4 Wetlands Module

Introduction

A decades long, abundant literature describes tidal wetlands processes and interactions between tidal wetlands and open waters of the Chesapeake Bay system. Wetlands processes relevant to management include: nitrogen removal through denitrification (Neubauer et al. 2005; Hopfensperer et al. 2009; Seldomridge and Prestegaard 2014); nitrogen removal through burial (Morse et al. 2004; Neubauer et al. 2005; Boynton et al. 2008; Palinkas and Cornwell 2012); phosphorus removal through burial (Morse et al. 2004; Boynton et al. 2008; Palinkas and Cornwell 2012); production and burial of organic carbon (Flemer et al. 1978; Neubauer et al. 2000; Neubauer et al. 2002; Morse et al. 2004); burial of organic and inorganic solids (Stevenson et al. 1985; Ward et al. 1998; Morse et al. 2004; Palinkas et al. 2013); and dissolved oxygen consumption through respiration (Neubauer et al. 2000; Neubauer et al. 2002; Neubauer and Anderson 2003). In recognition of wetland effects, protocols have been developed to provide nutrient and sediment mass reduction credits for shoreline management projects that include restoration of vegetation (Drescher and Stack 2015). Wetlands loss, associated with sea-level rise and diminishing sediment inputs, has been noted in the Bay for decades (Stevenson et al. 1985; Ward et al. 1998; Kearney et al. 2002). Concern over potential wetlands loss is increasing in parallel with concern over sea-level rise associated with climate change (Glick et al. 2008).

The effect of wetlands respiration on adjacent open water was included in the 2010 Chesapeake Bay model (Cerco et al. 2010). In view of the load-reduction credits recommended for wetlands restoration and the potential ecosystem effects of wetlands loss, a more detailed wetlands module has been incorporated into the 2015 Chesapeake Bay model. The module focuses on wetlands functions which have management implications: nutrient removal, solids removal, and respiration.

Formulations

Formulation of a detailed model of wetlands biogeochemical processes is a formidable prospect in view of the process complexity and the variety of wetlands in the Chesapeake Bay system. We focus here on basic relationships which describe the desired functions. The relationships incorporate rate-limiting functions which provide “feedback” between the rate of material removal by wetlands and the amount of material available in the adjacent open water column.

Potential effects of wetlands location and type are accommodated by local variations in parameter assignment.

Denitrification

The effect of wetland denitrification on adjacent open water is represented through a nitrate-removal algorithm. Nitrate removal is not exactly equivalent to denitrification (Neubauer et al. 2005; Seldomridge 2014) but the removal process is readily inferred and easily parameterized through nitrate observations in the water column. The relationship is:

$$V \cdot \frac{dC}{dT} = Transport + Kinetics - MTC \cdot f(T) \cdot C \cdot Aw \qquad (1)$$

in which:

V = volume of water-quality model cell adjacent to wetlands (m^3)
C = nitrate concentration (g m^{-3})
MTC = mass-transfer coefficient (m d^{-1})
f(T) = temperature effect
Aw = area of wetland adjacent to water-quality model cell (m^2)

The temperature effect is an exponential relationship in which denitrification doubles for a 10 ^oC temperature increase.

Particle Settling

Settling of all particles, organic and inorganic is represented by the same formulation:

$$V \cdot \frac{dC}{dT} = Transport + Kinetics - WSw \cdot C \cdot Aw \qquad (2)$$

in which:

C = particle concentration (g m^{-3})
WSw = wetland settling velocity (m d^{-1})

Differences in settling rates for different particle types are accommodated by varying parameter WSw.

Respiration

Net dissolved oxygen uptake is represented:

$$V \cdot \frac{dDO}{dT} = Transport + Kinetics - f(DO) \cdot f(T) \cdot WOC \cdot Aw \qquad (3)$$

in which:

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})
WOC = wetlands oxygen consumption (g m^{-2} d^{-1})

Process Observations

Observations of relevant wetlands processes are concentrated in several "hot spots" around the Bay system (Figure 1). These hotspots include reaches in the York (MPNON, PMKOH) and Patuxent Rivers (PAXOH), and in the vicinity of the Nanticoke River (NANOH, NANMH, FSBMH, WICMH). Additional observations useful for parameter evaluation and for comparison with the model are found in the Potomac (POTTF), Bush (BSHOH), and Chester Rivers (CHSMH). 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 relevant units, and summarized for use in the wetlands module (Table 2).

Wetlands Areas

Tidal wetlands areas were obtained from an application of the SLAMM (Sea Level Affecting Marshes Model). 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. GIS files of wetlands areas adjoining Chesapeake Bay were provided by Dr. Lora Harris of the University of Maryland Center for Environmental Science. 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). Wetlands areas from SLAMM for the year 1996 were employed in our model. Chesapeake Bay tidal wetlands totaled 130,000 hectares. More than 90% was classified as salt or brackish marsh with the remainder tidal freshwater (Figure 2). The SLAMM areas were compared to projections from a 1996 National Wetlands Inventory (NWI) provided by the Chesapeake Bay Program. Good agreement was noted between the SLAMM area and the sum of NWI "emergent" wetlands, 125,000 hectares.

GIS projections of tidal wetlands were combined with projections of the Bay watershed and of the model grid (Figure 3). Next, contiguous wetlands were divided into a "fishnet" of sub-segments (Figure 4). Sub-segment areas were assigned to the nearest model surface cell (Figure 5), taking care not to cross local "HUC 10" watershed boundaries (Figure 6). The final product was a table of tidal wetlands area associated with surface cells on the model grid. Roughly 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. For some regions, the area of adjacent tidal wetlands equals or exceeds the open-water area (Figures 7, 8). These regions are expected to demonstrate the greatest influence of tidal wetlands on water-quality constituents.

Initial Model Results

The observed removal rates are often quantified by methods, such as analysis of sediment profiles, which provide rates averaged over lengthy periods. Some studies also describe rates at small spatial scales not represented in the model. The various methodologies, time scales, and spatial scales restrict the nature of model-data comparisons. The comparisons we provide here are of long-term average model rates versus the range of rates observed in each of the regions with observations (Figure 1). Comparisons for burial of carbon, nitrogen, phosphorus, and fixed solids are shown in Figures 9-12, based on an initial parameter set presented in Table 3. An initial judgment is that the model wetlands are burying less material, on average, then depicted in the range of observations. One inference from this judgement is that the initial wetlands settling rates should be increased. An alternate explanation is that the observed burial rates for carbon, nitrogen and phosphorus are not comprised exclusively of particulate material removed from the water column, as represented in the module. Burial may include carbon fixed by wetlands vegetation and dissolved nutrients converted by vegetation to particulate organic form. Modeled wetlands nitrate uptake is less than the range of observations (Figure 13) suggesting need for revision of the initial nitrate mass-transfer coefficient. Parameter assignment and judgments of model performance will both require revision following revision to watershed loads and examination of water quality model calibration status.

The Water Quality Goals Implementation Team has provided values for nutrient reduction credits associated with vegetation restoration (Drescher and Stack 2015). The values, 0.026 g N m^{-2} d^{-1} and 0.016 g P m^{-2} d^{-1}, are based on an extensive literature survey which includes studies outside the limited geographic range considered here. The model nitrogen removal rates, which combine denitrification and burial, are representative of the recommended credits (Figure 14). Model phosphorus removal, equivalent to burial, is much less than the recommended credit (Figure 11). Model phosphorus removal can be increased through an increase in the wetlands settling velocity but the recommended credit is outside the range of the observed burial rates considered herein.

A uniform wetlands oxygen consumption rate of 0.5 g m^{-2} d^{-1} was implemented in the module. The implemented rate is reduced, on average, by local dissolved oxygen availability and seasonal temperature variation (Figure 15). The model rate is less than limited reported rates (Table 2) although larger instantaneous rates are expected from the model based on local temperature and dissolved oxygen conditions.

Preliminary sensitivity runs demonstrate the ability of the wetlands module to improve water quality model performance. Nitrate computations in a 40-km reach of the York River are improved when wetlands nitrate uptake is represented in the model (Figure 16). Dissolved oxygen sags in the Patuxent and York River are explained by wetlands respiration (Figure 17) and total nitrogen computations in the Nanticoke River are improved when wetlands nitrogen removal is considered (Figure 18).

The wetlands module is still under development. Major changes in the formulations are not expected but comparisons to observations will be revised following implementation of final watershed model loads and additional calibration of the water quality model and the wetlands module.

References

Cerco, C., Kim, S.-C. and Noel, M. (2010). "The 2010 Chesapeake Bay eutrophication model," Chesapeake Bay Program Office, US Environmental Protection Agency, Annapolis MD. (available at http://www.chesapeakebay.net/publications/title/the_2010_chesapeake_bay_eutrophication_model1)

Bryan, J. (2014). "Effects of sea level rise on tidal marshes," Thesis submitted to the faculty of the graduate school of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of Master of Science.

Boynton, W., Hagy, J., Cornwell, J., Kemp, W., Greene, S., Owens, M., Baker, J., and Larsen, R. (2008). "Nutrient budgets and management actions in the Patuxent River estuary," *Estuaries and Coasts*, 31, 623-651.

Drescher, S., and Stack, B. (2015). "Recommendations of the expert panel to define removal rates for shoreline management projects," Chesapeake Bay Partnership. (available at http://www.chesapeakebay.net/documents/Shoreline_Management_Protocols_Final_Approved_07132015-WQGIT-approved.pdf)

Flemer, D., Heinle, D., Keefe, C., and Hamilton, D. (1978). "Standing crops of marsh vegetation of two tributaries of Chesapeake Bay," *Estuaries*, 1(3), 157-163

Glick, P., Clough, J., and Nunley, B. (2008). "Sea-level rise and coastal habitats in the Chesapeake Bay region," National Wildlife Federation. (available at https://www.nwf.org/~/media/PDFs/Global-Warming/Reports/SeaLevelRiseandCoastalHabitats_ChesapeakeRegion.ashx)

Hopfensperer, K., Kaushal, S., Findlay, S., and Cornwell, J. (2009). "Influence of plant communities on denitrification in a tidal freshwater marsh of the Potomac River, United States," *Journal of Environmental Quality*, 38, 618-626

Kearney, M., Rogers, J., Townshend, E., Rizzo, E., Stutzer, D., Stevenson, J., and Sundborg, K. (2002). "Landsat Imagery Shows Decline of Coastal Marshes in Chesapeake and Delaware Bays," *Eos* 83(16), 173, 177-178.

Merrill, J., and Cornwell, J. (2002). "The role of oligohaline marshes in estuarine nutrient cycling," in Concepts and Controversies in Tidal Marsh Ecology, Weinstein, M., and Kreeger, D., eds. Springer, Dordrecht. pp 425-441.

Morse, J., Megonigal, J., and Waldbridge, M. (2004). "Sediment nutrient accumulation and nutrient availability in two tidal freshwater marshes along the Mattaponi River, Virginia, US," *Biogeochemistry*, 69, 175-206

Neubauer, S., Miller, W., and Anderson, I. (2000). "Carbon cycling in a tidal freshwater marsh ecosystem: a carbon gas flux study," *Marine Ecology Progress Series*, 199, 13-30.

Neubauer, S., Anderson, I., Constantine, J., and Kuel, S. (2002). "Sediment deposition and accretion in a Mid-Atlantic (U.S.) tidal freshwater marsh," *Estuarine, Coastal and Shelf Science*, 54, 713-727.

Neubauer, S., and Anderson, I. (2003). "Transport of dissolved inorganic carbon from a tidal freshwater marsh to the York River estuary," Limnology and Oceanography, 4891), 299-307

Neubauer, S., Anderson, I., and Neikirk, B. (2005). "Nitrogen cycling and ecosystem exchanges in a Virginia tidal freshwater marsh," *Estuaries*, 28(6), 909-922.

Palinkas, C., and Cornwell, J. (2012). "A preliminary sediment budget for the Corsica River (MD): Improved estimates of nitrogen burial and implications for restoration," *Estuaries and Coasts*, 35, 546-558.

Palinkas, C., Engelhardt, K., and Cadol, D. (2013). "Evaluating physical and biological influences on sedimentation in a tidal fresh marsh with 7Be," *Estuarine, Coastal and Shelf Science*, 129, 152-161

Seldomridge, E., and Prestegaard, K. (2014). "Geochemical, temperature, and hydrologic transport limitations on nitrate retention in tidal freshwater wetlands, Patuxent River, Maryland," *Wetlands*, 34, 641-651.

Stevenson, J., Kearney, M., and Pendleton, E. (1985). "Sedimentation and erosion in a Chesapeake Bay brackish marsh system," *Marine Geology*, 67, 213-235.

Ward, L., Kearney, M., and Stevenson, J. (1998). "Variations in sedimentary environments and accretionary patterns in estuarine marshes undergoing rapid submergence, Chesapeake Bay," *Marine Geology*, 151, 111-134.

Table 1
Studies Contributing to Process Data Base

Authors	Year	Citation
Boynton, W., Hagy, J., Cornwell, J., Kemp, W., Greene, S., Owens, M., Baker, J., and Larsen, R.	2008	Estuaries and Coasts, 31, 623-651
Flemer, D., Heinle, D., Keefe, C., and Hamilton, D.	1978	Estuaries, 1(3), 157-163
Hopfensperer, K., Kaushal, S., Findlay, S., and Cornwell, J.	2009	Journal of Environmental Quality, 38, 618-626
Merrill, J., and Cornwell, J.	2002	Weinstein, W., and Kreeger, D., eds., EBSCO Publishing
Morse, J., Megonigal, J., and Waldbridge, M.	2004	Biogeochemistry, 69, 175-206
Neubauer, S., Anderson, I., and Neikirk, B.	2005	Estuaries, 28(6), 909-922
Neubauer, S., Miller, W., and Anderson, I.	2000	Marine Ecology Progress Series, 199, 13-30
Newbauer, S., and Anderson, I	2003	Limnology and Oceanography, 4891, 299-307
Newbauer, S., Anderson, I., Constantine, J., and Kuel, S	2002	Estuarine, Coastal and Shelf Science, 54, 713-727
Palinkas, C., and Cornwell, J.	2012	Estuaries and Coasts, 35, 546-558
Palinkas, C., Engelhardt, K., and Cadol, D.	2013	Estuarine, Coastal and Shelf Science, 129, 152-161
Seldomridge, E., and Prestegaard, K.	2014	Wetlands, 34, 641-651
Stevenson, J., Kearney, M., and Pendleton, E.	1985	Marine Geology, 67, 213-235
Ward, L., Kearney, M., and Stevenson, J.	1998	Marine Geology, 151, 111-134

Table 2
Summary of Wetlands Process Observations for Use in Model Parameterization and Validation.

CBPS	C deposition, g m^{-2} d^{-1}	N deposition, g m^{-2} d^{-1}	P deposition, g m^{-2} d^{-1}	denitrification, g N m^{-2} d^{-1}	solids deposition, g m^{-2} d^{-1}	respiration, g DO m^{-2} d^{-1}
BSHOH		0.008 to 0.032	0.001 to 0.006			
CHSMH		0.02 to 0.064	0.01 to 0.019		3.6	
FSBMH	0.16 to 0.33				0.3	
MPNOH	0.24 to 2.77	0.019 to 0.238	0.004 to 0.085		1.43 to 42.0	
MPNTF						
NANMH	0.033 to 0.126				1.61 to 8.12	
NANOH	0.033 to 0.126				1.61 to 8.12	
PAXOH		0.008	0.002		5.75	
PAXTF		0.033 to 0.064	0.01	0.108 to 0.197	5.75	
PMKOH	0.61	0.05		0.04		1.12 to 2.77
POTTF	1.44			0.043 to 0.06	5.88	
WICMH	0.033 to 0.126	0.037	2.74 e-5 to 0.004		1.61 to 8.12	
CHOMH		0.053 to 0.074	4.9 e-4 to 0.005			
WQGIT			0.0016	0.026		

Table 3
Wetlands Module Parameters

Parm	Definition	Value	Units
WSl	settling velocity of labile organic particles	0.05	$m\ d^{-1}$
WSr	settling velocity of refractory organic particles	0.05	$m\ d^{-1}$
WSg3	settling velocity of G3 organic particles	0.05	$m\ d^{-1}$
WSb1	settling velocity of Group 1 phytoplankton	0.005	$m\ d^{-1}$
WSb2	settling velocity of Group 2 phytoplankton	0.005	$m\ d^{-1}$
WSb3	settling velocity of Group 3 phytoplankton	0.005	$m\ d^{-1}$
WSpip	settling velocity of particulate inorganic phosphorus	0.01	$m\ d^{-1}$
WSfclay	settling velocity of fine clay	0.05	$m\ d^{-1}$
WSclay	settling velocity of clay	0.13	$m\ d^{-1}$
WSsilt	settling velocity of silt	0.432	$m\ d^{-1}$
WOC	wetlands oxygen consumption at 20 ^oC	0.5	$g\ DO\ m^{-2}\ d^{-1}$
Kh	DO concentration at which wetlands consumption is halved	1	$g\ m^{-3}$
MTC	nitrate mass-transfer coefficient	0.05	$m\ d^{-1}$

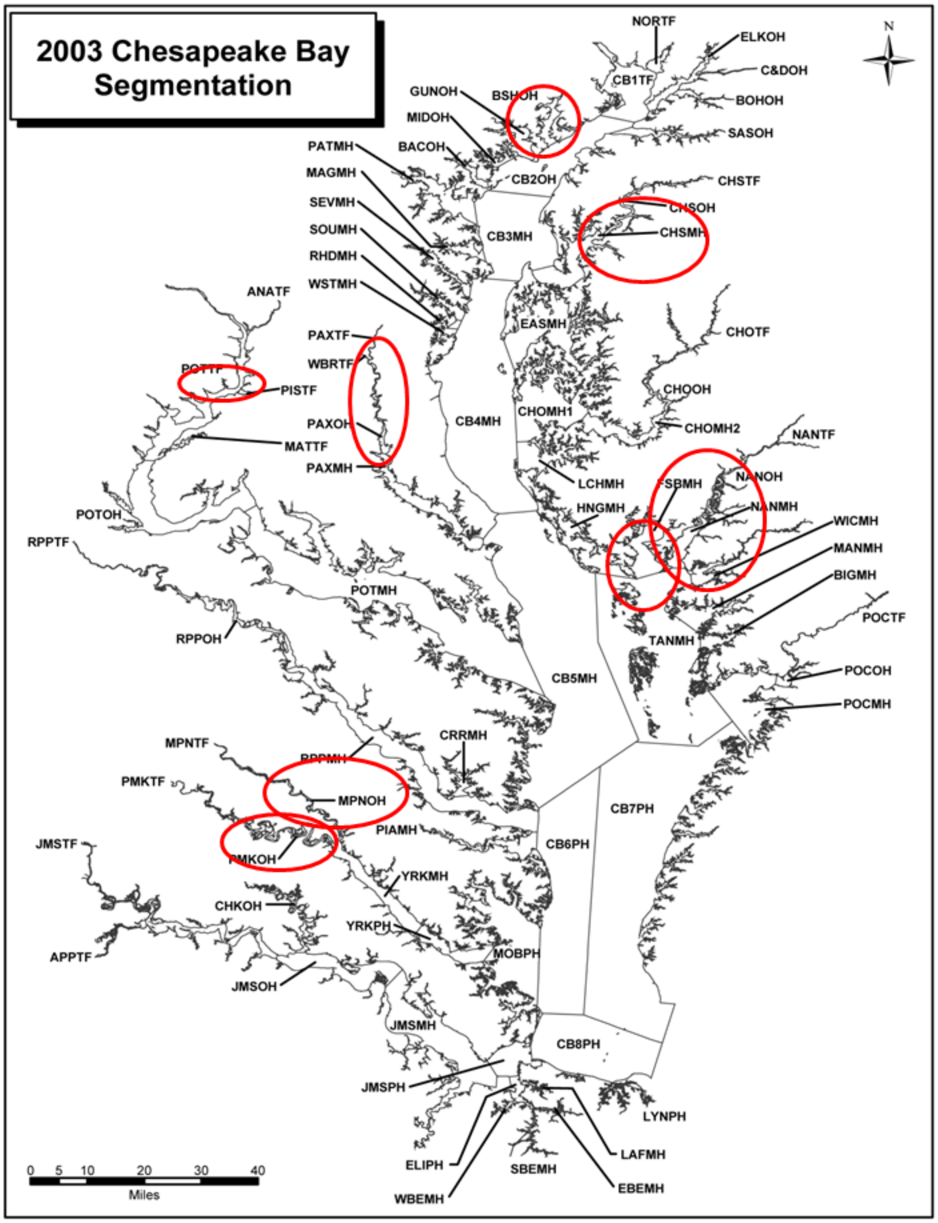

Figure 1. Regions with wetlands observations used to parameterize the wetlands module of the water quality model.

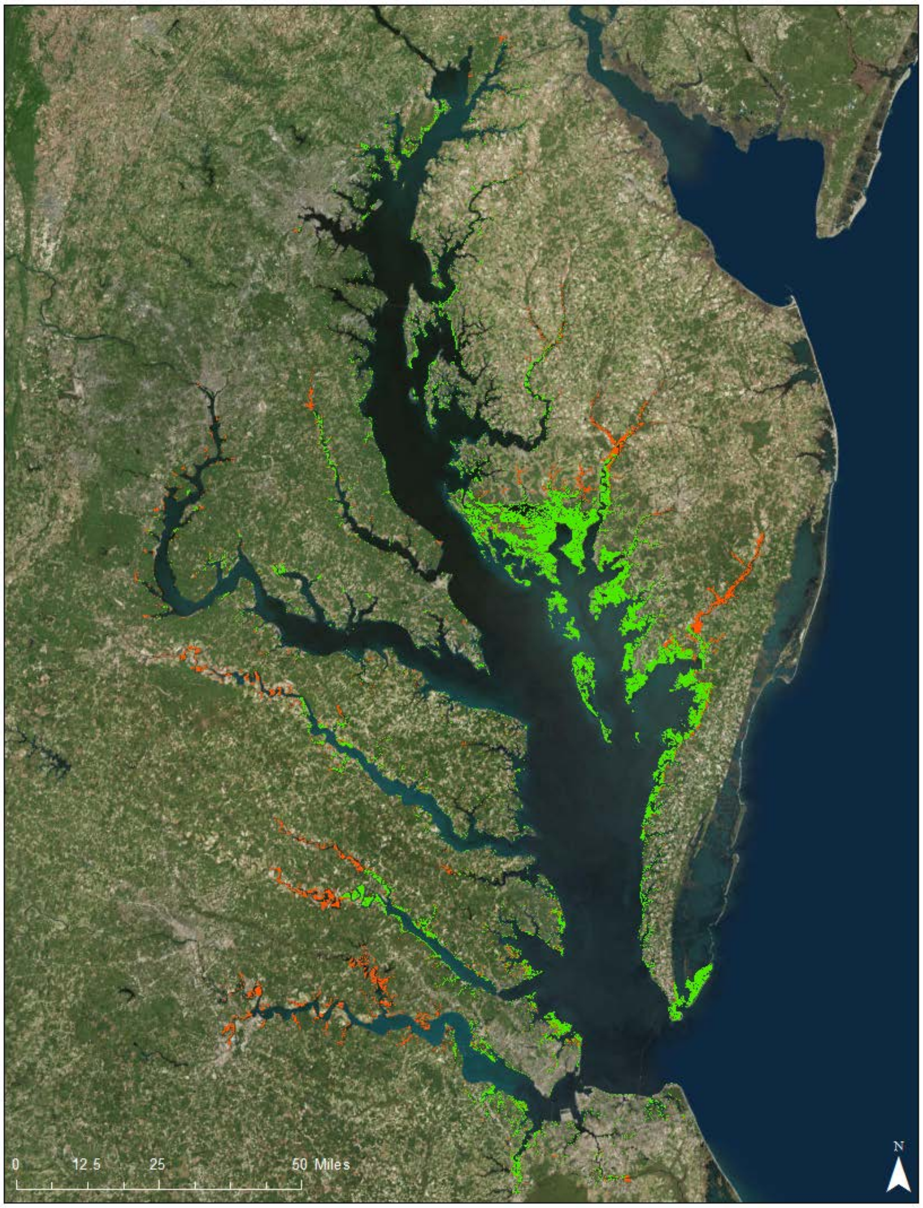

Figure 2. Chesapeake Bay tidal wetlands. Salt and brackish wetlands are shown in green, freshwater wetlands are shown in red.

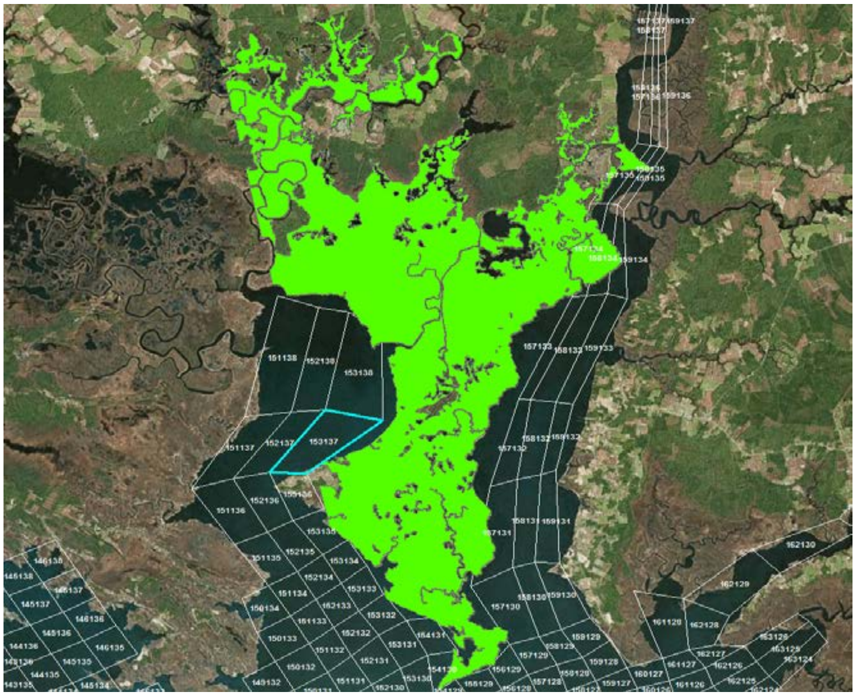

Figure 3. Example of wetlands area combined with model grid and Bay watershed.

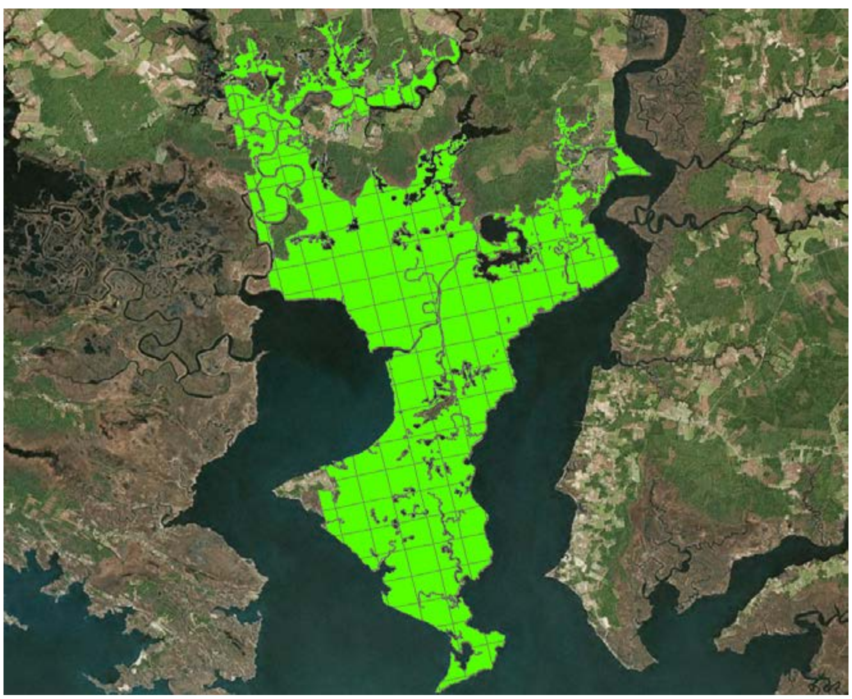

Figure 4. Example of "fishnet" superimposed on wetlands area.

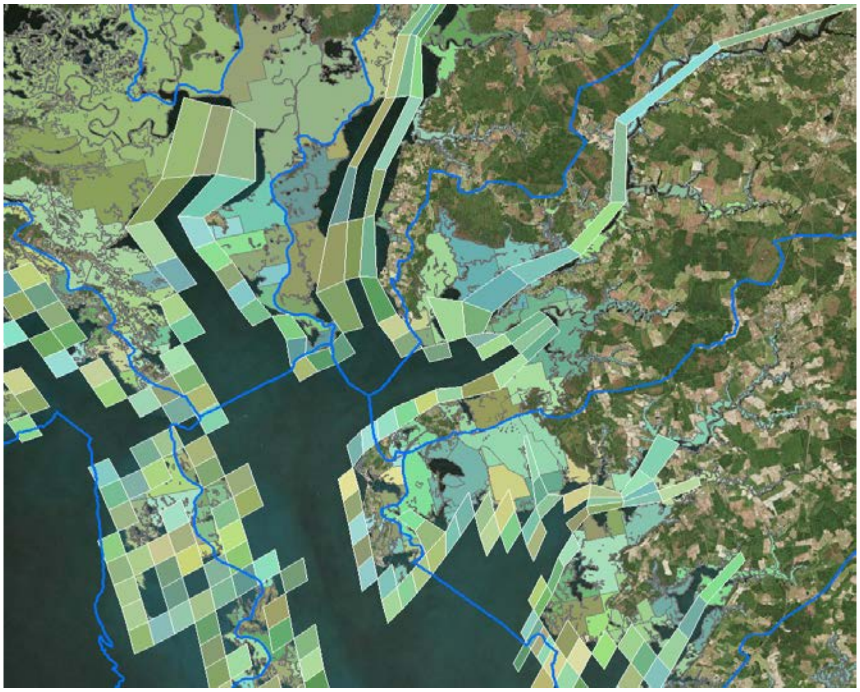

Figure 5. Example of wetlands area mapped to model cells. Wetlands squares from the fishnet are shown in the same color as the cells to which they are mapped.

Figure 6. Example of HUC 10 local watershed boundaries superimposed on map of Bay watershed. Mapping of wetlands to model cells was restricted to not cross local watershed boundaries.

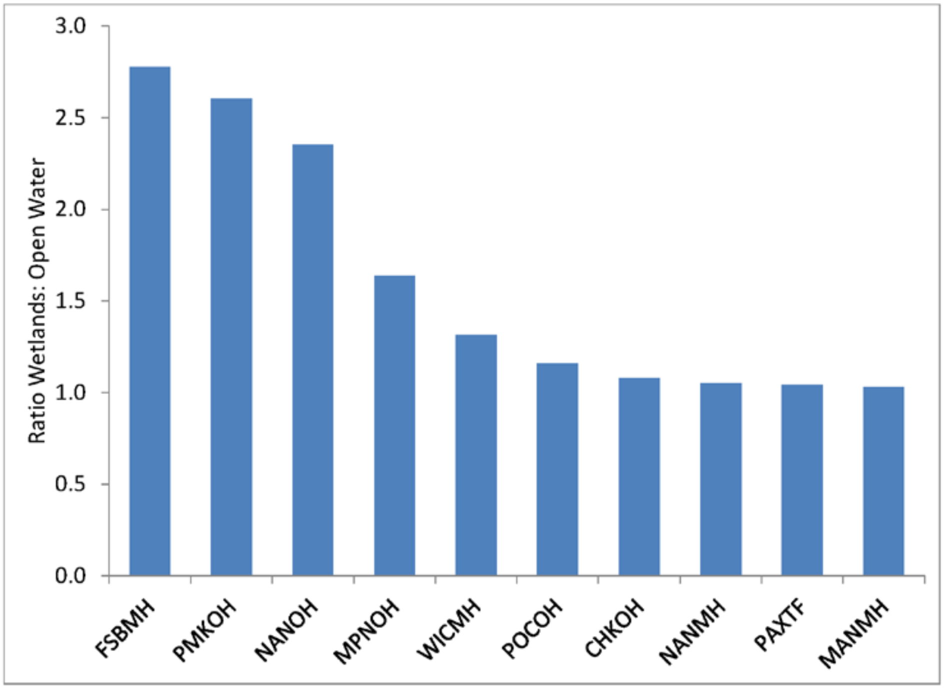

Figure 7. Ten regions of the Bay with the greatest ratio of tidal wetlands to open-water area. Open-water areas are as represented on the model grid.

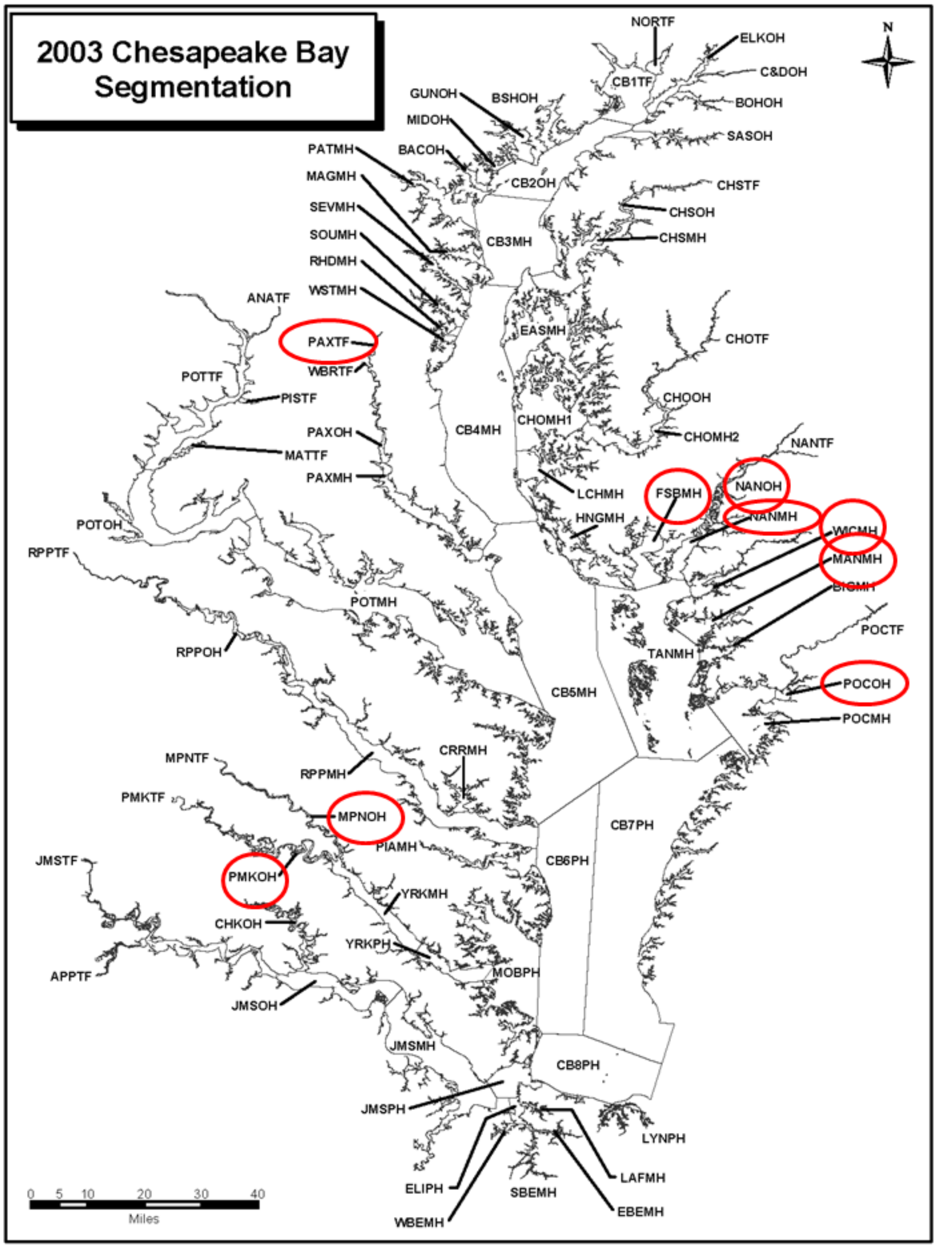

Figure 8. Locations of ten regions with greatest ratio of tidal wetlands area to open-water area.

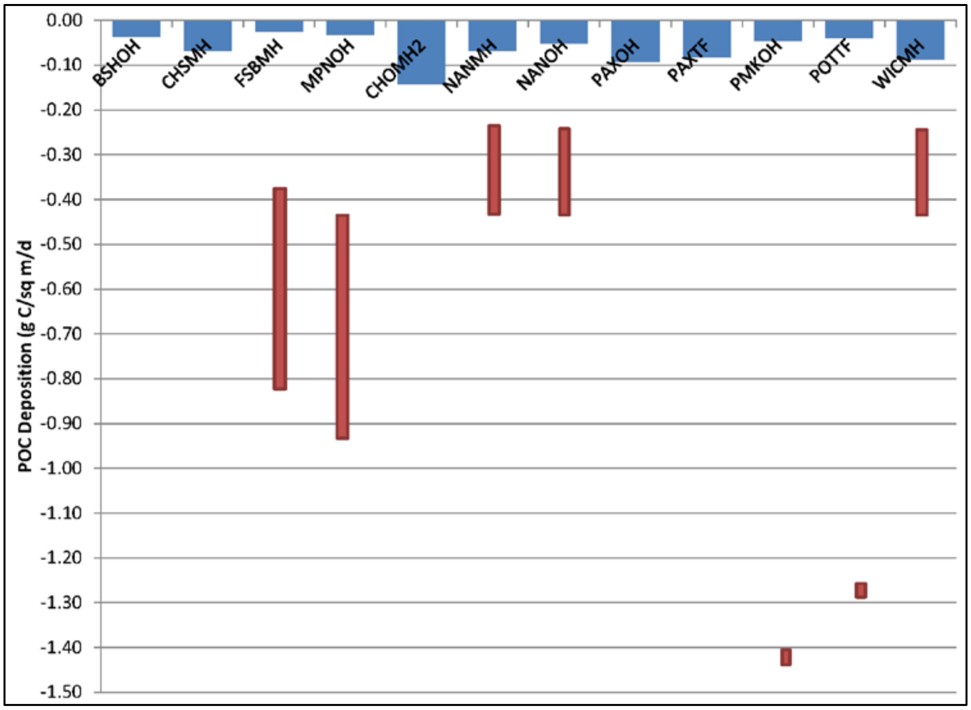

Figure 9. Comparison of computed daily-average wetlands carbon deposition (blue bars) with range of reported rates (red bars). Observed rates in MPNOH, PMKOH, POTTF represent accumulation on tiles. Remaining observations are long-term burial rates.

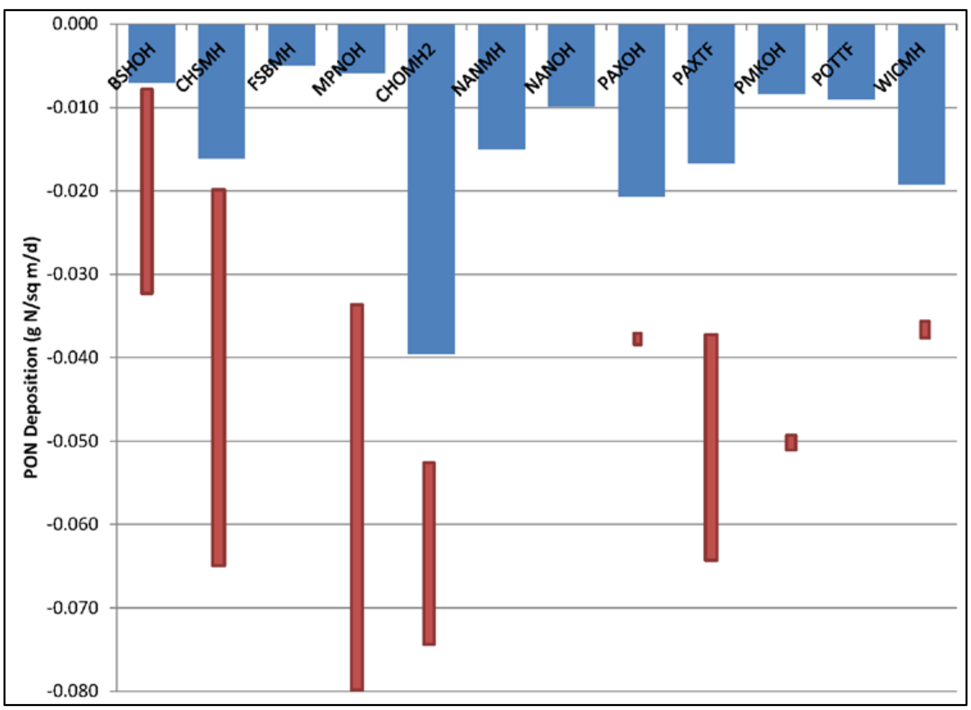

Figure 10. Comparison of computed daily-average wetlands particulate nitrogen deposition (blue bars) with range of reported rates (red bars). Observed rates in

MPNOH represent accumulation on tiles. Remaining observations are long-term burial rates.

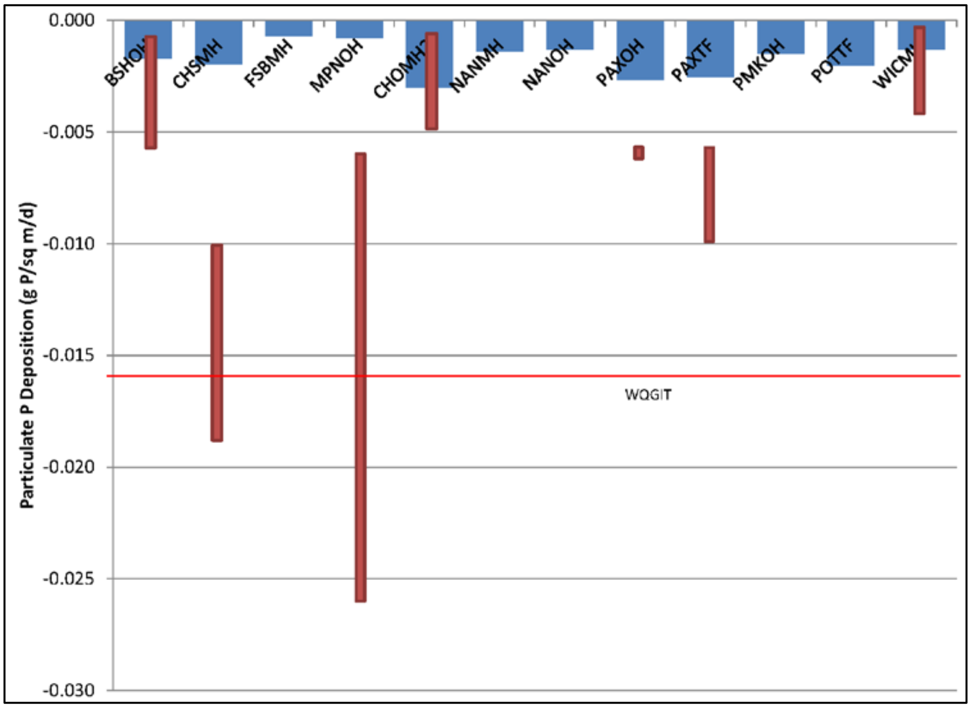

Figure 11. Comparison of computed daily-average wetlands particulate phosphorus deposition (blue bars) with range of reported rates (red bars).

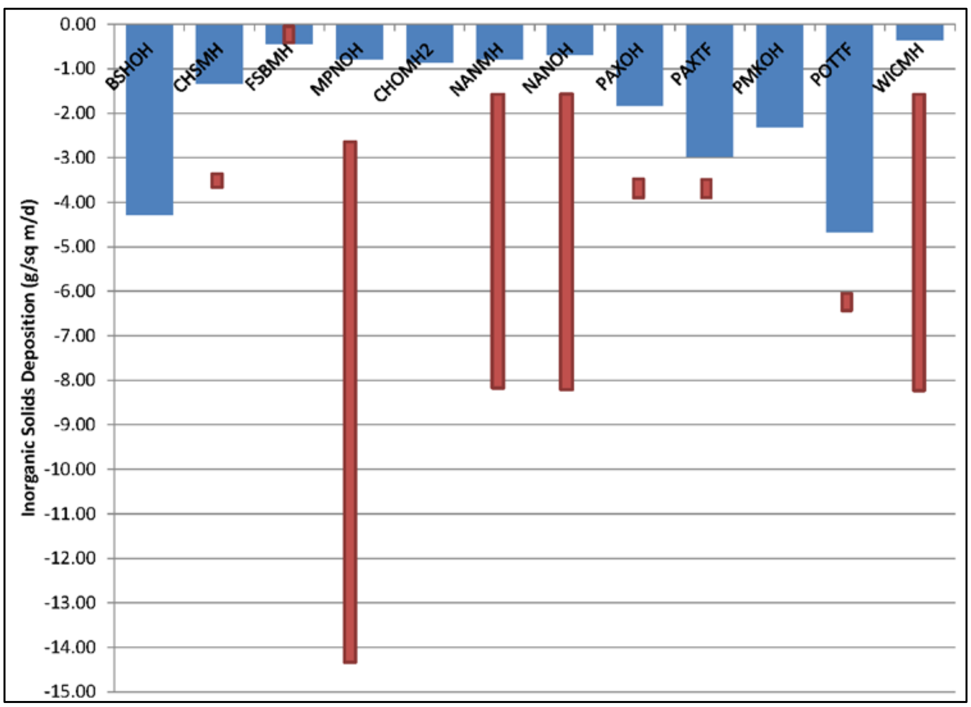

Figure 12 Comparison of computed daily-average wetlands fixed solids deposition (blue bars) with range of reported rates (red bars).

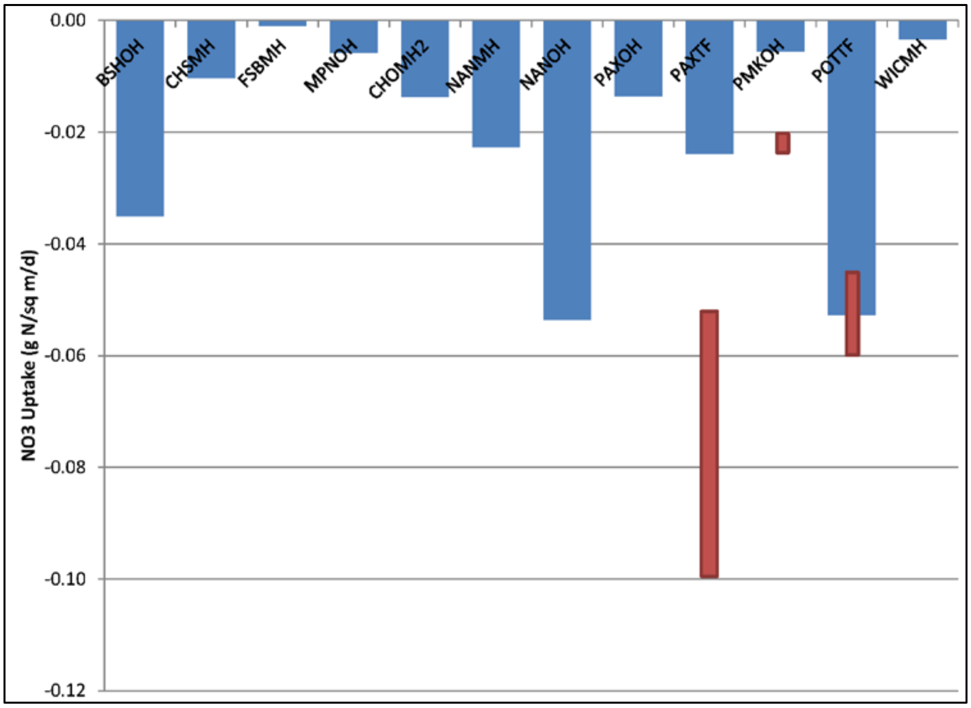

Figure 13. Comparison of computed daily-average wetlands nitrate uptake (blue bars) with range of reported rates (red bars).

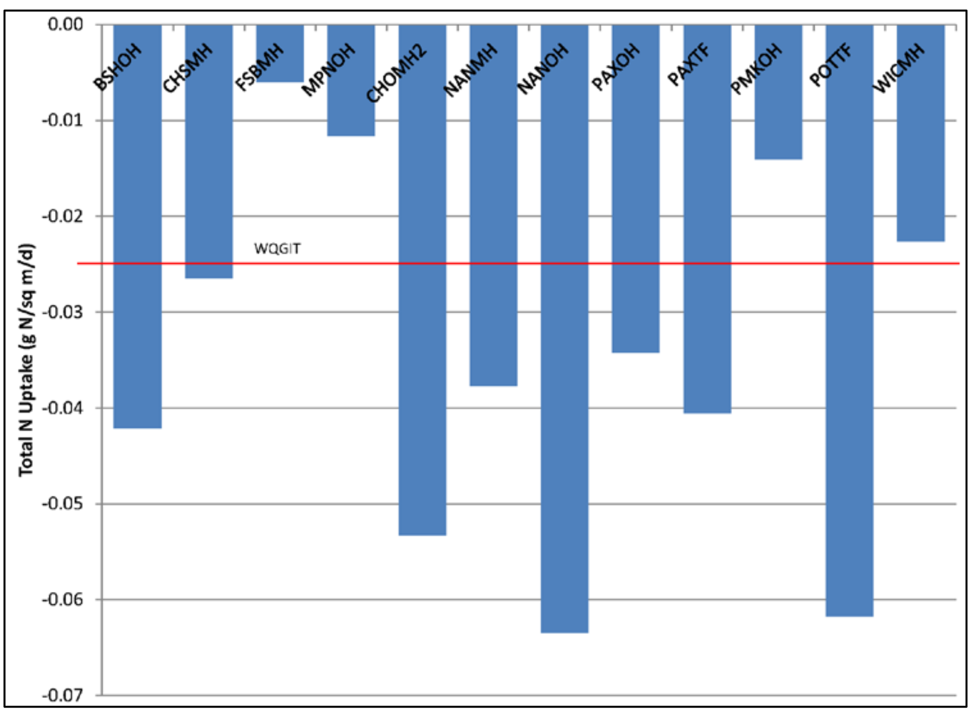

Figure 14. Comparison of computed daily-average wetlands nitrogen removal (blue bars) with recommended rate (red line).

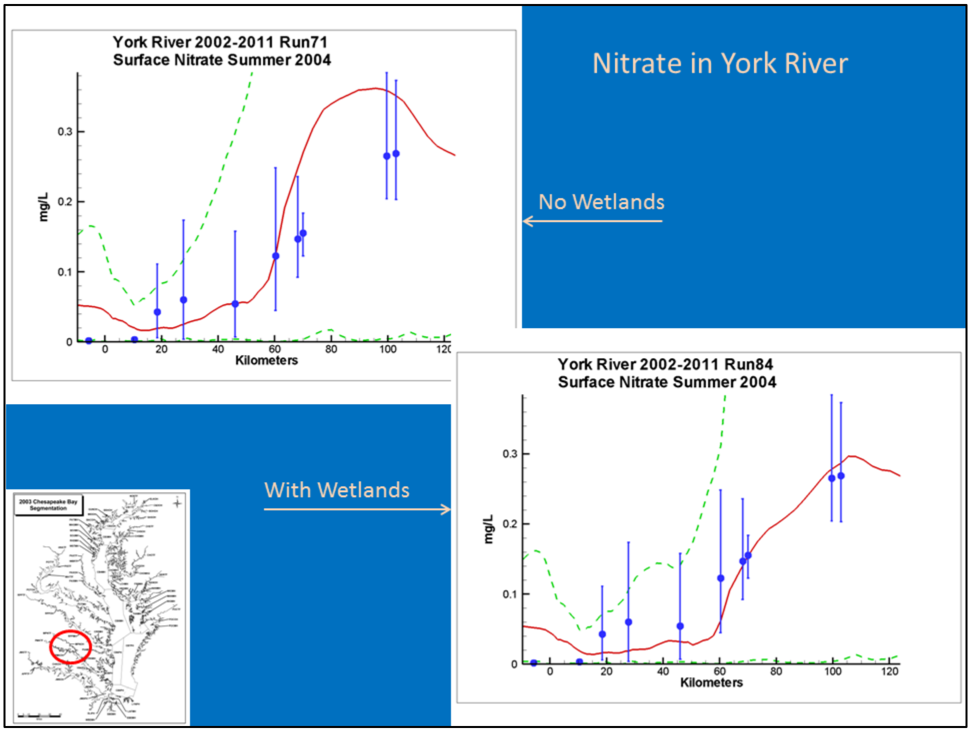

Figure 15. Sensitivity of York River model nitrate concentration to wetlands removal. Comparison shown for summer 2004.

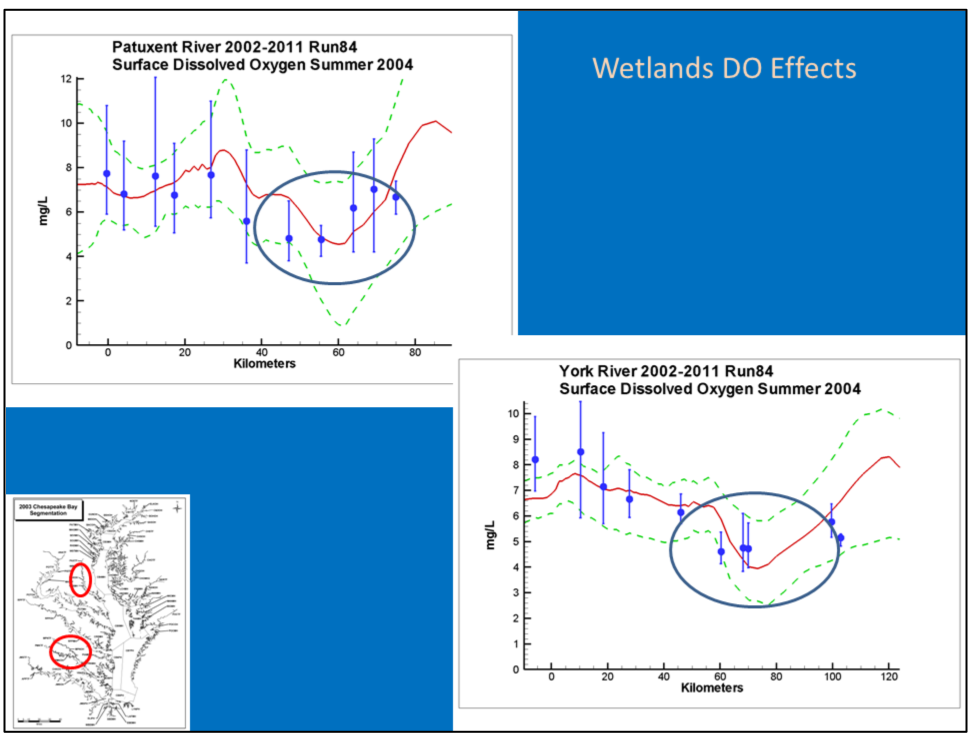

Figure 16. Effect of wetlands oxygen uptake on dissolved oxygen computations in the Patuxent and York Rivers. Results shown for summer 2004.

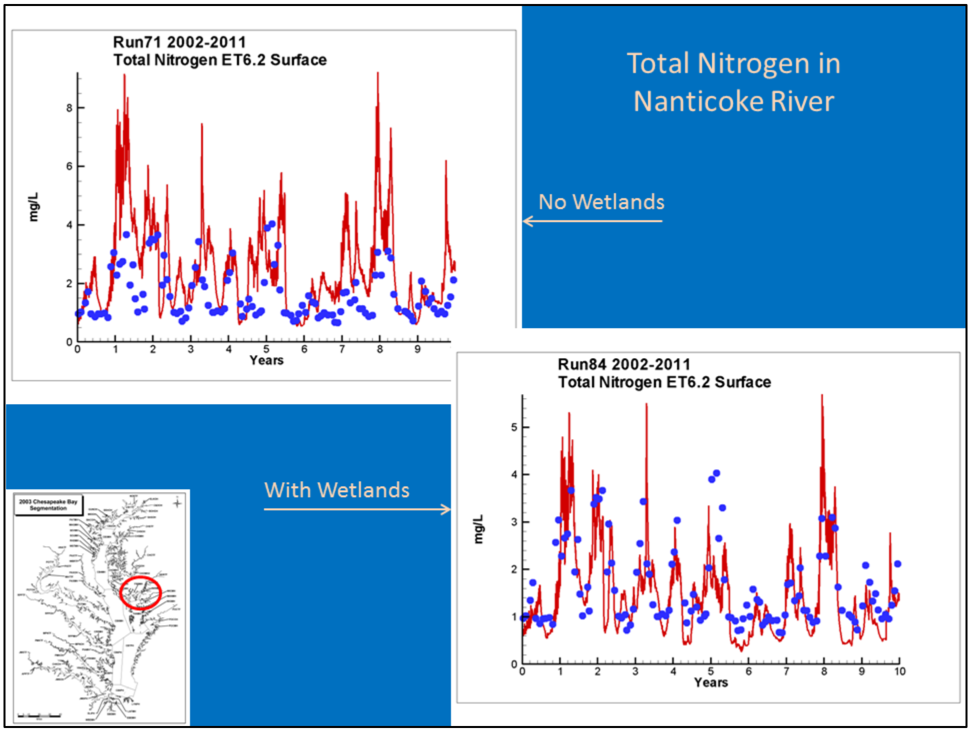

Figure 17. Effect of wetlands nitrogen removal on computed total nitrogen concentration in the Nanticoke River. Ten year time series 2002 – 2011.