the case of the Chester, the tributary demonstrates two species of hypoxia. Near the mouth, the Chester experiences seasonal, deep-water hypoxia, similar to the mainstem Bay. Elsewhere, the system exhibits diel cycling of hypoxia due to diel cycling of production and respiration.

The investigators employ the ROMS hydrodynamic model and the RCA eutrophication model (Testa et al., 2014) applied to an independent, detailed Chester River computational grid. They examine the effects of temperature change, nutrient load reductions, and alterations in the open-mouth boundary conditions. Temperature increases of 0.75 and 1.25°C simulate the impact of climate change. Nutrient load reductions (50% nitrate or phosphate) test sensitivity to potential management actions. Changes in the DO boundary condition (increased to reflect reduced hypoxia in Chesapeake Bay) test the sensitivity of Chester River to conditions independent of local management actions.

The investigators note the DO concentration and hypoxic volume are more sensitive to temperature increases and alterations in boundary conditions than to local nutrient load reductions. Increased temperature produces increased respiration and increased hypoxic volume. The improvement in DO concentration at the mouth increases the oxygen content of water exchanged with Chesapeake Bay and reduces hypoxic volume in the Chester. The limited sensitivity to local nutrient load reductions may be due to the existing turbid conditions in the Chester. Production in the system may be currently light-limited and, thus, less sensitive to nutrient controls. In addition, the limited sensitivity illustrates the influence of the current, severely enriched nutrient conditions present in the Chester. Reduction in local loads is insufficient to reduce nutrients to limiting concentrations. The reader is cautioned against concluding nutrient load reductions provide minimal benefit to the Chester River. Rather, Bay-wide nutrient load reductions are required to improve DO in this relatively small tributary. The reduction in Chesapeake Bay hypoxia resulting from Bay-wide load reductions will improve conditions in the Chester by increasing the oxygen concentration of water entering the Chester River mouth.

The investigation of the Chester is consistent with the current management emphasis on shallow-water, nearshore environments. One significant conclusion is that improvement in Chester River hypoxia requires improvement in the adjacent portions of Chesapeake Bay. The paper presents detailed insights into primary production, respiration, and hypoxia. Clearly, investigation of additional shallow tributary systems is warranted to demonstrate the extent to which insights from the Chester River are generally applicable.

2.3 | Effects of altered sea level on Chesapeake Bay

The CH3D hydrodynamic model employed by Tian et al. (2022) operates on a structured computational grid composed of quadrilateral elements. The CH3D model provides good representation of physical processes in the mainstem Bay and larger tributaries. The use of quadrilateral elements, however, restricts the ability of the model to conform to the complicated geometry of nearshore areas. A hydrodynamic model based on an unstructured grid, composed of triangular elements, would likely provide improved representation in these regions. Cai, Zhang, et al. (2022) employ just such a model: SCHISM (Zhang et al., 2016). SCHISM operates on a hybrid computational grid which combines triangular and quadrilateral elements. As applied to Chesapeake Bay, quadrilateral elements are used in major channels while triangular elements are used in smaller tributaries and nearshore areas. SCHISM is combined with ICM eutrophication kinetics and a sediment diagenesis model nearly identical to Tian et al. (2022).

The SCHISM-ICM combination is first validated in a continuous application to the Bay system for the years 1991–1995. Model results are compared to observed salinity, chlorophyll, DO, nitrate, primary production, and hypoxic volume. Comparisons are made in a variety of graphical and statistical formats. Their work demonstrates the ability of the SCHISM structure to represent eutrophication processes in regions of complex geometry and bathymetry.

Cai, Shen, et al. (2022) next employ the SCHISM-ICM combination to examine the effects of climate-induced change in sea level on Chesapeake Bay. Three increases in sea level are considered: 0.17, 0.5, and 1.0 m. To isolate the effect of rise in sea level, all other factors employed in the 1991–1995 validation (Cai, Zhang, et al., 2022) are left unchanged. This investigation contrasts with Tian et al. (2022) where change in temperature is considered but not sea level.

The investigators conduct a thorough investigation of physical and biological impacts in the mainstem Bay and tributaries. The primary physical effect is an increase in the volume of water exchanged with coastal waters due to enhanced gravitational circulation. The larger volume of oxygen-rich coastal water increases the bottom-water DO concentration up to 0.2 g/m^3 in the deep channel of the lower Bay. The pycnocline also rises, relative to the bottom, resulting in an increase in sub-pycnocline volume.

The primary biological effect is an increase in gross planktonic primary production in upper tributaries and shoal areas. The increase is attributed to an effective increase in the depth of the photic zone. The increased depth leads to increased light utilization in shallow areas of tributaries and shoals. The increase in gross primary production is accompanied by a general decrease in bottom DO in the same regions. Apparently, the additional oxygen production escapes to the atmosphere while additional organic matter settles to the bottom and results in enhanced respiration.

The increases in sea level are accompanied by increases in peak hypoxic volume, defined as the volume of water less than 2 g/m^3 DO. The authors note that numerous factors contribute to the increased hypoxic volume including enhanced respiration of organic matter and reduced vertical transport of DO to deep waters. The increased hypoxic volume appears to be largely attributable to the increased sub-pycnocline volume, however, since the increase in hypoxic volume is a relatively stable fraction, 10%–15%, of the increase in total volume.

The authors note that reviews of multiple model applications (St-Laurent et al., 2019) indicate the reviewed models share with SCHISM-ICM the same trends in DO resulting from sea level increase: increased DO in the bottom waters of the main channel and reduced DO in shallow regions. Other models do not necessarily concur with the SCHISM-ICM application that hypoxic volume increases. Numerous factors are cited which may contribute to the varied results. Differences in bathymetry may be a prime influence.

2.4 | Wetland migration and erosion

Rising sea level, induced by climate change, increases erosion at the seaward edge of tidal marshes resulting in net loss of marsh area and increase in the area of open-water regions. Marsh loss is associated with loss of “ecosystem services” including nutrient burial and nitrogen removal via denitrification. The eroded material may also release nutrients, while suspended in the water column or deposited to bottom sediments, thereby contributing to the eutrophication process. Cornwell et al. (2022) assemble and contribute essential observations and provide first-order estimates of the net effect of marsh erosion on nutrient exchange between marshes and adjoining open waters. Observations are assembled from 10 sites in upper Chesapeake Bay and include soil composition (carbon, nitrogen, phosphorus), denitrification rates, and nutrient burial rates. The authors also report on measurements of decomposition rates of marsh soil collected from four sites. Next, they estimate the net influence of marsh erosion on nutrient budgets of an idealized 1 ha upper Chesapeake Bay tidal marsh.

The decomposition studies indicate the first-order decay rate of eroded organic material is $5–10 \times 10^{-5}$ per day. Based on the low decay rate, the authors consider that only a small fraction of the eroded nutrients will be released before the eroded material is buried in sediments underlying the open waters which receive the eroded material. The assembly of data from multiple sites results in a range of observations and corresponding ranges in the estimated effects of marsh erosion. Results are summarized in a simple mass balance, based on net marsh loss rate of 1% per year. The total contribution of marsh nitrogen and phosphorus (erosion plus lost trapping) to open waters is ~2.5% of upper bay loading from the adjacent watershed. Less than 10% of this total mass is reactive and available, however. The authors conclude that the main biogeochemical consequence of losing marsh area is loss of denitrification and nutrient burial services rather than the addition of eroded nutrients to Chesapeake Bay.

Cerco and Tian (2022) examine the risk to Chesapeake Bay DO standards due to tidal wetlands loss and migration associated with rising sea level. They consider a range of sea-level increments up to 1.0 m by the year 2100. The spatial distribution of wetlands area is obtained from a preceding application of the Sea Level Affecting Marshes Model (SLAMM; Glick et al., 2008). SLAMM indicates a net increase in total Chesapeake Bay wetlands area, over 1996 base conditions, for rise in sea level up to 0.13 m. Net loss occurs for additional sea-level increments. Despite the loss in total wetlands area, some Bay segments experience an increase in local wetlands area due to wetlands migration into upland regions.

The influence of tidal wetlands on adjacent open waters is computed via a wetlands module which is incorporated into the ICM eutrophication model (Cerco & Noel, 2019). The module computes the exchange between wetlands and the adjacent water column of particulate carbon, nitrogen, and phosphorus and of dissolved nitrate, phosphorus, carbon, and oxygen. The module is parameterized based on observations and on mass balances around selected wetlands.

Results of the investigation indicate two risks to Chesapeake Bay DO standards. The first risk is to deep water and deep channel segments of the Bay. Declines in seasonal (June–September) average DO concentration up to 0.05 g/m^3 are possible. The DO declines are associated with wetlands loss and diminished nutrient removal. Diminished removal is the equivalent of an increase in watershed nutrient loading.

The second risk is to surface DO in open-water segments of the Bay. Declines in DO occur in shallow embayments and in tidal fresh regions and are caused by increased local wetlands area associated with landward wetlands migration. The DO declines are caused by direct wetlands respiration and may range from 1 to 2 g/m^3. DO increases up to ~0.4 g/m^3 are also possible in open-water segments which experience wetlands loss due to rise in sea level. The loss reduces DO uptake via wetlands respiration.

2.5 | Additional contributions

Several additional contributions to this Featured Collection are in various stages of review and production as of this writing. An overview of the watershed model and an examination of the influence of land use scenarios on future watershed loads supplement the current contributions on the watershed model. An additional examination of the effects of temperature increase on eutrophication processes in the Bay is anticipated. Finally, management implications of climate change in the Bay, including required revisions to watershed TMDL loads, are described. The reader is advised to watch for these contributions in future revisions to this Featured Collection.

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