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Impact of Wetlands Loss and Migration, Induced by Climate Change, on Chesapeake Bay DO Standards

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Research Impact Statement: Wetlands loss results in diminished DO in the deep channel due to diminished nutrient removal. Wetlands migration results in diminished DO in open surface water due to wetlands respiration.

ABSTRACT: A predictive wetlands module is added to an existing eutrophication model of Chesapeake Bay in order to evaluate the impact of wetlands loss and migration on dissolved oxygen (DO) standards. Loss and migration are expected due to increases in sea level associated with climate change. The module calculates fluxes of carbon, nitrogen, and phosphorus between wetlands and the adjacent water column. Calculations are performed for a range of sea-level increments up to 1 m. Wetlands areas, as a function of sea level, are obtained from an existing, independent, model applied to Chesapeake Bay. The results indicate two risks to DO standards. The first results from wetlands loss and simultaneous reductions in nutrient removal and burial by wetlands. Reduction in burial is the equivalent of a nutrient load increase and produces diminished DO in deep water and deep channel portions of the Bay. The second risk results from wetlands migration into upland areas adjoining shallow embayments and tidal fresh waters of the Bay. An increase in wetlands area in these regions may result in diminished DO concentration in adjacent open water due to direct wetlands respiration.

(KEYWORDS: wetlands; Chesapeake Bay; climate change; dissolved oxygen.)

INTRODUCTION

Determination of nutrient load reduction targets for Chesapeake Bay is an ongoing, iterative process. Since the earliest determination of nutrient load reductions necessary to restore the Bay, circa 1992, the process has included periodic examination of progress toward desired endpoints and revision of target loads, if necessary. The most recent specification of loads was the 2010 evaluation of the Total Maximum Daily Load (TMDL), at that time perhaps the most extensive and detailed estuarine TMDL determination (USEPA 2010). The TMDL was designed to meet desired goals of dissolved oxygen (DO) concentration, chlorophyll concentration, and light attenuation. In keeping with the precedent of periodic reexaminations, the Chesapeake Bay Program (CBP) has completed the "2017 Mid-Point Reassessment of the 2010 TMDL" (USEPA 2018). The Reassessment determined a set of Phase III Watershed Implementation Plan (WIP3) loads to be achieved by the year 2025. Subsequent to the Reassessment, the impact of climate change on the newly determined loads is presently under consideration.

The influence of tidal wetlands respiration on DO concentration in adjacent open waters (OWs) was explicitly included in the model used to guide the determination of the TMDL (Cerco et al. 2010). Other potential wetlands effects on OWs were implicitly incorporated into the model through parameter evaluation which sought to match computations with

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observed water quality conditions. Extensive losses of tidal wetlands have been observed in the Bay (Stevenson et al. 1985; Ward et al. 1998; Kearney et al. 2002) and the losses appear to be accelerating with rising sea level associated with climate change (Boon 2012; Kopp et al. 2014). Evidence has also been presented for compensating increases in wetlands area due to upland drowning (Schieder et al. 2017). Wetlands loss and migration may impact the conditions projected for the WIP3 loads which implicitly and explicitly incorporate effects of existing wetlands. Loss and migration certainly need to be considered in the evaluation of climate change on the reassessed loads.

The objective of this study was to isolate and examine the influence of varying wetlands area, induced by sea-level rise, on conditions projected under WIP3 loads. Emphasis is placed on DO since the attainment of DO criteria is a key determinant of the loads. Completion of the objective requires the calculation of conditions under WIP3 loads, projections of sea-level rise, projections of wetlands area as a function of sea level, and calculation of wetlands influences on the adjacent water column.

WIP3 CONDITIONS

Determination of WIP3 conditions is aided by several interactive predictive models. These include a Watershed Model (WSM) and a Water Quality and Sediment Transport Model (WQSTM).

Watershed Model

The WSM calculates loads of various forms of nitrogen, phosphorus, and suspended solids, on a daily basis, throughout the 166,000 km^2 Chesapeake Bay watershed (USEPA 2017). The WSM incorporates distributed loads, point-source loads, and loads from bank erosion. These are routed, on a daily basis, to the perimeter of the tidal Bay system for subsequent use by the WQSTM.

Water Quality and Sediment Transport Model

The WQSTM simulates eutrophication processes throughout Chesapeake Bay and the tidal portions of its tributaries. The model solves the three-dimensional conservation of mass equation for multiple state variables on a computational grid of 50,000 elements, roughly $1\ \text{km} \times 1\ \text{km} \times 1.7\ \text{m}$. State variables include multiple forms of carbon, nitrogen, phosphorus, and suspended solids as well as DO. The model has undergone a continuous cycle of application and development for more than 30 years and has been extensively documented. Recent, relevant publications include the application of the model to guide the development of TMDLs for the Bay (Cerco et al. 2010) and guidance for 2017 Mid-Point Reassessment of the 2010 TMDL (Cerco and Noel 2019). This last reference describes the model employed here, to which a novel wetlands module has been added.

Transport processes for the WQSTM are provided by the Computational Hydrodynamics in Three Dimensions (CH3D) hydrodynamic model (Johnson et al. 1993). CH3D solves the three-dimensional equations of motion, via finite difference algorithms, on the same computational grid as the WQSTM. The integration time step is roughly 5 s. Volumetric transport and diffusivity are stored at hourly intervals for subsequent use by the WQSTM.

Application Period

The WSM and WQSTM have been applied over various intervals, commencing in 1985. The application period here is 1991–2000. This period has been covered by multiple versions of the models and allows for direct comparison of results between versions. The interval includes a three-year period, 1993–1995, which is emphasized in the development of water quality criteria. This interval incorporates various hydrological conditions and provides a consistent basis for iterative re-evaluations of predicted conditions under various load scenarios. Complete climate-change scenarios incorporate alterations in temperature, sea level, boundary conditions, and other influences. To isolate wetlands impacts, climate change scenarios here are restricted to variations in the wetlands area.

SEA-LEVEL RISE

Increments in sea-level rise were determined by the Chesapeake Bay Program Climate Change Resilience Work Group, based on projections from Boon (2012) and Kopp et al. (2014). The increments, from 1995 base conditions were 0.22, 0.31, 0.42, and 0.53 m for the years 2025, 2035, 2045, and 2055, respectively. In addition, a rise of 1m by 2100 was considered based on projections available from Glick et al. (2008).

WETLANDS AREAS

Wetlands areas were obtained from an application of the Sea Level Affecting Marshes Model (SLAMM; Warren Pinnacle Consulting 2018). The SLAMM application (Glick et al. 2008) projected wetlands areas in the Chesapeake and Delaware Bay regions as a function of sea-level rise associated with climate change. The Chesapeake Bay portion of the SLAMM application was extracted previously as part of a study of nitrogen removal by Chesapeake Bay tidal wetlands (Bryan 2014). For this study, SLAMM wetlands types, Tidal Freshwater Marsh, Brackish Marsh, Transitional Salt Marsh, and Salt Marsh, were considered. Wetlands areas from SLAMM for the year 1996 were employed as the base condition in our model (Figure 1). Wetlands projections as a function of sea-level rise were obtained from a fixed-rate scenario that considered a 1 m rise by the year 2100. For this scenario, developed land was assumed to be protected through the construction of dikes or other measures. The scenario considered four discrete increments in sea level: 0.13 m by 2025, 0.28 m by 2050, 0.48 m by 2075, and 1 m by 2100.

Tidal wetlands area under base conditions totals 130,000 ha (Figure 2). When grouped by salinity regime, roughly 95% of the total falls in saline segments. Roughly 70% of the wetlands are in mesohaline (MH) segments. The SLAMM indicates a small increase in total wetlands area for a sea-level rise of 0.13 m and a total area equivalent to current conditions for a 0.28 m increase in sea level (Figure 2). The total falls off thereafter. More than 35% of the existing total wetlands area is lost for a 1m rise in sea level. A change in distribution in wetlands is also predicted. Wetlands in tidal fresh (TF) and oligohaline (OH) segments increase in extent, at the expense of MH and polyhaline (PH) wetlands, for a 0.28 m increase in sea level. PH wetlands rebound for a 1 m increase in sea level, however. At this level, both TF and PH wetlands indicate a net increase from base conditions although wetlands in the remaining segments decline in extent.

Assignment to Model Grid

GIS projections of SLAMM tidal wetlands were combined with projections of local Bay watersheds and of the model computational grid (Cerco and Noel 2019). Next, contiguous wetlands were divided into a "fishnet" of subsegments which were assigned to the nearest model grid surface cell, taking care not to cross local "hydrologic unit code 10" watershed boundaries. The final product was a table of tidal wetlands area associated with surface cells on the model grid for base conditions and for SLAMM increments of sea-level rise. Under base conditions, 2,300 of the total 11,000 surface cells adjoin tidal wetlands. The tidal wetlands area is roughly 11% of the open-water area of the bay system, as represented on the model grid, although for some regions the area of adjacent tidal wetlands equals or exceeds the open-water area. Wetlands areas for model scenarios of base conditions and 1 m sea-level rise were obtained from SLAMM results for 1996 existing areas and 1 m sea-level rise. Wetlands areas for remaining CBP sea-level increments were obtained by interpolation of areas at SLAMM sea-level increments.

THE WETLANDS MODULE

The wetlands module computes exchange between tidal wetlands and adjacent OWs of particulate forms of carbon, nitrogen, and phosphorus, and dissolved forms of nitrate, phosphate, carbon, and oxygen. The module consists of a set of kinetics terms added to the conservation of mass equation in the WQSTM. The WQSTM solves the complete three-dimensional conservation of mass equation, including transport and kinetics, for each cell on the computational grid (Cerco and Noel 2019). For brevity, transport and pre-existing kinetics are omitted from the description of the Wetlands Module.

Particle Settling

Settling of all particles is represented by the same formulation:

$$V \cdot \frac{\mathrm{d}C}{\mathrm{d}t} = \mathrm{Transport} + \mathrm{Kinetics} - \mathrm{WSw} \cdot C \cdot \mathrm{Aw}, \quad (1)$$

where V = volume of water-quality model cell adjacent to wetlands (m^3), C = particle concentration (g/m^3), WSw = wetland settling velocity (m/day), and Aw = area of wetland adjacent to water-quality model cell (m^2).

Settling is computed for three reaction classes of particulate organic carbon, particulate organic nitrogen, and particulate organic phosphorus (POP), and particulate inorganic phosphorus (PIP). Potential differences in settling rates for different particle types are accommodated by varying parameter WSw.

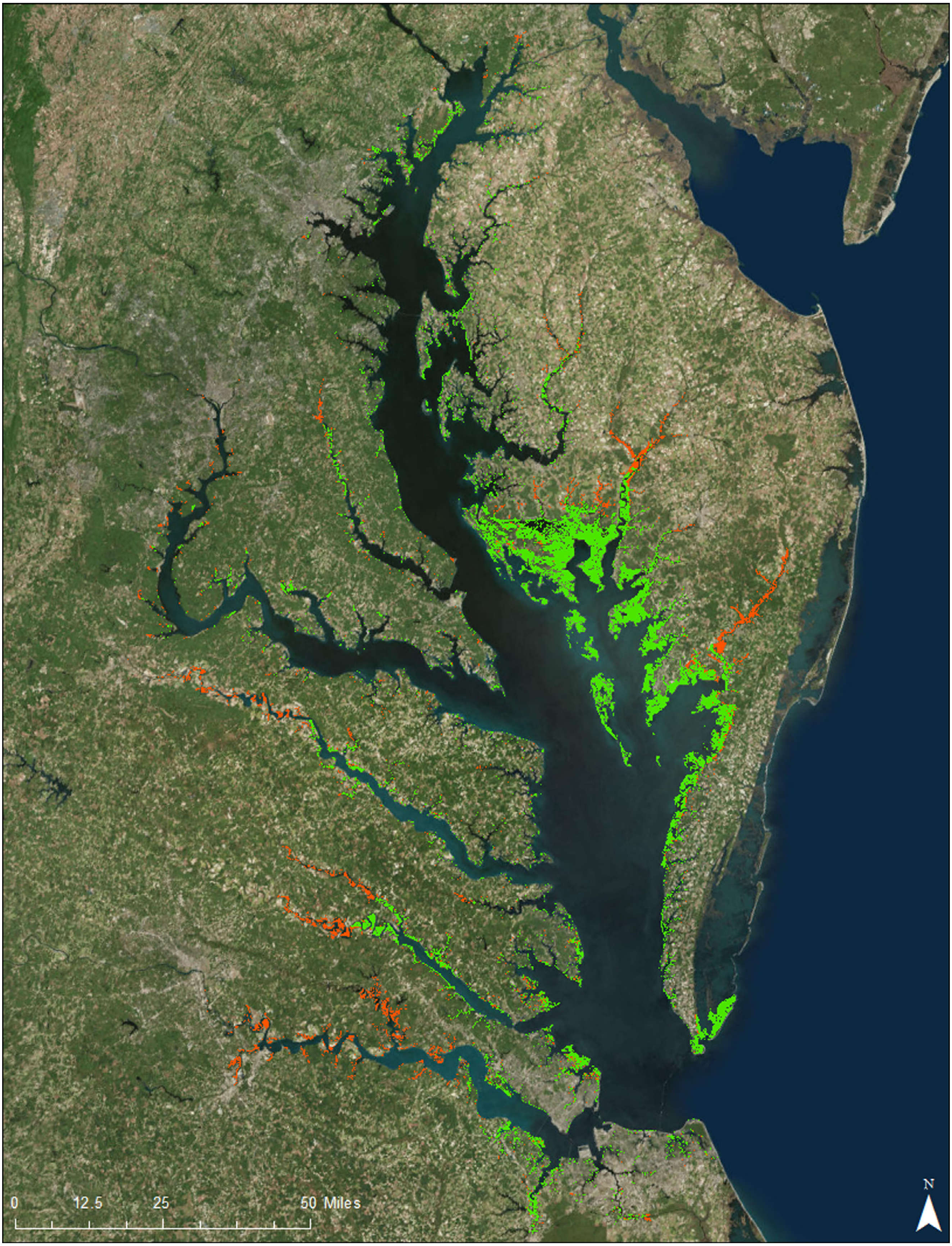

FIGURE 1. Chesapeake Bay tidal wetlands, 1996, as per Sea Level Affecting Marshes Model (SLAMM). Saline and brackish wetlands are shown in green, freshwater wetlands are shown in red.

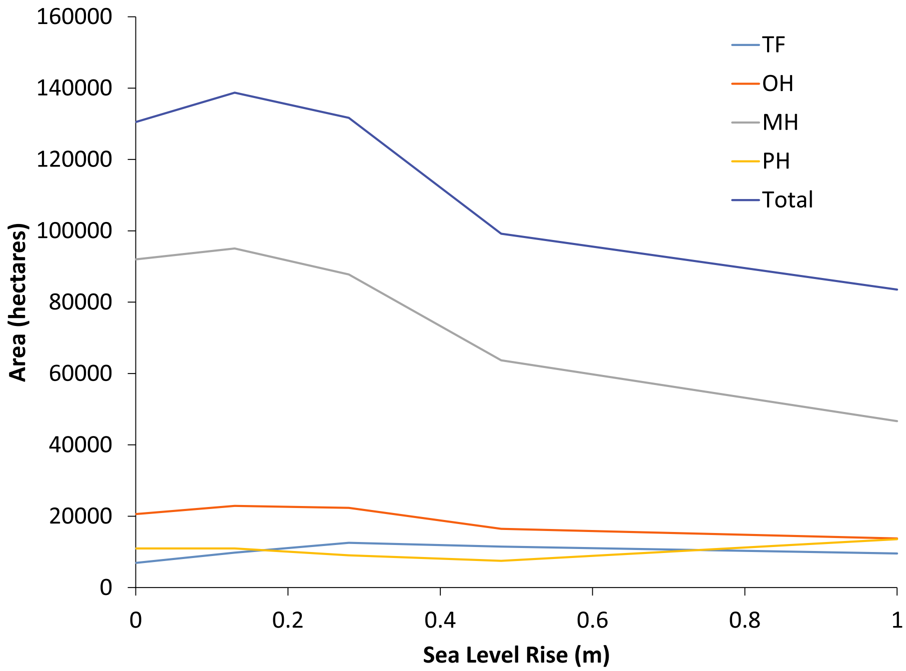

FIGURE 2. Chesapeake Bay tidal wetlands area, predicted by SLAMM, as a function of the rise in sea level. Areas are grouped by salinity regime: tidal fresh (TF), oligohaline (OH), mesohaline (MH), and polyhaline (PH).

Nitrate and Phosphate

The module considers wetlands uptake of nitrate and phosphate. Nitrate uptake is supported by direct observation (Seldomridge and Prestegaard 2014), by observations of denitrification (Merrill and Cornwell, 2002; Hopfensperer et al. 2009), and by nitrate observations in the water column adjacent to wetlands (Cerco and Noel 2019). Phosphate uptake is developed empirically by the need to mass balance phosphate in the wetlands module and the water column. Nitrate and phosphate uptake are based on a mass transfer coefficient and availability in the water column:

$$V \cdot \frac{\mathrm{d}C}{\mathrm{d}t} = \mathrm{Transport} + \mathrm{Kinetics} - \mathrm{MTC} \cdot f(T) \cdot C \cdot \mathrm{Aw}, \tag{2}$$

where C = nitrate or phosphate concentration (g/m^3), MTC = mass-transfer coefficient (m/day), and $f(T)$ = temperature effect. The temperature effect is an exponential relationship in which uptake doubles for a 10°C temperature increase (Cerco and Noel 2019). Ammonium exchange between wetlands and the adjacent water column also exists. Budgetary analysis (Neubauer et al. 2005) indicates the exchange is small, however, compared to fluxes of particulate nitrogen and nitrate considered here. Observations are sparse, as well. Consequently, ammonium exchange is not considered in the wetlands module.

Respiration

Net DO uptake (Neubauer and Anderson 2003) is represented:

$$V \cdot \frac{\mathrm{dDO}}{\mathrm{d}t} = \mathrm{Transport} + \mathrm{Kinetics} - f(\mathrm{DO}) \cdot f(T) \cdot \mathrm{WOC} \cdot \mathrm{Aw}, \tag{3}$$

where DO = dissolved oxygen concentration (g/m^3), f(DO) = limiting factor: DO/(Kh + DO), Kh = dissolved oxygen concentration at which uptake is halved (g/m^3), and WOC = wetlands oxygen consumption (g/m^2/day)

The limiting factor prevents wetlands from removing more DO than is available in the adjacent waters. In the event oxygen consumption is limited by oxygen availability in the water column, chemical oxygen demand is released from the wetlands so that total respiration, in oxygen equivalents, equals the specified WOC.

Dissolved Organic Carbon (DOC)

DOC export from wetlands (Clark et al. 2020) is represented:

$$V \cdot \frac{\mathrm{dDOC}}{\mathrm{d}t} = \mathrm{Transport} + \mathrm{Kinetics} + \mathrm{WDOC} \cdot \mathrm{Aw}, \quad (4)$$

where DOC = dissolved oxygen-carbon concentration (g/m^3), and WDOC = wetlands DOC release rate (g/m^2/day). Analogous exports of dissolved organic nitrogen (DON) and phosphorus (DOP) may also exist. Observations to verify these exports are absent, however, and explicit consideration of DON is omitted from at least one detailed wetlands nitrogen budget (Neubauer et al. 2005). In view of the sparse data and apparent insignificance of DON fluxes, exports of DON and DOP are not considered in the wetlands module.

WETLANDS MODULE PARAMETER ASSIGNMENT

Chesapeake Bay Program Segments

For management and reporting purposes, the United States Environmental Protection Agency (USEPA) CBP divides the Bay and tributaries into roughly 90 Chesapeake Bay Program Segments (CBPS). Segment extent is determined largely by salinity regime and shoreline geometry. The salinity regimes include TF, OH, MH, and PH. These segments and designations are employed here for data assembly, parameter assignment, and reporting of results.

Observations

Observations of relevant wetlands processes are concentrated in several "hotspots" around the Bay system (Figure 3). These hotspots include reaches in the York (MPNOH, PMKOH) and Patuxent Rivers (PAXOH, PAXTF), and in the vicinity of the Nanticoke River (FSBMH, NANMH, NANOH, WICMH). Additional observations useful for parameter evaluation and for comparison with the model are found in the Potomac (POTTF), Bush (BSHOH), Chester (CHSMH), and Choptank (CHOMH) Rivers and in Parker Creek (tributary to CB4). The observations were collected for varying purposes and represent a wide variety of methods, reporting units, and time frames. Reports from multiple studies (Table 1) were assembled, converted to a relevant and common set of units, and summarized for use in the wetlands module (Table 2).

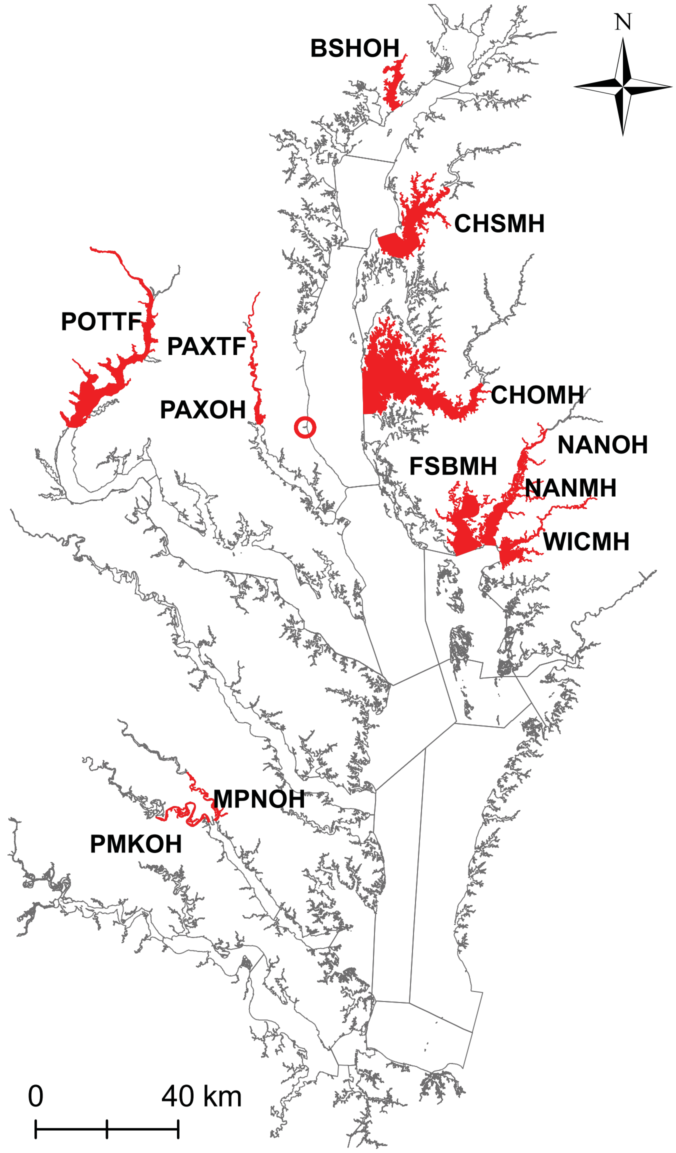

FIGURE 3. Chesapeake Bay Program Segments (CBPS), highlighted in red, which provide observations for parameterization of the Wetlands Module. The red circle shows Parker Creek, a tributary of segment CB4.

While process observations are abundant, these do not always correspond to observations of the specific parameters used in the wetlands module. Although observations of deposition from water to wetlands are available, the predominant observations are burial out of wetland surficial sediments. Burial is analogous to but not identical to deposition. Observations of direct nitrate uptake are available but additional measures are available of denitrification which is similar to but not exactly equivalent to wetlands uptake. Our approach is to construct carbon, nitrogen, and phosphorus budgets of CBPS for which sufficient observations are available. The budgets combine

TABLE 1. Primary sources of observations used in parameterizing the Wetlands Module. Location of CBPS is shown in Figure 3.

Source	Process	CBPS
Flemer et al. (1978)	Primary production	PAXTF, CB4
Stevenson et al. (1985)	Carbon burial	FSBMH
Boynton et al. (2008)	Denitrification, nitrogen burial, phosphorus burial	PAXTF, PAXOH
Neubauer and Anderson (2003)	Primary production, carbon burial, respiration	PMKOH
Hopfensperer et al. (2009)	Denitrification, nitrogen burial, phosphorus burial	POTTF
Palinkas and Cornwell (2012)	Nitrogen and phosphorus burial	CHSMH
Morse et al. (2004)	Carbon, nitrogen, phosphorus burial	MPNOH
Merrill and Cornwell (2002)	Nitrogen burial, denitrification, phosphorus burial	CHOMH, WICMH, PAXTF, BSHOH
Ward et al. (1998)	Carbon burial	NANMH, NANOH
Palinkas et al. (2013)	Carbon burial	POTTF

observed and modeled processes. Parameter assignments are validated by verifying that their use in the model provides a reasonable balance of relevant budgets. Model elements of the budgets are daily average values from a ten-year simulation, 1991–2000, based on existing conditions and loads. Model values are spatially averaged across existing wetlands areas in designated CBPS.

The Carbon Budget

The carbon budget consists of macrophyte primary production (PP, source), deposition from the adjacent OW (C_{dep}, source), respiration (Resp, sink), DOC export (C_{exp}, sink), and burial to deep, inactive sediments (C_{burial}, sink). The budget is arranged so that PP is balanced by the remaining sources and sinks:

$$PP = C_{burial} + C_{resp} + C_{exp} - C_{dep}, \quad (5)$$

C_{burial} is derived from observations at individual CBPS. C_{resp} and C_{exp} are specified model parameters (Table 3). C_{resp} is expressed in carbon equivalents derived from available observations as oxygen consumption. C_{dep} is the long-term average carbon deposition calculated within the module (Equation 1). The budget is considered balanced if the PP derived from Equation (5) is comparable to observations. PP measurements are sparse and unavailable for most CBPS under consideration. The observed range, 0.98–1.77 g C/m^2/day (Table 2), compares well with the preponderance of values required to balance budgets at individual CBPS (Table 4) and the carbon budget is considered balanced. That is, the parameter assignment and model calculations are considered acceptable.

The Nitrogen Budget

The nitrogen budget consists of deposition from adjacent OW (N_{dep}, source), nitrate uptake from adjacent OW (NO3up, source), denitrification (Denit, sink), and burial to deep, inactive sediments (N_{burial}, sink). The budget is arranged so that denitrification is balanced by the remaining sources and sinks:

$$Denit = N_{dep} + NO3up - N_{burial}, \quad (6)$$

N_{dep} is the long-term average nitrogen deposition calculated within the module (Equation 1). NO3up is the long-term average nitrate uptake based on

TABLE 2. Summary of observations used in parameterizing the Wetlands Module.

CBPS	Primary production (g C/m^2/day)	Respiration (g O_2/m^2/day)	Carbon burial (g C/m^2/day)	Nitrogen burial (g N/m^2/day)	Denitrification (g N/m^2/day)	Phosphorus burial (g P/m^2/day)
PAXTF	1.55			0.037–0.064	0.037	0.006–0.01
CB4	0.98					
FSBMH			0.39–0.82			
PAXOH				0.037	0.027	0.006
PMKOH	1.77	1.12–2.77	0.61	0.05		
POTTF			1.27		0.043–0.059	
CHSMH				0.02–0.064		0.01–0.019
MPNOH			0.42–0.93	0.034–0.082		0.006–0.026
CHOMH				0.053–0.074		4.9×10^{-4}–0.005
WICMH			0.22–0.43	0.037		2.74×10^{-5}–0.004
BSHOH				0.008–0.032		0.001–0.006
NANMH			0.22–0.43			
NANOH			0.22–0.43			

TABLE 3. Wetland Module assigned parameters.

Parameter	Definition	Value
Kh	Dissolved oxygen (DO) concentration at which oxygen consumption is halved	1.0 g DO/m^3
MTC	Mass-transfer coefficient for nitrate and phosphate	0.06 m/day
WDOC	Wetlands dissolved organic carbon release rate	0.3 g C/m^2/day
WSw	Settling velocity of organic particles	0.1 m/day
	Settling velocity of phytoplankton	0.01 m/day
	Settling velocity of particulate inorganic phosphorus	0.02 m/day
WOC	Wetlands oxygen consumption	1.25 g DO/m^2/day

calculated NO3 concentration and assigned mass-transfer coefficient (Table 3). N_{burial} is derived from observations at individual CBPS. The budget is considered balanced if Denit derived from Equation (6) is comparable to observations. Results indicate a wide range of denitrification rates, –0.060 to 0.088 g N/m^2/day, is required to balance the nitrogen budgets at various CBPS (Table 5). Negative values for denitrification indicate net nitrogen fixation is required to balance the budget. The denitrification rates greater than zero are in rough agreement with observations and indicate a satisfactory nitrogen budget in these CBPS. Merrill and Cornwell (2002) observed nitrogen fixation during summer in the TF Patuxent River although they concluded an annual budget indicated net denitrification. They suggested denitrification was limited by nitrate availability. Model results indicate a similar mechanism. CBPS with predominant calculated nitrogen fixation (MPNOH, PMKOH, WICMH) exhibit much lower rates of nitrate uptake than the remaining segments (Table 5). These CBPS also exhibit comparatively low rates of particulate nitrogen deposition from the water column. Model sensitivity analyses indicate the limited potential to increase N_{dep} and NO3up through parameter adjustment. These processes are limited by nitrogen availability in the water column. Measurements and modeling of NO3up in PMKOH (Neubauer et al. 2005) indicate a rate of 0.023 g N/m^2/day, much greater than the modeled rate of 0.006 g N/m^2/day. These results indicate a potential shortfall of modeled nitrogen transfer to wetlands in several CBPS due to a shortfall of nitrogen in the modeled water column.

The Phosphorus Budget

The phosphorus budget consists of deposition from adjacent OW (P_{dep}, source), phosphate uptake from adjacent OW (PO4up, source), and burial to deep, inactive sediments (P_{burial}, sink). The budget indicates burial must be balanced by particulate deposition and dissolved uptake from the water column:

$$P_{\mathrm{burial}} = P_{\mathrm{dep}} + \mathrm{PO4up} + \Delta P, \quad (7)$$

P_{burial} is derived from observations at individual CBPS. P_{dep} is the long-term average deposition of particulate organic (POP) and PIP calculated within the module (Equation 1). PO4up is the long-term average phosphate uptake based on calculated PO4 concentration and assigned mass-transfer coefficient (Table 3). The ΔP is the difference between calculated phosphorus sources and observed sinks. Under ideal circumstances, $\Delta P = 0$, a condition which is achieved for one CBPS, PAXOH (Table 6). For other CBPS (BSHOH, PAXTF, WICMH), ΔP ranges between positive and negative values depending on the range of observed P_{burial}. The remaining segments are distributed between shortfalls in transfer from the water column ($\Delta P > 0$) and excess transfer ($\Delta P < 0$). In view of the range in burial rates, a perfect balance between sources and sinks cannot be achieved. The results show no consistent bias and the overall wetlands phosphorus budget is considered balanced.

TABLE 4. Summary of carbon budgets. Maximum and minimum primary production are values required to balance the budget based on remaining calculated and assigned parameters. The budget is considered balanced when the required primary production reflects observed values.

CBPS	Maximum primary production (g C/m^2/day)	Minimum primary production (g C/m^2/day)	Deposition (g C/m^2/day)	Maximum burial (g C/m^2/day)	Minimum burial (g C/m^2/day)	Respiration (g C/m^2/day)	DOC export (g C/m^2/day)
FSBMH	1.503	1.073	0.030	0.820	0.390	0.413	0.300
MPNOH	1.594	1.084	0.050	0.930	0.420	0.414	0.300
NANMH	1.043	0.833	0.098	0.430	0.220	0.412	0.300
NANOH	1.066	0.856	0.079	0.430	0.220	0.415	0.300
PMKOH	1.259	1.259	0.072	0.610	0.610	0.421	0.300
POTTF	1.907	1.907	0.077	1.270	1.270	0.414	0.300
WICMH	1.025	0.815	0.118	0.430	0.220	0.413	0.300

TABLE 5. Summary of nitrogen budgets. Maximum and minimum denitrification rates are values required to balance the budget based on remaining calculated and assigned parameters. Negative values of denitrification indicate net nitrogen fixation is required to balance the budget. CBPS which require predominant nitrogen fixation may underestimate nitrogen removal from the adjacent water column.

CBPS	Maximum burial (g N/m²/day)	Minimum burial (g N/m²/day)	Deposition (g N/m²/day)	NO3 uptake (g N/m²/day)	Maximum denitrification (g N/m²/day)	Minimum denitrification (g N/m²/day)
BSHOH	0.0320	0.0080	0.0544	0.0414	0.0878	0.0638
CHSMH	0.0640	0.0200	0.0411	0.0122	0.0333	−0.0177
MPNOH	0.0820	0.0340	0.0156	0.0065	−0.0119	−0.0599
CHOMH	0.0740	0.0530	0.0806	0.0149	0.0426	0.0215
PAXOH	0.0370	0.0370	0.0480	0.0152	0.0263	0.0263
PAXTF	0.0640	0.0370	0.0569	0.0277	0.0476	0.0206
PMKOH	0.0500	0.0500	0.0198	0.0065	−0.0237	−0.0237
WICMH	0.0370	0.0370	0.0295	0.0040	−0.0035	−0.0035

TABLE 6. Summary of phosphorus budgets. The columns headed "Shortfall" indicate the imbalance between calculated and assigned fluxes in the remaining columns. Ideally, the shortfall values would be zero. In view of the range in burial rates, a perfect balance between sources and sinks is seldom achieved. The results show no consistent bias and the overall wetlands phosphorus budget is considered balanced.

CBPS	Maximum burial (g P/m²/day)	Minimum burial (g P/m²/day)	Particulate organic phosphorus deposition (g P/m²/day)	Particulate inorganic phosphorus deposition (g P/m²/day)	Dissolved phosphate uptake (g P/m²/day)	Maximum shortfall (g P/m²/day)	Minimum shortfall (g P/m²/day)
BSHOH	0.0060	0.0010	0.0016	0.0017	0.0003	0.0025	−0.0025
CHSMH	0.0190	0.0100	0.0016	0.0021	0.0004	0.0149	0.0059
MPNOH	0.0260	0.0060	0.0006	0.0008	0.0001	0.0246	0.0046
CHOMH	0.0050	0.0005	0.0025	0.0028	0.0013	−0.0015	−0.0061
PAXOH	0.0060	0.0060	0.0017	0.0030	0.0013	0.0000	0.0000
PAXTF	0.0100	0.0060	0.0019	0.0029	0.0019	0.0033	−0.0007
WICMH	0.0040	0.0000	0.0009	0.0010	0.0003	0.0017	−0.0022

RESULTS

Dissolved Oxygen Criteria

Results are reported with respect to Chesapeake Bay DO criteria. The USEPA Region III (USEPA 2003) has derived a set of DO criteria to protect specific aquatic life communities and reflect the natural processes that define distinct habitats. Relevant criteria are summarized in Table 7. Linker et al. (2016) detail the assessment applied to model results to evaluate attainment of criteria. Assessments are conducted for each of the 92 CBPS with emphasis on the years 1993–1995. The assessment examines the percent of time and volume that DO is outside an allowed exceedance. A variance may be allowed when natural conditions violate criteria or when criteria are unattainable.

TABLE 7. Summary of Chesapeake Bay DO standards.

Designated use	Criteria	Temporal application
Open-water fish and shellfish use	30-day mean >5.5 g/m³ (salinity <0.5 ppt); >5.0 g/m³ (salinity >0.5 ppt)	Year-round
	Instantaneous minimum >3.2 g/m³	Year-round
Deep-water seasonal fish and shellfish use	30-day mean >3 g/m³	June 1–September 30
	Instantaneous minimum >1.7 g/m³	June 1–September 30
Deep-channel seasonal refuge use	Instantaneous minimum >1.0 g/m³	June 1–September 30

Deep Water and Deep Channel Segments

Model results indicate that wetlands migration and loss, induced by rising sea levels, produce an increase in exceedances (Tables 8 and 9) in multiple OW, Deep Water (DW), and Deep Channel (DC) segments (Figure 4). As sea level rises beyond 0.22 m, total wetlands area declines (Figure 2) as

TABLE 8. Exceedance of DO standards as a function of sea level for Deep Channel (DC) and Deep Water (DW) segments. Exceedance is the percent of time and volume that DO concentration violates standards. Bold indicates exceedance is outside an allowed variance. R^2 indicates the relationship between exceedance and fractional watershed nitrogen load reduction by wetlands. Average Target DO is the July–September average DO for individual years 1993–1995 with no change in sea level. Maximum delta DO is the maximum change in target DO due to a change in sea level. Negative values indicate a DO decline.

	Exceedances (%)								
CBPS	**Target**	**0.22 m**	**0.31 m**	**0.42 m**	**0.53 m**	**1.0 m**	R^2	**Average target DO (g/m^3)**	**Maximum delta DO (g/m^3)**
CB4MH (DC)	**0.060**	**0.061**	**0.063**	**0.066**	**0.068**	**0.072**	0.996	1.50–2.02	−0.05
EASMH (DC)	**0.041**	**0.041**	**0.041**	**0.043**	**0.043**	**0.044**	0.977	0.82–1.12	−0.03
CB4MH (DW)	**0.057**	**0.057**	**0.058**	**0.058**	**0.059**	**0.060**	0.993	4.50–5.14	−0.03

TABLE 9. Exceedance of DO standards as a function of sea level for Open Water segments. Exceedance is the percent of time and volume that DO concentration violates standards. Bold indicates exceedance is outside an allowed variance. R^2 indicates the relationship between exceedance and fractional change in wetlands area within a segment. Average Target DO is the July–September average DO for individual years 1993–1995 with no change in sea level. Maximum delta DO is the maximum change in target DO due to a change in sea level. Negative values indicate a DO decline. Positive values indicate a DO increase.

	Exceedances (%)								
CBPS	**Target**	**0.22 m**	**0.31 m**	**0.42 m**	**0.53 m**	**1.0 m**	R^2	**Average target DO (g/m^3)**	**Maximum delta DO (g/m^3)**
PAXTF	**0.028**	**0.054**	**0.076**	**0.056**	**0.033**	0.000	0.504	8.04–9.00	−0.39
CRRMH	**0.079**	**0.118**	**0.098**	**0.079**	**0.060**	**0.060**	0.637	6.95–7.53	−0.01
MPNTF	0.013	**0.246**	**0.255**	**0.162**	**0.162**	**0.046**	0.876	7.26–7.79	−0.42
PMKTF	**0.069**	**0.662**	**0.709**	**0.603**	**0.474**	**0.045**	0.887	7.10–7.67	−1.28
PMKOH	0.004	**0.065**	**0.050**	0.014	0.007	0.000	0.130	5.07–6.09	0.39
CHKOH	0.000	**0.050**	**0.072**	**0.072**	**0.050**	0.000	0.953	6.38–7.10	−1.23
SBEMH	**0.255**	**0.310**	**0.364**	**0.420**	**0.453**	**0.493**	0.929	6.33–7.18	−0.65
FSBMH	0.000	**0.283**	0.009	0.000	0.000	0.000	0.310	4.98–6.29	−0.58
WICMH	**0.111**	**0.115**	**0.169**	**0.219**	**0.219**	**0.111**	0.064	5.65–6.58	0.09
MANMH	0.006	**0.046**	**0.046**	0.006	0.000	0.000	0.345	5.86–6.71	0.05
POCTF	0.000	**0.698**	**0.775**	**0.775**	**0.775**	**0.546**	0.886	7.59–8.21	−2.91
POCOH	0.000	**0.698**	**0.775**	**0.775**	**0.775**	**0.546**	0.471	7.26–7.93	0.29

does the net amount of nutrients removed by wetlands (Figure 5). Under target WIP3 loads and base sea level, wetlands remove roughly 10% of the watershed nitrogen loads and 19% of the watershed phosphorus loads. The fractions removed decline to roughly 7% and 13% of the nitrogen and phosphorus loads, respectively, for a 1 m rise in sea level. The fractional increase in exceedances in DW and DC segments is very strongly and negatively correlated with the fractional reduction in nutrient removal (Table 8). Effectively, the wetlands act as controls on nutrient loads. Removing wetlands amounts to increasing nutrient loads which result in deteriorated DO in DW and DC segments. Averaged over the June through September criteria application period, the decline in DO is small, <0.05 g/m^3. The decline is significant, however, when the DC DO concentration under target conditions is 2 g/m^3 or less. Moreover, regulatory requirements prohibit any diminishment of water quality below standards.

Open Water Segments

The DW and DC segments which experience increased exceedances are expansive, deep segments with low ratios (<0.1) of wetlands area to water surface area. In contrast, the OW segments which experience increased exceedances are shallow and located at the headwaters of small tributaries or in enclosed embayments. The median ratio of wetlands area to water surface area (>1) is an order of magnitude greater than the DC and DW segments. The percent exceedances are generally related to change in wetlands surface area (Table 9) although the relationships are not as strong as the relation between nutrient removal and exceedances in DW and DC segments. The percent exceedances, when related to sea-level rise, may transition through a maximum and then diminish when wetlands area shows similar behavior. The maximum potential decline in DO, up to −2.9 g/m^3, is much greater than the maximum decline in DW and DC segments. DO increases up to

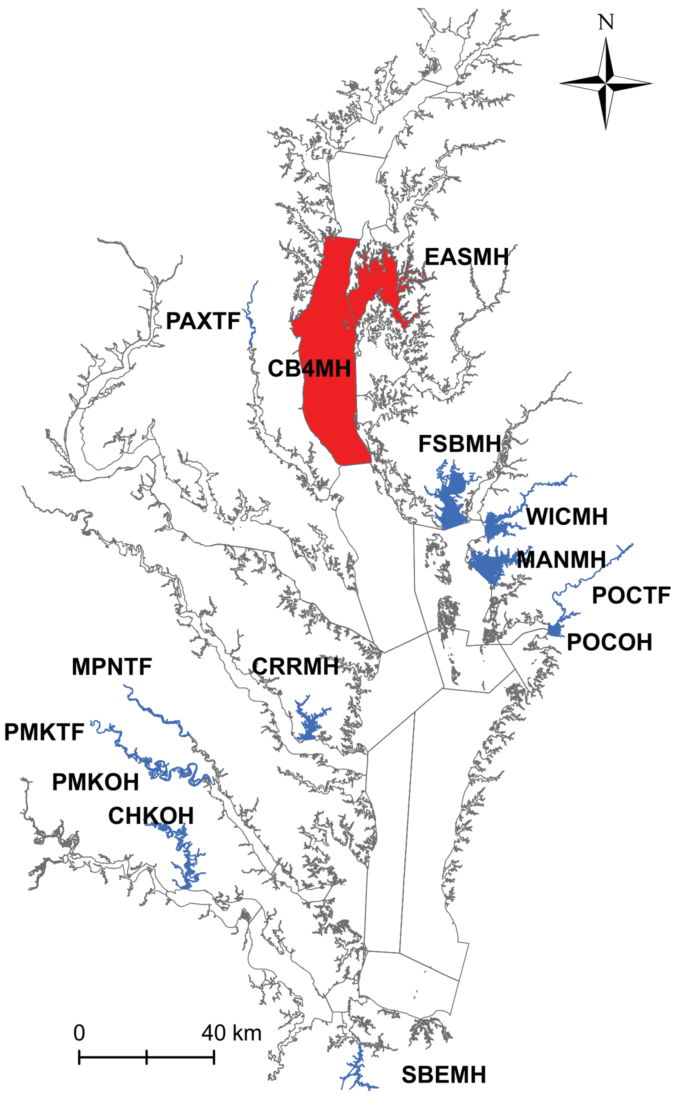

FIGURE 4. CBPS which show an increase in criteria exceedances caused by wetlands migration and loss due to the rise in sea level. Segments highlighted in red show increased exceedances in Deep Water and Deep Channel regions. Segments highlighted in blue show increased exceedances in Open Water regions.

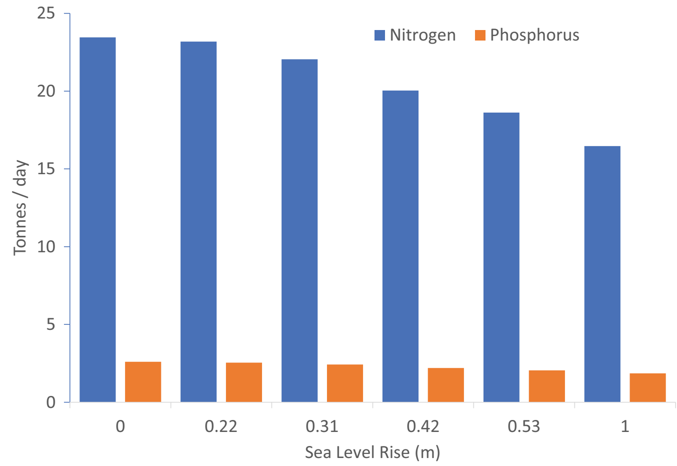

FIGURE 5. Nitrogen and phosphorus removal by wetlands as a function of sea-level rise.

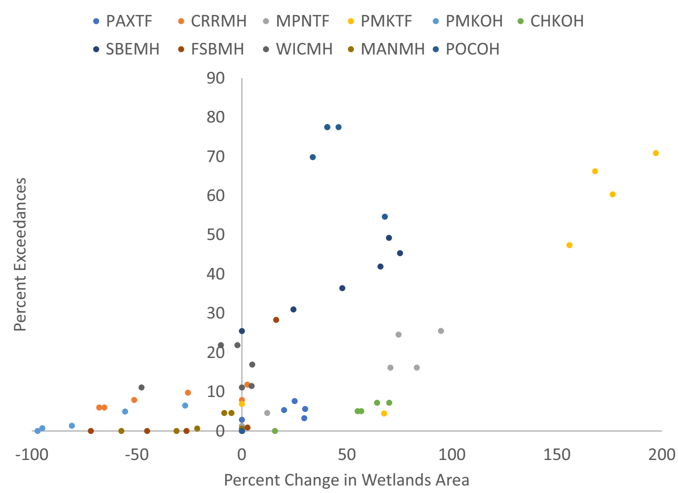

FIGURE 6. Percent DO exceedances vs. percent change in wetlands area for open-water segments. Note the rough linear relationship between exceedance and area change.

0.39 g/m^3 are also possible when net wetlands loss occurs in an OW segment.

The variations in OW exceedances are attributed to variations in wetland areas. The DO balance in a model cell is directly related to the area of adjacent wetlands (Equation 3). Under ideal conditions, the DO concentration will increase or decrease in proportion to changes in the wetlands area. The model largely demonstrates this behavior although in some cases, the relationship is weak or, apparently, absent. Several factors may account for the absence of strong linear relationships. One factor is that the percent exceedance cannot go less than zero so a linear relationship between wetlands area and exceedances will be weak or absent when exceedances approach zero. Another factor is that the spatial distribution of wetlands within a segment is subject to change independent of the total wetlands area. A third factor is the potential influence of adjacent segments which exchange water with the subject segment. Despite these factors, the relationship between exceedances and wetlands remains apparent (Figure 6).

DISCUSSION

Our model indicates wetlands transitions due to sea level rise potentially impact DO standards through two processes. The first process is diminished nutrient burial due to wetlands loss. Diminished burial is equivalent to an increase in nutrient loading. The equivalent load increase results in an increase in exceedances in DC and DW segments. The second process is an increase in wetlands respiration in segments which experience an increase in the wetlands area. These segments tend to be at the headwaters of small tributaries and enclosed embayments with a high ratio of wetlands area to the open-water surface area. The increase in respiration results in additional exceedances in OW segments.

The SLAMM model predicts an increase in total wetlands area at the first sea level increment considered (0.13 m, Figure 3). At the second SLAMM increment, 0.28 m, total wetlands area is equivalent to the area at base sea level although the wetlands spatial distribution changes. Wetlands loss in PH and MH salinity regimes is compensated by wetlands gains in OH and TF regimes. Beyond 0.28 m, total wetland area declines in all salinity regimes except PH although individual segments may show net gains as far as 1 m sea level rise. Attempts to validate the SLAMM predictions to date, through examination of aerial photography, have proven inconclusive (P. Claggett, April 8, 2020, presentation to USEPA CBP, https://www.chesapeakebay.net/channel_files/40216/slamm_evaluation_v2.pdf). Available photography is challenging to interpret for land-to-water transitions in shallow tidal areas due to the unknown tidal stage and limited spectral bands in pre-2000 imagery. Alternate models and examination of data collected over decades (Kirwan et al. 2016; Schieder et al. 2017) suggest wetlands loss in some regions of the Bay will be entirely compensated by gains in other areas.

While precise spatial and temporal predictions of wetlands loss, gain, and transition are impossible, both observations and models indicate losses will occur in some regions while net gains are likely in OH and TF segments. We prefer to interpret our model results in terms of risk to Chesapeake Bay DO standards. Potential net wetlands loss involves risk to standards in DW and DC segments. Declines in seasonal average DO up to 0.05 g/m^3 and increases in exceedances up to 1.2% are computed. An increase in allowed exceedances or additional load reductions may be required to offset the effect of net wetlands loss. Potential wetlands migration and expansion create a risk to standards in certain OW segments. Declines in seasonal-average DO >1–2 g/m^3 are possible in some segments as are exceedances which occur more than 50% of the time-volume integral. Since the exceedances result from wetlands respiration they are unlikely to be countered by additional load reductions. The allowance of additional exceedances may be required.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Supplementary Material Figures provide an example of the mapping of tidal wetlands areas to model grid cells.

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AUTHORS' CONTRIBUTIONS

Carl F. Cerco: Conceptualization; investigation; methodology; writing-original draft. **Richard Tian:** Formal analysis; software; visualization.

LITERATURE CITED

Boon, J. 2012. "Evidence of Sea Level Acceleration at U.S. and Canadian Tide Stations, Atlantic Coast, North America." *Journal of Coastal Research* 28 (6): 1437–45.

Boynton, W., J. Hagy, J. Cornwell, W. Kemp, S. Greene, M. Owens, J. Baker, and R. Larsen. 2008. "Nutrient Budgets and Management Actions in the Patuxent River Estuary." *Estuaries and Coasts* 31: 623–51.

Bryan, J. 2014. "Effects of Sea Level Rise on Tidal Marshes." MS thesis, University of Maryland.

Cerco, C., S.-C. Kim, and M. Noel. 2010. "The 2010 Chesapeake Bay Eutrophication Model." http://www.chesapeakebay.net/publications/title/the_2010_chesapeake_bay_eutrophication_model1.

Cerco, C., and M. Noel. 2019. "2017 Chesapeake Bay Water Quality and Sediment Transport Model." https://www.chesapeakebay.net/channel_files/28679/2017_chesapeake_bay_water_quality_and_sediment_transport_model.pdf.

Clark, J., W. Long, and R. Hood. 2020. "A Comprehensive Estuarine Dissolved Organic Carbon Budget Using an Enhanced Biogeochemical Model." *Journal of Geophysical Research: Biogeosciences*. https://doi.org/10.1029/2019JG005442.

Flemer, D., D. Heinle, C. Keefe, and D. Hamilton. 1978. "Standing Crops of Marsh Vegetation of Two Tributaries of Chesapeake Bay." *Estuaries* 1 (3): 157–63.

Glick, P., J. Clough, and B. Nunley. 2008. "Sea-Level Rise and Coastal Habitats in the Chesapeake Bay Region." https://www.nwf.org/~/media/PDFs/Global-Warming/Reports/SeaLevelRiseandCoastalHabitats_ChesapeakeRegion.ashx

Hopfensperer, K., S. Kaushal, S. Findlay, and J. Cornwell. 2009. "Influence of Plant Communities on Denitrification in a Tidal Freshwater Marsh of the Potomac River, United States." *Journal of Environmental Quality* 38: 618–26.

Johnson, B., K. Kim, R. Heath, B. Hsieh, and L. Butler. 1993. "Validation of a Three-Dimensional Hydrodynamic Model of Chesapeake Bay." *Journal of Hydraulic Engineering* 119: 2–20.

Kearney, M., J. Rogers, E. Townshend, E. Rizzo, D. Stutzer, J. Stevenson, and K. Sundborg. 2002. “Landsat Imagery Shows Decline of Coastal Marshes in Chesapeake and Delaware Bays.” *Eos, Transactions American Geophysical Union* 83 (16): 173–78.

Kirwan, M., S. Temmerman, E. Skeehan, G. Guntenspergen, and S. Fagherazzi. 2016. “Overestimation of Marsh Vulnerability to Sea Level Rise.” *Nature Climate Change*. https://doi.org/10.1038/NCLIMATE2909.

Kopp, R., R. Horton, C. Little, J. Mitrovica, M. Oppenheimer, D. Rasmussen, B. Strauss, and C. Tebaldi. 2014. “Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide-Gauge Sites.” *Earth's Future* 2: 383–406. https://doi.org/10.1002/2014EF000239.

Linker, L., R. Batiuk, C. Cerco, G. Shenk, R. Tian, P. Wang, and G. Yactayo. 2016. “Influence of Reservoir Infill on Coastal Deep Water Hypoxia.” *Journal of Environmental Quality*. https://doi.org/10.2134/jeq2014.11.0461.

Merrill, J., and J. Cornwell. 2002. “The Role of Oligohaline Marshes in Estuarine Nutrient Cycling.” In *Concepts and Controversies in Tidal Marsh Ecology*, edited by M. Weinstein and D. Kreeger, 425–41. Dordrecht: Springer.

Morse, J., J. Megonigal, and M. Waldbridge. 2004. “Sediment Nutrient Accumulation and Nutrient Availability in Two Tidal Freshwater Marshes Along the Mattaponi River, Virginia, US.” *Biogeochemistry* 69: 175–206.

Neubauer, S., and I. Anderson. 2003. “Transport of Dissolved Inorganic Carbon from a Tidal Freshwater Marsh to the York River Estuary.” *Limnology and Oceanography* 48 (1): 299–307. https://doi.org/10.4319/lo.2003.48.1.0299.

Neubauer, S., I. Anderson, and B. Neikirk. 2005. “Nitrogen Cycling and Ecosystem Exchanges in a Virginia Tidal Freshwater Marsh.” *Estuaries* 28 (6): 909–22.

Palinkas, C., and J. Cornwell. 2012. “A Preliminary Sediment Budget for the Corsica River (MD): Improved Estimates of Nitrogen Burial and Implications for Restoration.” *Estuaries and Coasts* 35: 546–58.

Palinkas, C., K. Engelhardt, and D. Cadol. 2013. “Evaluating Physical and Biological Influences on Sedimentation in a Tidal Fresh Marsh with 7Be.” *Estuarine, Coastal and Shelf Science* 129: 152–61.

Schieder, N., D. Walters, and M. Kirwan. 2017. “Massive Upland to Wetland Conversion Compensated for Historical Marsh Loss in Chesapeake Bay, USA.” *Estuaries and Coasts*. https://doi.org/10.1007/s12237-017-0336-9.

Seldomridge, E., and K. Prestegaard. 2014. “Geochemical, Temperature, and Hydrologic Transport Limitations on Nitrate Retention in Tidal Freshwater Wetlands, Patuxent River, Maryland.” *Wetlands* 34: 641–51.

Stevenson, J., M. Kearney, and E. Pendleton. 1985. “Sedimentation and Erosion in a Chesapeake Bay Brackish Marsh System.” *Marine Geology* 67: 213–35.

USEPA. 2003. “Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries.” https://www.chesapeakebay.net/content/publications/cbp_13142.pdf.

USEPA. 2010. “Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus, and Sediment.” https://www.epa.gov/chesapeake-bay-tmdl/chesapeake-bay-tmdl-document.

USEPA. 2017. “Phase 6 Modeling Tools.” https://www.chesapeakebay.net/documents/Phase_6_Modeling_Tools_1-page_factsheet_12-18-17.pdf.

USEPA. 2018. “EPA Final Evaluation of 2016–2017 Milestone and Midpoint Progress and 2018–2019 Milestone Commitments in the Chesapeake Bay Watershed.” https://www.epa.gov/chesapeake-bay-tmdl/epa-final-evaluation-2016-2017-milestone-and-midpoint-progress-and-2018-2019.

Ward, L., M. Kearney, and J. Stevenson. 1998. “Variations in Sedimentary Environments and Accretionary Patterns in Estuarine Marshes Undergoing Rapid Submergence, Chesapeake Bay.” *Marine Geology* 151: 111–34.

Warren Pinnacle Consulting. 2018. “SLAMM: Sea Level Affecting Marshes Model.” http://warrenpinnacle.com/prof/SLAMM/.