4-2006

Development of a Tidal Wetland Inventory and Assessment for York River, Virginia Watershed

Center for Coastal Resources Management, Virginia Institute of Marine Science

Recommended Citation
Center for Coastal Resources Management, Virginia Institute of Marine Science. (2006) Development of a Tidal Wetland Inventory and Assessment for York River, Virginia Watershed. Virginia Institute of Marine Science, College of William and Mary. https://doi.org/10.25773/s69w-zs23

Development of a Tidal Wetland Inventory and Assessment for York River, Virginia Watershed

EPA #CD-973079-01
Final Report

Virginia Institute of Marine Science, College of William and Mary
Center for Coastal Resources Management

April 2006

Introduction

As part of the Chesapeake 2000 agreement, the Commonwealth of Virginia pledged to a wetland policy of no net-loss. Through conscientious resource protection and management, Virginia's non-tidal and tidal wetland permit programs, administered by the Virginia Department of Environmental Quality (DEQ) and The Virginia Marine Resources Commission (VMRC) respectfully, are committed to reaching this goal. In order to assist these agencies in realizing no-net loss of wetlands, the availability of baseline data is essential in defining our existing resources and is the basis from which future status and trends can be evaluated along with the effectiveness of permitting and management programs. In addition, these data provide valuable information in identifying wetland restoration opportunities, evaluating appropriate mitigation ratios, and determining cumulative impacts within a watershed.

Center for Coastal Resource Management (CCRM) scientists at the Virginia Institute of Marine Science (VIMS) have participated with the Virginia Department of Environmental Quality (DEQ) in Mid-Atlantic Wetland Workgroup (MAWWG) efforts to develop wetland assessment methodologies necessary in reporting wetland condition as required by Section 305 (b) of the Clean Water Act (CWA). Currently, CCRM is conducting a Level I and Level II assessment of the Commonwealth's coastal plain non-tidal wetlands (EPA Region III Wetland Program Development Grant #BG-983925-01). As this research effort continues, CCRM will provide valuable information to DEQ and other local, state and federal agencies regarding the extent and condition of the Commonwealth's non-tidal wetland resources in the coastal plain and piedmont physiographic regions. These data will help provide the information necessary to make informed resource management and wetland permitting decisions.

Objectives

The CCRM Wetland Advisory Program has developed and maintains an extensive database that has tracked impacts to tidal wetland habitat permitted across the Commonwealth of Virginia through the regulatory permit process since the early 1980's. The cumulative total annual loss of tidal wetlands serves as the basis from which current and future management and regulatory policy and decisions can be formulated.

The objective of this study was to provide the Virginia Marine Resources Commission (VMRC) and the Virginia Department of Environmental Quality (DEQ) wetland regulatory programs the ability to report on the current status of tidal wetlands in the Commonwealth and the baseline data necessary to report on trends resulting from cumulative impacts to these resources over time. A Level I tidal wetland assessment provides DEQ with information necessary to report on the condition of tidal and non-tidal wetlands (EPA #CD-983380-01 and #BG-983925-01) on a watershed scale, develop new or modify existing permitting strategies and compensation ratios, and identify potential wetland restoration and enhancement opportunities. In addition, a tidal wetland assessment affords VMRC the ability to track permitted tidal wetland loss by wetland type, conduct cumulative impact assessments, and review the effectiveness of Virginia's tidal wetland regulatory program.

Methods

The Level I inventory and assessment developed in this study relies extensively upon the use of remotely sensed geographic information systems (GIS)-based datasets, hereafter referred to as a coverage. These data were utilized to determine the boundaries and aerial extent of estuarine and palustrine wetlands, salinity, hydrology, bathymetry, surrounding land use classification, submerged aquatic vegetation, oyster reefs, and conservation sites within the York River watershed from the Goodwin Islands to the limits of tidal influence (tidal fresh) on the Mattaponi and Pamunkey Rivers above the town of West Point, Virginia (14-digit HUCs F-13, 14, 23, 24, 25, 26, 27). Estuarine and palustrine tidal wetlands as classified by the hierarchical Cowardin system (Cowardin et al., 1979) were identified using the U.S. Department of the Interior's National Wetland Inventory (NWI) coverage. A total of 2,188 tidal wetland polygons were identified in the tidal portion of the York River watershed. This total is comprised of 2,169 tidal wetland polygons and 19 linear wetland features. Table 1 lists the various tidal wetland types included in this study.

Table 1. NWI wetland types included in Level I assessment of York River, Virginia. Asterick (*) denotes any modifier to: water regime, water chemistry, soil, etc., when applicable.

E2*EM*	Estuarine intertidal emergent
E2*SS*	Estuarine intertidal scrub-shrub
E2*FO*	Estuarine intertidal forested
R1EM	Riverine tidal emergent
PSS*S	Palustrine scrub-shrub temporary-tidal
PSS*R	Palustrine scrub-shrub seasonal-tidal
PSS*T	Palustrine scrub-shrub semi-perm.-tidal
PSS*V	Palustrine scrub-shrub permanent-tidal
PEM*S	Palustrine emergent temporary-tidal
PEM*R	Palustrine emergent seasonal-tidal
PEM*T	Palustrine emergent semi-perm.-tidal
PEM*V	Palustrine emergent permanent-tidal
PFO*S	Palustrine forested temporary-tidal
PFO*R	Palustrine forested seasonal-tidal
PFO*T	Palustrine forested semi-perm.-tidal
PFO*V	Palustrine forested temporary-tidal

Utilizing the most recent versions of available GIS coverages, CCRM scientists identified various metrics to assess every tidal wetland polygon or line feature for three basic ecological functions; habitat, water quality and erosion protection. This census approach to wetland assessment, whereby each wetland is evaluated individually, is one of the strengths and advantages of a methodology based on remotely sensed data. The decision to focus our assessment on these three functions was based on our current scientific understanding of the ecological services provided by these systems. The available scientific literature and the collective best professional judgment of CCRM wetland scientists was used to develop and refine the various metrics that comprise the three functional value scores calculated for each wetland. Reporting functional scores at various resolutions, from an entire NWI wetland class within the York River watershed to an individual tidal wetland polygon, is facilitated using ArcInfo® GIS software to calculate total wetland size (hectares) and NWI classification.

Although combining the individual function scores to obtain a cumulative functional value score to rank wetlands amongst one another would appear desirable from a resource management and regulatory perspective, no scientific rationale currently exists that would permit users to weigh one function against another. Although managing a wetland resource to maximize a specific function could have its applications, typically, a managing for a suite of functions is a more common resource management practice. Until further research and our scientific understanding support the valuation of one function over another, it is unadvisable to compare scores across ecological functions. Therefore, at this time we do not recommend the cumulative comparison of function scores for tidal wetlands as a means to rank individual wetland polygons using the assessment methodology described here.

Water Quality

In selecting the most important and valuable ecological functions performed by wetlands it would be difficult to select one more important to general aquatic health than water quality. Tidal wetlands play an important role in removing sediment and nutrients from surface water runoff entering an estuary from the surrounding watershed. Estuaries play an important role in the flushing of toxins, nutrients and suspended sediments from the system. Residence time, a function of freshwater input, currents, and tidal influence, provides a relative rate at which these materials move through the estuarine system. Though it is more desirable to prevent pollutants from entering surface waters than to address the problems associated with eutrophication and turbidity after-the-fact, certain wetlands based on their position within the watershed possess provide more opportunity for these materials to be sequestered in the marsh as opposed to being exported down-estuary then offshore to the continental shelf.

In this study, salinity was used as a proxy for residence time within the estuarine system. Salinity coverage for the York River was obtained from the National Oceanic and Atmospheric Administration (NOAA). The salinity coverage is a dataset composite (1986-2000) of seasonally (spring, summer, fall) interpolated data. Salinity was clipped to the study area boundary (York River watershed). Average-maximum value was used to group the salinity values into regimes with salinity scores:

Tidal regime	score
Tidal fresh ≤0.5 ppt	1.0
Oligohaline >0.5 – 5.0 ppt	0.75
Mesohaline >5.0 - 18.0 ppt	0.50
Polyhaline >18.0 – 30.0 ppt	0.25
Euhaline >30.0 ppt	0.10

Lines were drawn from the boundaries of the salinity regimes to the edge of the study area boundary to create a large polygon coverage. This coverage was unioned with the NWI coverage to add salinity values to all tidal wetlands.

Following the stratification of the wetlands by salinity regime, the upland/wetland interface was determined. Wetland polygons were then buffered 10m along the upland/wetland arc. The buffer was then overlaid with the wetland and the percentage of wetland within the wetland side of the buffer was determined. This metric is identified by the name: wtlnd10m. Scores for this metric range from 0.1 to 1.0. All linear tidal wetlands receive a score of 0.1, as do polygons without an upland/wetland interface i.e. surrounded by other wetland polygons.

Habitat

Following the water quality benefits provided by tidal wetlands, the provision of habitat for innumerable plant and animal species is arguably the second most important function provided by these systems. Tidal wetlands provide valuable forage, spawning and nursery habitat for many marine and terrestrial species. Many animals important to sustaining ecosystem health spend at least a portion of their life history in tidal marshes. Often, a combination or mosaic of various habitat types can provide a synergism of habitat function not possible when habitats are found separately. Oyster reefs and seagrass beds are examples of habitats that can increase the ecological functional value of an adjacent marsh. For this reason, wetland habitat function is improved through association with submerged aquatic vegetation (SAV), oyster reefs and other wetlands.

The SAV data used for this study is a 10 year composite of data collected from 1993 to 2003. These data are represented as the presence/absence of these habitat types. The percent of SAV within the 100m aquatic buffer and the 200 m aquatic buffer were calculated in hectares (sav1h and sav2h). The 100m buffer score = (area of SAV / aquatic area) X 2 and the 200m buffer score = (area SAV / aquatic area). Area of SAV located within 100m is therefore weighted twice that located between 100-200 m from the wetland. Oyster reefs are point data obtained from VMRC. The points are buffered 10 m. A wetland with a buffered oyster reef occurring within the 100 m or 200 m aquatic buffer scores a 1.0 (oyster1h or oyster2h). Three buffers, 3 m, 100 m, and 200 m, are used to capture wetland proximity to other wetlands. All wetland types located within the various buffers are used in this scoring, but are differentiated as tidal or non-tidal wetlands. Wetland proximity is scored as follows where only the closest wetland receives a score:

Tidal	score	Non-Tidal	score
3 m	1.0	3 m	0.5
100 m	0.5	100 m	0.25
200 m	0.25	200 m	0.125
1000 m	0.0	1000 m	0.0

The land use surrounding a wetland can dramatically influence its ability to provide and sustain habitat function. A wetland surrounded by undisturbed forested land typically provides excellent habitat function to the wetland whereas urban and industrial surrounding land use types can limit the ability for the wetland to provide significant habitat. To identify land use classifications within the York River watershed, National Land Cover Data (NLCD) 1992 and NLCD 2001 were used. The methodology we developed for use with non-tidal wetlands (EPA #CD-983380-01) was also employed in this study. Wetlands are buffered with four distances (3 m, 100 m, 200 m, 1000 m). These buffers are combined into one polygon coverage. Buffer coverage is intersected with the landuse coverage. A frequency is run to determine the landuse types within the buffers. Total area is determined for each buffer width (0-3 m, 3-100 m, 100 m-200 m, and 200 m-1000 m). The percentage of each landuse type within each buffer was then calculated. Functional values are calculated by multiplying the percentage of each landuse type within the buffer by the value assigned for each landuse type. Land cover types and initial habitat value scores are listed below. Functional values for each buffer width are then summed for each wetland.

Landuse type	score
Wetland (woody and emergent)	1.0
Forest (deciduous, evergreen, and mixed)	1.0
Open water	1.0
Pasture	0.7
Cropland	0.5
Bare rock/sand, transitional	0.5
Residential (low den. res. & urban/rec. grass)	0.2
Urban/Industrial	0.0

Adjacency to open water and access to the marsh interior directly affects the quality of the marsh habitat by affording access onto the marsh surface for refuge and feeding during high water levels. To evaluate the availability of the marsh to aquatic species, stream density is measured for each wetland using Virginia Base Map Program (VBMP) arcs (coded level = 44 streams/rivers). NWI polygons were used to clip the VBMP arcs. Minor errors associated with clipping the arcs were unavoidable due to alignment offsets. All stream segments were assigned a default width of 1 m. Stream density is expressed as a percentage of the total area where ((total stream length x 1 m) / area of wetland polygon) x 10.

Wetlands often provide valuable or even critical habitat for rare, threatened and endangered species of plants and animals. Because of the importance of protecting these species and the habitats that support them, conservation sites were identified using the Virginia Department of Conservation and Recreation, Division of Natural Heritage coverage. Tidal wetlands that fall within conservation sites are identified and are scored based upon the biodiversity rank (B1-B5) of the conservation site they overlay. If a wetland overlaps more than one conservation site, the wetland score represents the highest-ranking site.

Biodiversity Rank:	B1	B2	B3	B4	B5
Score:	2.0	1.5	1.0	0.75	0.5

Erosion Protection

Miles of Virginia's tidal shoreline is hardened each year by property owners seeking to provide their property with erosion protection. Although structural solutions to shoreline protection such as rock revetments and breakwaters have application in high wave energy environments, often a more environmentally sensitive approach that utilizes wetland vegetation to buffer wave energy is more appropriate and desirable in lower energy environments. Though all vegetated wetlands afford some protection to typical wind generated waves and boat wakes, marshes can also provide considerable buffering of tidal shorelines when subject to storm tides and large wind generated waves over large expanses of open water (fetch). We assessed the erosion protection afforded by tidal wetlands in the York River using the NWI shoreline and the 2m depth contour based on NOAA bathymetry available through the Chesapeake Bay Program. Mid-point of the arc(s) were determined for wetlands intersecting the shoreline. COGO (coordinate geometry) is used to create short arcs in 16 directions (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW). Arcs are extended to intersect the bathymetry and shoreline. Directions and distances are then written back to the wetland. If there are two midpoints, the midpoint with the longest fetch is identified and that data written data back to the wetland. If there are three or more shoreline segments for a single wetland polygon, the maximum fetch and direction for each midpoint is determined. The 16 directions are then condensed into four quadrants (NE, SE, SW, NW). The predominant fetch direction is then determined based upon the number of points in each quadrant. The longest fetch is selected from the predominant quadrant and data written to the wetland. If two or more quadrants have an equal number of points, then the longest fetch is selected from among those quadrants.

The assessment of wetland islands, where a single wetland is completely surrounded by open water, requires a slightly different analysis. A centroid point is established within the wetland. Arcs are created from this point and radiate out in 16 directions to intersect with the wetland's perimeter. From each of these intersection points, 16 additional arcs are created and extended to the nearest shoreline and 2m bathymetric contour. The arc with the longest fetch is written back to the wetland. The direction of the arc with the longest fetch is then used to determine the distance to the 2m contour.

Fetch	score
≥ 1000m	1.0
< 1000m	0.5
= 0 m	0

Distance to 2m contour	score
≤ 100m	1.0
> 100m	0.5
= 0 m	0
= fetch (shallow water)	0.25

Discussion

The tidal segments of the York River and its two main tributaries, the Mattaponi and Pamunkey Rivers (14-digit HUCs F-13, 14, 23, 24, 25, 26, 27) were utilized as the prototype watershed in the development of this Level I tidal wetland assessment (Figure 1). Scoring for each of the 2,188 wetlands evaluated in this study for the York River are available for viewing at the VIMS/CCRM website http://ccrm.vims.edu Examples of the scoring protocols are depicted in Appendix I (Figures 2 through 10). Three different wetland polygons are used to illustrate the range of the individual metric scores that comprise the overall scores for water quality, habitat and erosion protection functions.

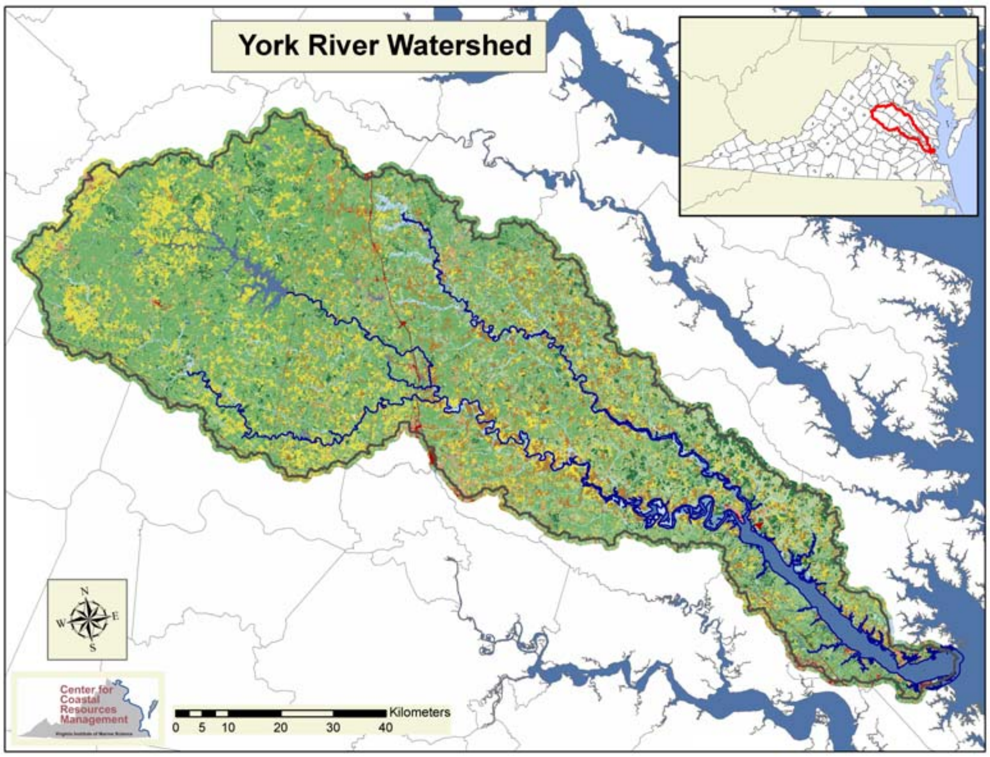

Figure 1. York River, Virginia watershed.

This study provides the basis from which a multi-level assessment methodology is being developed for the Mid-Atlantic region (EPA #CD-973252-01). This Level I assessment allows DEQ and VMRC to begin reporting comprehensively on the extent and condition of tidal wetlands within one specific watershed. By design, our approach in developing a multi-level tidal wetland inventory and assessment methodology is similar, yet unique, to that employed in the development of Virginia's non-tidal wetland assessment (EPA #CD-983380-01 and #BG-983925-01). The Level I methodology developed here to assess the tidal wetlands of the York River thus provides the framework by which comprehensive reporting on the extent and condition of tidal and non-tidal wetlands within other Virginia watersheds can be achieved. It is our intention that the protocols developed under this study are transferable to other tidal watersheds in Virginia and beyond to other states of the Mid-Atlantic region.

Appendix I. Examples of Functional Scores for Three Wetlands

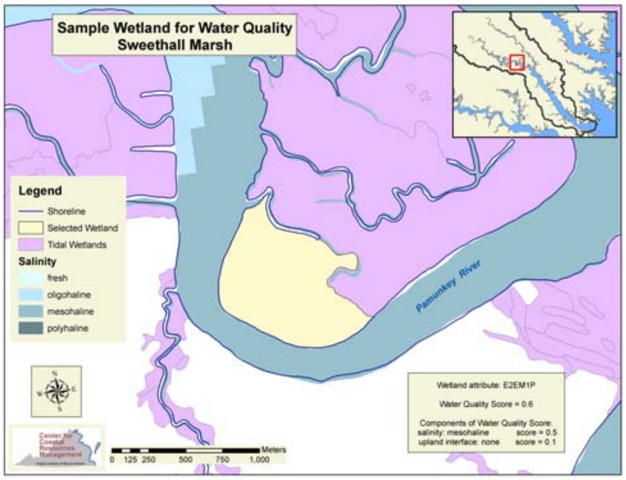

Figure 2. Water quality score wetland polygon #758, upper York River.

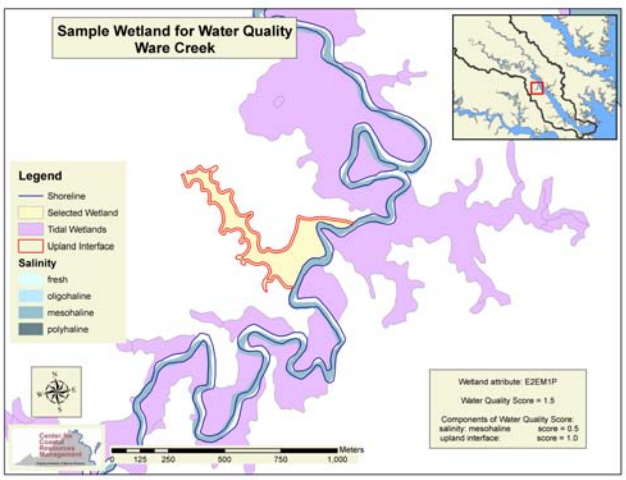

Figure 3. Water quality score for wetland polygon #1256, middle York River.

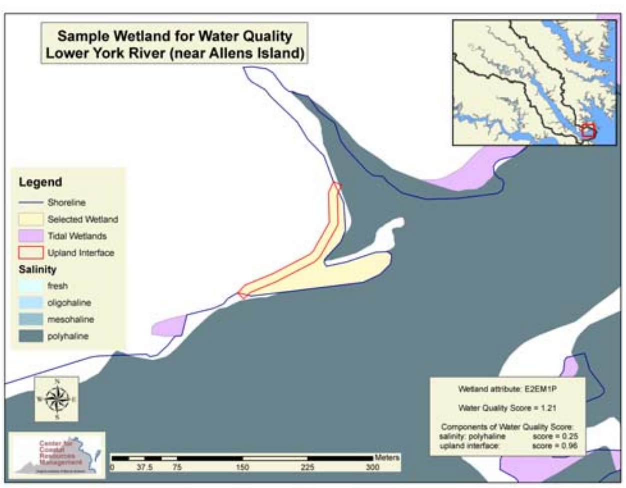

Figure 4. Water quality score for wetland polygon #2135, lower York River.

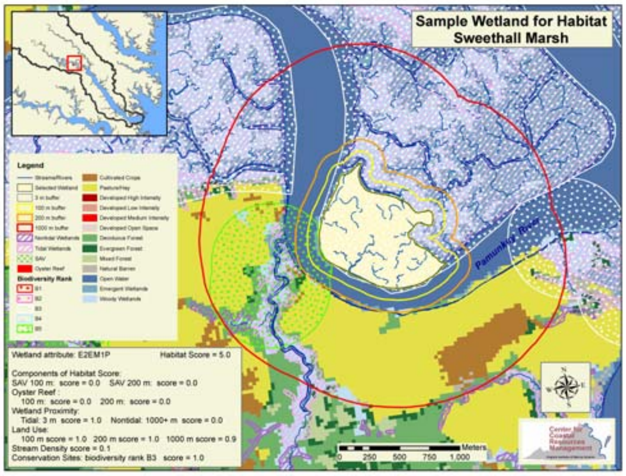

Figure 5. Habitat score for wetland polygon #758, upper York River.

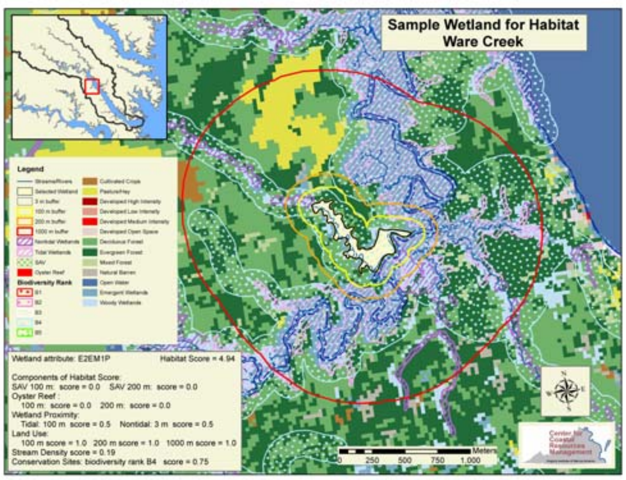

Figure 6. Habitat score for wetland polygon #1256, middle York River.

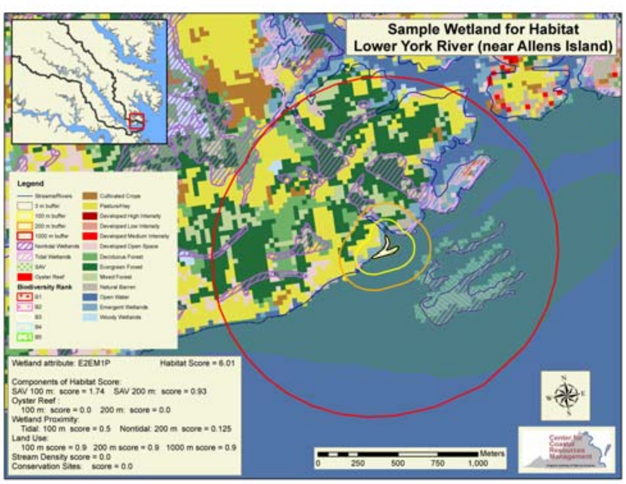

Figure 7. Habitat score for wetland polygon #2135, lower York River.

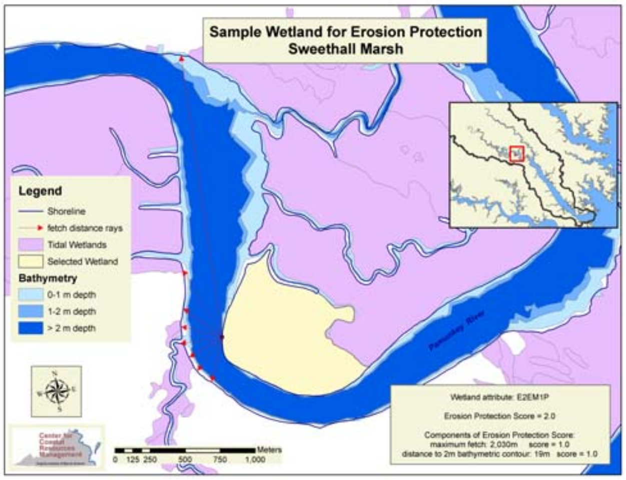

Figure 8. Erosion score for wetland polygon #758, upper York River.

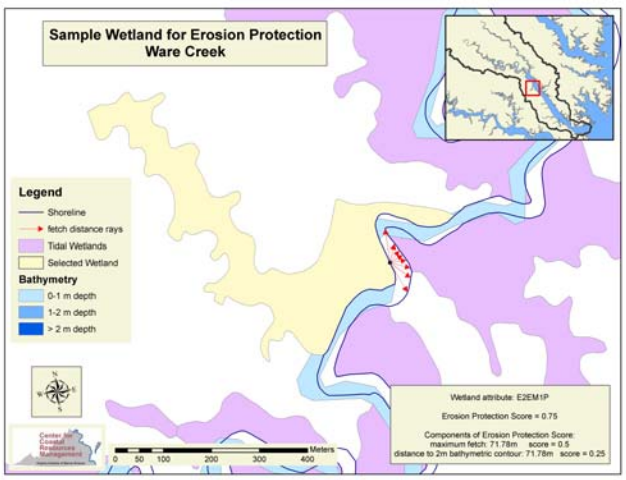

Figure 9. Erosion score for wetland polygon #1256, middle York River.

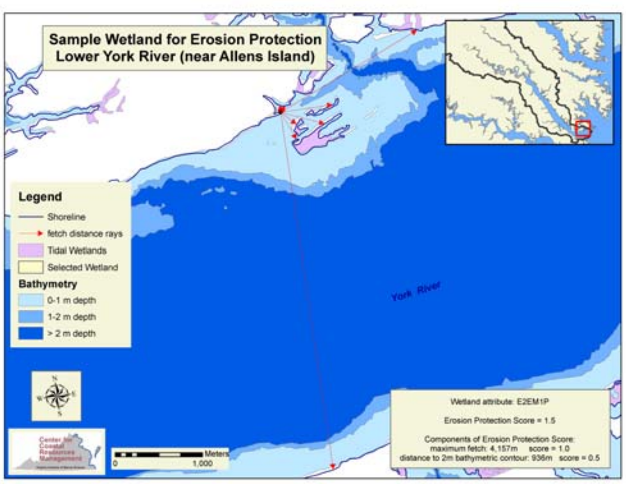

Figure 10. Erosion score for wetland polygon #2135, lower York River.

Appendix II. Selected References

Able, K. W., D. M. Nemerson, et al. 2004. Evaluating salt marsh restoration in Delaware Bay: Analysis of fish response at former salt hay farms. Estuaries 27(1): 58-69.

Able, K. W., S. M. Hagan, et al. 2003. Mechanisms of marsh habitat alteration due to phragmites: Response of young-of-the-year Mummichog (Fundulus heteroclitus) to treatment for Phragmites removal. Estuaries 26(2B): 484-494.

Able, K. W., D. M. Nemerson, et al. 2001. Spatial variation in Delaware Bay (USA) marsh creek fish assemblages. Estuaries 24(3): 441-452.

Bagwell, C. E. and C. R. Lovell 2000. Microdiversity of culturable diazotrophs from the rhizoplanes of the salt marsh grasses Spartina alterniflora and Juncus roemerianus. Microbial Ecology 39(2): 128-136.

Botton, M. L., R. E. Loveland, et al. 1994. Site Selection by Migratory Shorebirds in Delaware Bay, and Its Relationship to Beach Characteristics and Abundance of Horseshoe-Crab (Limulus-Polyphemus) Eggs. Auk 111(3): 605-616.

Burdick, D. and R. A. Konisky. 2003. Determinants of expansion for *Phragmites australis*, common reed, in natural and impacted coastal marshes. Estuaries 26(2B): 407-416.

Callaway, J. 2005. The challenge of restoring functioning salt marsh ecosystems. Journal of Coastal Research 40: 24-36.

Carlisle, B. and C. Wigand. 2004. Draft: Rapid assessment method for characterizing the condition of New England salt marshes. Version 1.1.

Chambers, R.M., L.A. Meyerson, and K. Saltonstall. 1999. Expansion of *Phragmites australis* into tidal wetlands of North America. Aquatic Botany 64: 261-273.

Christiansen, T., P. L. Wiberg, et al. 2000. Flow and sediment transport on a tidal salt marsh surface. Estuarine Coastal and Shelf Science 50(3): 315-331.

Clarke, J.A., B.A. Harrington, T. Hruby, and F.E. Wasserman. 1984. The effect of ditching for mosquito control on salt marsh use by birds in Rowley, Massachusetts. J. Field Ornithol., 55(2): 160-180.

Currin, C. A., S. Y. Newell, et al. 1995. The Role of Standing Dead Spartina-Alterniflora and Benthic Microalgae in Salt-Marsh Food Webs - Considerations Based on Multiple Stable-Isotope Analysis. Marine Ecology-Progress Series 121(1-3): 99-116.

DeLuca, W.V., C.E. Studds, L.L. Rockwood, and P.P. Marra. 2004. Influence of land use on the integrity of marsh bird communities of Chesapeake Bay, USA. Wetlands 24(4): 837-847.

Dittel, A. I., C. E. Epifanio, et al. 2000. Carbon and nitrogen sources for juvenile blue crabs Callinectes sapidus in coastal wetlands. Marine Ecology-Progress Series 194: 103-112.

Eastman, K. W. and T. M. Church 1984. Behavior of Iron, Manganese, Phosphate and Humic-Acid During Mixing in a Delaware Salt-Marsh Creek. Estuarine Coastal and Shelf Science 18(4): 447-458.

Erwin, R. M. 1996. Dependence of waterbirds and shorebirds on shallow-water habitats in the mid-Atlantic coastal region: An ecological profile and management recommendations. Estuaries 19(2A): 213-219.

Erwin, R. M., D. K. Dawson, et al. 1991. Open Marsh Water Management in the Mid-Atlantic Region - Aerial Surveys of Waterbird Use. Wetlands 11(2): 209-228.

Ewing, K., K.L. McKee, and I.A. Mendelssohn. 1997. A field comparison of indicators of sublethal stress in the salt-marsh grass *Spartina patens*. Estuaries 20(1): 48-?

Fantle, M. S., A. I. Dittel, et al. 1999. A food web analysis of the juvenile blue crab, Callinectes sapidus, using stable isotopes in whole animals and individual amino acids. Oecologia 120(3): 416-426.

Findlay, S.E.G., E. Kiviat, W.C. Nieder, and E.A. Blair. 2002. Functional assessment of a reference wetland set as a tool for science, management and restoration. Aquat. Sci. 64: 107-117.

Goslee, S.C., R.P. Brooks, and C.A. Cole. 1997. Plants as indicators of wetland water source. Plant Ecology 131(2): 199-206.

Gross, M. F., M. A. Hardisky, P.L. Wolf, and V. Klemas. 1991. Relationship between Aboveground and belowground biomass of *Spartina alterniflora* (smooth cordgrass). Estuaries 14(2): 180-191.

Grothues, T. M. and K. W. Able. 2003. Response of juvenile fish assemblages in tidal salt marsh creeks treated for Phragmites removal. Estuaries 26(2B): 563-573.

Grothues, T. M. and K. W. Able. 2003. Discerning vegetation and environmental correlates with subtidal marsh fish assemblage dynamics during *Phragmites* eradication efforts: Interannual trend measures. Estuaries 26(2B): 574-586.

Harding, E. K. and E. Stevens 2001. Using stable isotopes to assess seasonal patterns of avian predation across a terrestrial-marine landscape. Oecologia 129(3): 436-444.

Havens, K. J., L. M. Varnell, and J.G. Bradshaw. 1995. An assessment of ecological conditions in a constructed tidal marsh and two natural reference tidal marshes in coastal Virginia. Ecological Engineering 4(2): 117-141.

Huang, S. C., D. A. Kreeger, and R.I.E. Newell. 2003. Seston available as a food resource for the ribbed mussel (Geukensia demissa) in a North American, mid-Atlantic saltmarsh. Estuarine Coastal and Shelf Science 56(3-4): 561-571.

Huckle, J.M., R.H. Marrs, and J.A. Potter. 2001. Interspecific and intraspecific interactions between salt marsh plants: integrating the effects of environmental factors and density on plant performance. OIKOS 96: 307-312.

Hurd, L. E., G. W. Smedes, et al. 1979. Ecological Study of a Natural-Population of Diamondback Terrapins (Malaclemys-Terrapin-Terrapin) in a Delaware Salt-Marsh. Estuaries 2(1): 28-33.

James, M.L. and J.B. Zedler. 2000. Dynamics of wetland and upland sub-shrubs at the salt marsh-coastal sage scrub ecotone. Am. Midl. Nat. 143: 298-311.

Jivoff, P. R. and K. W. Able 2003. Evaluating salt marsh restoration in Delaware Bay: The response of blue crabs, Callinectes sapidus, at former salt hay farms. Estuaries 26(3): 709-719.

Jivoff, P. R. and K. W. Able 2003. Blue crab, Callinectes sapidus, response to the invasive common reed, Phragmites australis: Abundance, size, sex ratio, and molting frequency. Estuaries 26(2B): 587-595.

Johnston, R.J., G. Magnusson, M.J. Mazzotta, and J.J. Opaluch. 2002. Combing economic and ecological indicators to prioritize salt marsh restoration actions. American Agricultural Economics Association 84: 1362-1370.

Kennish, M.J. et al. 2004. Benthic macrofaunal community structure along a well-defined salinity gradient in the Mullica River – Great Bay Estuary. Journal of Coastal Research 45: 209-226.

Kim, G., L. Y. Alleman, et al. 2004. Accumulation records of radionuclides and trace metals in two contrasting Delaware salt marshes. Marine Chemistry 87(3-4): 87-96.

Kraft, J. C., H. I. Yi, et al. 1992. Geologic and Human-Factors in the Decline of the Tidal Salt-Marsh Lithosome - the Delaware Estuary and Atlantic Coastal Zone. Sedimentary Geology 80(3-4): 233-246.

Leamon, J. H., E. T. Schultz, et al. 2000. Variation among four health indices in natural populations of the estuarine fish, Fundulus heteroclitus (Pisces Cyprinodontidae), from five geographically proximate estuaries. Environmental Biology of Fishes 57(4): 451-458.

Leonard, L.A. and M.E. Luther. 1995. Flow hydrodynamics in tidal marsh canopies. Limnol. Oceanogr. 40(8): 1474-1484.

Leonard, L.A., P.A. Wren, and R.L. Beavers. 2002. Flow dynamics and sedimentation in *Spartina alterniflora* and *Phragmites australis* marshes of the Chesapeake Bay. Wetlands 22(2): 415-424.

Lerberg, S.B., A.F. Holland, and D.M. Sanger. 2000. Responses of tidal creek macrobenthic communities to the effects of watershed development. Estuaries 23: 838-853.

Lesser, C. R., F. J. Murphey, et al. 1976. Some Effects of Grid System Mosquito-Control Ditching on Salt-Marsh Biota in Delaware. Mosquito News 36(1): 69-77.

Lewis, D.B. and L.A. Eby. 2002. Spatially heterogeneous refugia and predation risk in intertidal salt marshes. OIKOS 96: 119-129.

Litvin, S. Y. and M. P. Weinstein (2003). Life history strategies of Estuarine Nekton: The role of marsh macrophytes, benthic microalgae, and phytoplankton in the trophic spectrum. Estuaries 26(2B): 552-562.

Morse, J.L., P. Megonigal, and M.R. Walbridge. 2004. Sediment nutrient accumulation and nutrient availability in two tidal freshwater marshes along the Mattaponi River, Virginia, USA. Biogeochem. 69: 175-206.

Naidoo, G., K.L. McKee, and I.A. Mendelssohn. 1992. Anatomical and metabolic responses to waterlogging and salinity in *Spartina alterniflora* and *S. patens* (Poaceae). American Journal of Botany 79(7): 765-770.

Neckles, H. A., M. Dionne, D.M. Burdick, C.T. Roman, R. Buchsbaum, and E. Hutchins. 2002. A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. Restoration Ecology 10(3): 556-563.

Nemerson, D. M. and K. W. Able 2004. Spatial patterns in diet and distribution of juveniles of four fish species in Delaware Bay marsh creeks: factors influencing fish abundance. Marine Ecology-Progress Series 276: 249-262.

Nemerson, D. M. and K. W. Able. 2003. Spatial and temporal patterns in the distribution and feeding habits of Morone saxatilis in marsh creeks of Delaware Bay, USA. Fisheries Management and Ecology 10(5): 337-348.

Neumeier, U. and P. Ciavolo. 2004. Flow resistance and associated sedimentary processes in a *Spartina maritime* salt marsh. Journal of Coastal Research 20(2): 435-447.

Niemi, G., D. Wardrop, R. Brooks, S. Anderson, V. Brady, H. Paerl, C. Rakocinski, M. Brouwer, B. Levinson, and M. McDonald. 2004. Rationale for a new generation of indicators for coastal waters. Environmental Health Perspectives 112(9): 979-986.

Odum, W.E. 1988. Comparative ecology of tidal freshwater and salt marshes. Ann. Rev. Ecol. Syst. 19: 147-176.

Pennings, S.C., V.D. Wall, D.J. Moore, M. Pattanayek, T.L. Buck, and J.J. Alberts. 2002. Assessing salt marsh health: a test of the utilities of five potential indicators. Wetlands 22(2): 405-411.

Porter, D. E., D. Edwards, G. Scott, B. Jones, and W.S. Street. 1997. Assessing the impacts of anthropogenic and physiographic influences on grass shrimp in localized salt-marsh estuaries. Aquatic Botany 58(3-4): 289-306.

Portnoy, J. W., B. L. Nowicki, C.T. Roman, and D.W. Urish. 1998. The discharge of nitrate-contaminated groundwater from developed shoreline to marsh-fringed estuary. Water Resources Research 34(11): 3095-3104.

Posey, M.H., T.D. Alphin, H. Harwell, and B. Allen. 2005. Importance of low salinity areas for juvenile blue crabs, *Callinectes sapidus*, in river-dominated estuaries of southeastern United States. Journal of Experimental Marine Biology and Ecology 319: 81-100.

Rozan, T. F., M. Taillefert, et al. 2002. Iron-sulfur-phosphorus cycling in the sediments of a shallow coastal bay: Implications for sediment nutrient release and benthic macroalgal blooms. Limnology and Oceanography 47(5): 1346-1354.

Schuyler, A.E., S.B. Andersen, and V.J. Kolaga. 1993. Plant zonation changes in the tidal portion of the Delaware River. Proceedings of The Academy of Natural Sciences of Philadelphia 144: 263-266.

Schwimmer, R. A. 2001. Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware, USA. Journal of Coastal Research 17(3): 672-683.

Scudlark, J. R. and T. M. Church (1993. Atmospheric Input of Inorganic Nitrogen to Delaware Bay. Estuaries 16(4): 747-759.

Shafer, D.J. and D.J. Yozzo. 1998. National Guidebook for application of Hydrogeomorphic Assessment to Tidal Fringe Wetlands. Technical Report WRP-DE-16, Final Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 76 pp.

Sherfy, M. H. and R. L. Kirkpatrick 2003. Invertebrate response to snow goose herbivory on moist-soil vegetation. Wetlands 23(2): 236-249.

Silliman, B. R., C. A. Layman, et al. 2004. Predation by the black-clawed mud crab, Panopeus herbstii, in Mid-Atlantic salt marshes: Further evidence for top-down control of marsh grass production. Estuaries 27(2): 188-196.

Stocks, K. I. and J. F. Grassle. 2003. Benthic macrofaunal communities in partially impounded salt marshes in Delaware: Comparisons with natural marshes and responses to sediment exposure. Estuaries 26(3): 777-789.

Strange, E., H. Galbraith, et al. 2002. Determining ecological equivalence in service-to-service scaling of salt marsh restoration. Environmental Management 29(2): 290-300.

Teal, J. M. and S. Peterson 2005. Restoration benefits in a watershed context. Journal of Coastal Research: 132-140.

Teal, J. M. and S. Peterson 2005. The interaction between science and policy in the control of Phragmites in oligohaline marshes of Delaware Bay. Restoration Ecology 13(1): 223-227.

Teal, J. M. and M. P. Weinstein. 2002. Ecological engineering, design, and construction considerations for marsh restorations in Delaware Bay, USA. Ecological Engineering 18(5): 607-618.

Teo, S. L. H. and K. W. Able 2003. Growth and production of the mummichog (Fundulus heteroclitus) in a restored salt marsh. Estuaries 26(1): 51-63.

Tiner, R.W. 2004. Remotely-sensed indicators for monitoring the general condition of "natural habitat" in watersheds: an application for Delaware's Nanticoke River watershed. Ecological Indicators 4(4): 227-243.

Tupper, M. and K. W. Able 2000. Movements and food habits of striped bass (Morone saxatilis) in Delaware Bay (USA) salt marshes: comparison of a restored and a reference marsh. Marine Biology 137(5-6): 1049-1058.

van Dam, R.A., C. Camilleri, and C.M. Finlayson. 1998. The potential of rapid assessment techniques as early warning indicators of wetland degradation: a review. Environmental Toxicology and Water Quality 13(4): 297-302.

van Dolah, R.F., D.E. Chestnut, J.D. Jones, P.C. Jutte, G. Riekerk, M. Levisen, and W. McDermott. 2003. The importance of considering spatial attributes in evaluating estuarine habitat condition: The South Carolina experience. Environmental Monitoring and Assessment 81(1-3): 85-95.

Varnell, L. M. and F. J. Havens 1995. A Comparison of Dimension-Adjusted Catch Data Methods for Assessment of Fish and Crab Abundance in Intertidal Salt Marshes. Estuaries 18(2): 319-325.

Wall, V.D., J.J. Alberts, D.J. Moore, S.Y. Newell, M. Pattanayek, and S.C. Pennings. 2001. The effect of mercury and PCBs on organisms from lower trophic levels of a Georgia salt marsh. Arch. Environ. Contam. Toxicol. 40: 10-17.

Warren, R. S. and W.A. Niering. 1993. Vegetation change on a Northeast tidal marsh: interaction of sea-level rise and marsh accretion. Ecology 74(1): 96-103.

Weinstein, M. P., S. Y. Litvin, et al. 2000. The role of tidal salt marsh as an energy source for marine transient and resident finfishes: A stable isotope approach. Transactions of the American Fisheries Society 129(3): 797-810.

Weisberg, S. B. and V. A. Lotrich 1986. Food Limitation of a Delaware Salt-Marsh Population of the Mummichog, Fundulus-Heteroclitus (L). Oecologia 68(2): 168-173.

Weisberg, S.B., J.A. Ranasingh, D.M. Dauer, L.C. Schaffner, R.J. Diaz, and J.B. Frithsen. 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. Estuaries 20: 149-158.

Whitelaw, D. M. and R. N. Zajac 2002. Assessment of prey availability for diamondback terrapins in a Connecticut salt marsh. Northeastern Naturalist 9(4): 407-418.

Wiegert, R.G. and B.J. Freeman. 1990. Tidal Salt Marshes of the Southeast Atlantic Coast: A Community Profile. U.S. Fish Widl. Serv., Biol. Rep. 85 (7.29). 70 pp.

Wigand, C. et al. 2004. Response of *Spartina patens* to dissolved organic nutrient additions in the field. Journal of Coastal Research 45: 134-149.

Wigand, C., R. Comeleo, R. McKinney, G. Thursby, M. Chintala, and M. Charpentier. 2001. Outline of a new approach to evaluate ecological integrity of salt marshes. Human and Ecological Risk Assessment 7(5): 1541-1554.

Williams, G. D. and J. B. Zedler 1999. Fish assemblage composition in constructed and natural tidal marshes of San Diego Bay: Relative influence of channel morphology and restoration history. Estuaries 22(3A): 702-716.

Zajac, R. N. and R. B. Whitlatch 2001. Response of macrobenthic communities to restoration efforts in a New England estuary. Estuaries 24(2): 167-183.

Zedler, J. B. 1993. Canopy Architecture of Natural and Planted Cordgrass Marshes - Selecting Habitat Evaluation Criteria. Ecological Applications 3(1): 123-138.

Zedler, J. B. and J. C. Callaway. 2000. Evaluating the progress of engineered tidal wetlands. Ecological Engineering 15(3-4): 211-225.

Zedler, J.B., J.C. Callaway, and G. Sullivan. 2001. Declining biodiversity: why species matter and how their functions might be restored in Californian tidal marshes. BioScience 51(12): 1005-1017.