Development of strategies to improve conservation of Virginia's headwater wetland ecosystems in the face of climate change:
Headwater Wetlands Vulnerability Index

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Headwater Wetlands Vulnerability Index Overview

To identify the relative risk to headwater wetlands systems in the York River Estuary coastal plain from climate and human stressors, we modeled inundation risk with sea level rise, surrounding land cover, and surface water sources within catchments with connected headwater- tidal wetland complexes (termed here as *headwater wetlands systems*).

To evaluate how multiple and interrelated climate and human stressors may impact headwater wetlands systems in the coastal plain, we developed 3 different but complementary geospatial modeling approaches and data layers:

1) Modeling marsh migration opportunities and limitations on the basis of simulated changes to tidal wetland appropriate elevations from sea level rise with considerations for migration barriers such as surrounding topography and adjacent human land use.
2) Evaluating surrounding land cover as a measure of future intensity of the human footprint and thus threat to headwater wetland systems (i.e., agriculture lands have a high probability of conversion to development).
3) Identifying headwater wetlands likely to be sensitive to climate change using the presence/absence of a perennial stream surface water source.

These geospatial data layers can be used individually or overlaid in combination to make management decisions. A Headwater wetland vulnerability index (HWVI) was developed to integrate information on relative risks from varied stressors into a composite index following [1]Pendleton et al. (2004) (**Equation 1**). The headwater wetland vulnerability index (HWVI) is comprised of the three measures of relative vulnerability of headwater wetlands: *inundation risk*, *future land use threats*, and *surface water inputs*. This index combined individual risk measures that were scaled as either low (1) or high (5) risk using the median value of the data distribution as a threshold, and then computed as the square root of the product of the ranked variables divided by the total number of variables. Information (e.g., land cover, perennial streams) was summarized at catchment spatial scales that encompass tidally connected wetland complexes following flow paths from headwater wetlands to tidal marshes.

Additional measures can be added or measures can be adjusted for different regions or with evolving information. For example, the importance of the resource to the overall York River system (e.g., Importance = headwater wetland area in catchment/total headwater wetlands in York River) can be used to weight or identify appropriate management decisions (e.g., conservation, restoration, facilitating wetland migration).

$$HWVI = [\frac{1}{3}(a * b * c)]^{1/2}$$

Equation 1. Median values of spatial data extracted from the York River catchments were used as thresholds for reclassification to high or low relative vulnerability and (1=low risk, 5=high risk). Where, a = Percentage of headwater wetlands inundated by 2100; (>8.2% (median) = high risk), b= Percentage of surrounding agricultural land cover within 1 km of headwater wetlands (>9.6% (median) =high risk); c= Percentage of headwater wetlands without perennial streams (>72.6% (median) of wetlands in the catchment do not possess a perennial stream = high risk).

Individual measures of relative vulnerability of headwater wetlands systems

1. **Inundation risk estimates** – There is growing concern about accelerating sea level rise and the impact it will have on marsh persistence. Marshes have the capacity to migrate landward with rising sea levels; however, the capacity of an individual marsh system is affected by their morphology and position in the landscape, their surrounding topography and adjacent human land use.

   Attached marshes in areas of low relief are ideal for marsh retreat. In areas with high banks, marsh retreat results in narrowing fringes and possibly complete loss. In areas where retreat is viable, the human use of the shoreline becomes a primary consideration. Although there is some contention that humans need to relinquish land to allow marsh retreat, under current policies, there should be no real expectation that significant areas of waterfront land will be abandoned and allowed to revert to marsh. Indeed, in many developed areas, migration of marshes would require not just the abandonment of the land, but an active removal of human structures including bulkheads, revetments and pavement.

   To estimate future inundation risk, we took the vegetated tidal marsh prism (In the York River this is approximately 2 vertical feet in elevation, from Mean Sea Level (MSL) to Highest Astronomical Tide (HAT) and moved it up the shoreline in 6 inch increments. This gives an estimate of the tidal wetland appropriate elevations in each step. Current sea level rise rates for the southern Chesapeake Bay suggest an increase of 2 feet by 2050. Land cover classes were used to categorize the type of land in the tidal matrix with impervious areas considered “Developed” and all other categories (e.g., wetland, pasture, forest) considered “Undeveloped”.

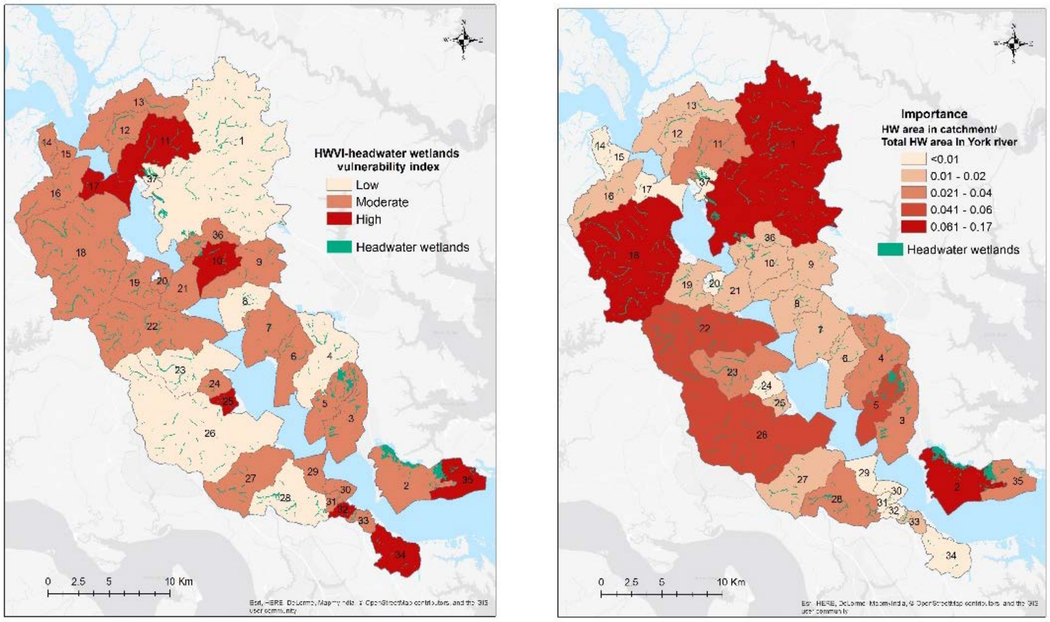
   We identified 4 general patterns of near and long-term change in tidal wetlands: a) continuous expansion, b) steady decline, c) near term increase, followed by a decline, and d) near-term decline, followed by stabilization at a lower acreage. We further quantified the percentage of headwater wetlands at risk to inundation by 2100 with projected sea level rise in each catchment. Nearly 10% (1.6 km^2) of headwater wetlands in the York River coastal plain (total 17.1 km^2) are at risk to inundation by 2100. However, the risk is not uniform across the river, ranging from 0 to 47% being inundated in the catchments. This information gives a relative risk to the wetlands within the headwater wetlands system (headwaters through tidal marshes) to conversion from sea level rise and salinity intrusion. Median values of spatial data extracted from the York River catchments were used as thresholds for reclassification to high or low relative vulnerability and (1=low risk, 5=high risk). Catchments with percentage of headwater wetlands inundated by 2100 greater than 8.2% were considered at high risk.

2. **Future land use threats to headwater wetlands**
   Future land cover conversion presents a threat to coastal plain headwater wetlands because a conversion to developed lands may become a barrier to headwater wetland migration under rising sea level conditions. The land cover likely to be converted to residential (impervious surface) is agricultural (row crops and/or pasture). For every existing headwater wetland in the York River Watershed we estimated surrounding land use and roads (within 1000 m and within the wetland drainage area). We then estimated the average percentage of agricultural land use surrounding headwater wetlands per catchment as a measure of risk. Catchments with a percentage of surrounding agricultural land cover within 1 km of headwater wetlands greater than 9.6% (median) were considered at high risk.

3. **Surface Water Input to headwater wetlands**
   The presence of a constant surface freshwater input to headwater wetlands is likely to lessen the vulnerability of the wetland to projected precipitation or temperature changes. This is particularly likely for precipitation driven wetlands and can be an indicator of relative vulnerability. We estimated the percent of headwater wetlands in each catchment that were associated with perennial streams as a measure of sensitivity. Catchments with a percentage of headwater wetlands without perennial streams greater than 72.6% (median) were considered at high risk.

IDENTIFY OPPORTUNITIES TO PROTECT HEADWATER RESOURCES AND PLAN FOR WETLAND RETREAT AS SEA LEVEL RISES

This vulnerability assessment of headwater wetland systems can help inform wetland conservation and restoration actions. The ***relative headwater wetland vulnerability index*** (**HWVI**) integrates three measures of relative risk of conversion or loss at the catchment level from 1) sea level rise and barriers to migration, 2) relative risk of non-tidal/tidal fresh wetland conversion from future land development, and 3) sensitivity of headwater wetlands to climate change (presence of perennial stream surface water source. These spatial data can be used in a variety of ways to meet management goals. For instance, catchments containing a significant proportion of the headwater wetlands acreage (*high importance*) that are highly vulnerable can be prioritized for conservation activities. Another management application example is the consideration of headwater wetlands with surrounding agricultural lands as potential areas for mitigation, wetland banking, and land preservation to accommodate future wetland migration (managed retreat). Lastly, wetlands in catchments with high vulnerability could be targeted for special permitting conditions (i.e., individual vs general permits).



The Headwater wetlands vulnerability index (L) and relative Importance of catchments for headwater wetlands (R) in the York River Estuary.

Fields	Field Description
location	Location of vulnerability analysis - York River Estuary, Virginia
Shape_Leng	Length of shape (catchment) in m2
Shape_Area	Area of shape (catchment) in m2
area_km2	Area of catchment in square kilometers
Catchments	Catchment number (1 to 37). Catchments contain connected headwater- tidal wetland complexes (termed here as headwater wetlands systems) that follow flow paths from the headwaters to the tidal waters.
CatchmentA	Catchment area in square kilometers
HeadwaterA	Headwater wetland area in a given catchment in square km
NontidalA	Nontidal wetland area in a given catchment in square km
TidalA	Tidal wetland area in a given catchment in square km
TotalWetlA	Total wetland area in a given catchment in square km
Perc_HW	Percent of wetlands that are headwater wetlands in a given catchment
PHWinnundate	Percent of Headwater wetlands that are projected to be inundated by 2100 from sea level rise
PHWperennial	Percentage of Headwater wetlands without a Perennial stream source of surface water
Pag1km	Future Threat of wetlands conversion is represented by the percentage of Agriculatural land use within 1km because agricultural lands are at risk of conversion to developed lands (residential)
HWVI	HWVI-headwater wetlands vulnerability index. Index combines three measures of relative vulnerability for the York River Estuary - inundation risk (percentage of headwater wetlands that will be inundated by 2100 in the catchment), Climate change sensitivity (Percentage of headwater wetlands without a perennial stream source), Future land conversion risk (percentage of Ag land use within 1km). The Headwater wetland vulnerability index (HWVI) was developed to integrate information on relative risks from varied stressors into a composite index following Pendleton et al. (2004). TThis index combined individual risk measures that were scaled as either low (1) or high (5) risk using the median value of the data distribution as a threshold, and then computed as the square root of the product of the ranked variables divided by the total number of variables.
HWVI_Level	HWVI_Level (low, moderate, or high vulnerability). Three values are mathamatically possible with the 3 measure composite index (0.58, 1.29, 2.89) and these were assigned Low, moderate, and high levels accordingly.

References and additional sources

[1]*Pendleton, EA, Williams, SJ, and ER Thieler. 2004. Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea-level rise. USGS. Open File Report 2004-1020.*

Additional details presented in and available by request:

Bilkovic, D.M., M. Mitchell, J. Herman, C. Hershner, K. Havens. 2017. Development of strategies to improve conservation of Virginia's headwater wetland ecosystems in the face of climate change. Final Report to the Environmental Protection Agency (Grant #: EPA CD96329601). Virginia Institute of Marine Science, Gloucester Point, Virginia. 53p.

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