VULNERABILITY OF SHALLOW TIDAL WATER HABITATS IN VIRGINIA TO CLIMATE CHANGE

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VULNERABILITY OF SHALLOW TIDAL WATER HABITATS IN VIRGINIA TO CLIMATE CHANGE

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EXECUTIVE SUMMARY

The Commonwealth of Virginia has extensive areas of shallow tidal water supporting essential habitats for estuarine flora and fauna along its thousands of miles of shoreline. Shallow water environments are vital to the coastal community, providing an enormous mix of ecological services. Managing coastal habitats for sustained ecosystem functioning, while accommodating increasing developmental pressures, has never been simple. The challenge is multiplied by the fact that the entire system is changing, driven by both human uses and climate change.

Chesapeake Bay is extremely vulnerable to climate change as rates of relative sea level rise (SLR) are currently more than double the global mean and rising (~4.2mm/yr in Chesapeake vs. 1.7 mm/yr globally). As climate change continues, sea level rise rates are expected to increase and additional negative effects likely will include intensified coastal flood and storm events, increased shore erosion, inundation of wetlands and low-lying lands, and salt-water intrusion into groundwater.

Climate change effects on coastal habitats and species will not occur in isolation, but within a socio-economic context. Land and shoreline development will likely affect the character and magnitude of climate impact, potentially exacerbating ecosystem integrity loss. Areas with shoreline and riparian development effectively prevent the migration of coastal habitats landward in response to climate changes.

In Virginia tidal waters

- *Approximately 11.1% of shoreline has been hardened* (793 km hardened/7134 km shoreline surveyed), and on average, 29 km of shoreline continue to be hardened each year.
- *Over one-quarter of riparian lands are currently developed* (including commercial, residential, industrial and paved land use).

The principal objective of this study was to develop a characterization of current shallow-water habitat components in Virginia tidal waters and predict climate driven changes to these habitats. To project broad-scale climate change effects on the abundance and distribution of coastal habitats, an inundation model based on anticipated relative sea-level rise, temperature and salinity projections, and coastal development were integrated into a GIS modeling framework. Using this framework, simple models were constructed that forecast the distribution of key coastal habitat parameters within the next 50 to 100 years including: shallow-water areas, tidal wetlands, submerged aquatic vegetation and estuarine beaches.

Projected shifts in coastal habitats

- Shallow-waters, highly productive nursery and spawning zones, were estimated to decrease dramatically with SLR ranging from 10-51% loss of habitat.

- More than 65% of existing eelgrass habitat zones will become inhospitable, if temperature and sea level continue to rise at or higher than historic rates. Unless eelgrass beds are able to migrate to shallower reaches with suitable summertime temperatures and water clarity, these critical nursery habitats may be substantially diminished.

- More than 85% of estuarine beaches in Virginia (701/812 km) are at high to moderate risk from sea level rise unless they are subsidized with sand.

- Up to 52% of tidal wetlands may be lost as sea level rises, including tidal sand and mud flats, which has implications for shorebird populations which rely on these habitats as a food source.

- Tidal marshes in the meso-polyhaline reaches of Virginia waters are at the highest relative risk due to land development and sea level rise pressures.

- Although 38% of existing marshes are moderately-highly vulnerable to SLR due to adjacent development, 62% of marshes may have opportunities for landward transgression. Preserving landscapes that allow for the transgression of the Bay's essential shallow-water habitats should be a high conservation priority.

Loss or reduction in function of these habitats could significantly alter the character of Chesapeake Bay from a highly productive shallow-water estuary that provides crucial spawning and nursery habitat for numerous species to a deep open-water system.

To enhance possible model applications, in addition to this report and maps illustrating potential model outputs (e.g. *Marsh Preservation Opportunities*), a companion webpage with an interactive web-based map interface was created using ESRI ArcIMS®. The interactive tool allows the user to view current habitat distribution, modeled climate change output, as well as all base layers used in the analyses (URL: http://ccrm.vims.edu/research/climate_change/index.html). Model output and interactive tools are not to be used for site-specific planning. They are intended to illustrate general regional trends in coastal habitat distribution and vulnerability to climate change. Once additional high resolution data become available, refinement of estimates and increased precision will become possible for future model iterations.

These and similar spatial analyses can be used to inform forward-looking management efforts to identify and protect areas where habitat complexes are most likely to be sustainable, as well as preserve opportunities for migration of habitat elements in an evolving system.

INTRODUCTION

The Commonwealth of Virginia has extensive areas of shallow tidal water along its thousands of miles of estuarine shoreline. Shallow water environments are vital to the coastal community, providing an enormous mix of ecological services. Managing coastal habitats for sustained ecosystem functioning, while accommodating increasing developmental pressures, has never been simple. The challenge is multiplied by the fact that the entire system is changing, driven by both human uses and climate change. Effective management requires some understanding of not only current conditions, but also potential future conditions. The state of scientific understanding does not yet support precise forecasting, but there is a sufficient array of information to begin assessing potentials for change in some key components of the system.

The principal objective of this study was to develop a characterization of current shallow-water habitat components in Virginia tidal waters and predict climate driven changes to these habitats. Forecasting potential future distributions of shallow water habitat parameters requires a wide mix of information. Virginia has reasonably well developed inventories of intertidal wetlands, submerged aquatic vegetation, riparian land uses, shoreline structures, topography and bathymetry, as well as water quality monitoring datasets. Combined with potential future climate scenarios developed for the mid-Atlantic region, this information can be used to assess potential changes in current distributions of key components of shallow tidal water habitat quality.

A wide variety of data regarding the littoral and riparian areas along Virginia's estuarine shorelines were integrated under a GIS framework. Simple models were constructed that forecast the distribution of key coastal habitat parameters within the next 50 to 100 years including: shallow-water areas, tidal wetlands, submerged aquatic vegetation and estuarine beaches. Drivers for the forecast models include sea-level rise, temperature, salinity, and land development. The spatially-explicit analysis describes potential outcomes under current management practices and reasoned forecasts of future conditions. The purpose is to inform management and planning efforts by identifying areas at significant risk for changes to habitat components, and areas with significant potential to support critical habitat components in the future. This will enable managers to make proactive decisions that can mitigate impacts and preserve opportunities for sustained habitat services as the estuarine system evolves. From a practical perspective, understanding potential futures can inform targeting of limited management resources to areas at greatest risk and/or areas with the greatest probability for successful outcomes.

COASTAL HABITAT DEFINITIONS & STRESSORS

The nearshore environment is generally defined as the area encompassing the transition from subtidal marine habitats to associated upland systems (Fig. 1). For this study, this area was inclusive of habitats from the estuarine riparian zone to the shallow subtidal waters (~2 m depth). Within this range strong interactions occur between the marine environment and upland habitats. For example, upland vegetation supports bank stability, captures nutrient run-off, shades the upper intertidal zone and adds terrestrial matter (e.g. woody debris for fish refuge) to the nearshore estuarine ecosystem. Nearshore habitats are highly vulnerable to change from anthropogenic and natural drivers in the system. In the Chesapeake Bay, significant coastal stressors include

- Conversion of land to commercial or residential uses
- Shoreline hardening and associated loss of intertidal habitat
- Problems associated with land development, such as stormwater runoff, vegetation removal, low dissolved oxygen, and harmful algal blooms
- Degradation of ecosystems from excess nutrients, sediments and contaminants
- Dredging or filling of important habitat
- Sea level rise and climate change

Since stressors are interactive, an examination of the potential combined effect of climate change and land development on nearshore habitats will enhance scientific understanding of system responses and the ability to manage for future conditions.

Coastal Habitats Evaluated

Within the shallow tidal waters of the Chesapeake Bay important habitats for flora and fauna are supported including tidal wetlands, submerged aquatic vegetation, estuarine beaches and shallow water areas (defined below). These habitats were included in initial modeling efforts to evaluate anticipated shifts in ecosystems due to climate change.

Shallow water areas

Inclusive of littoral waters between mean low water (MLW) and ≤ 2 m depth

Tidal wetlands

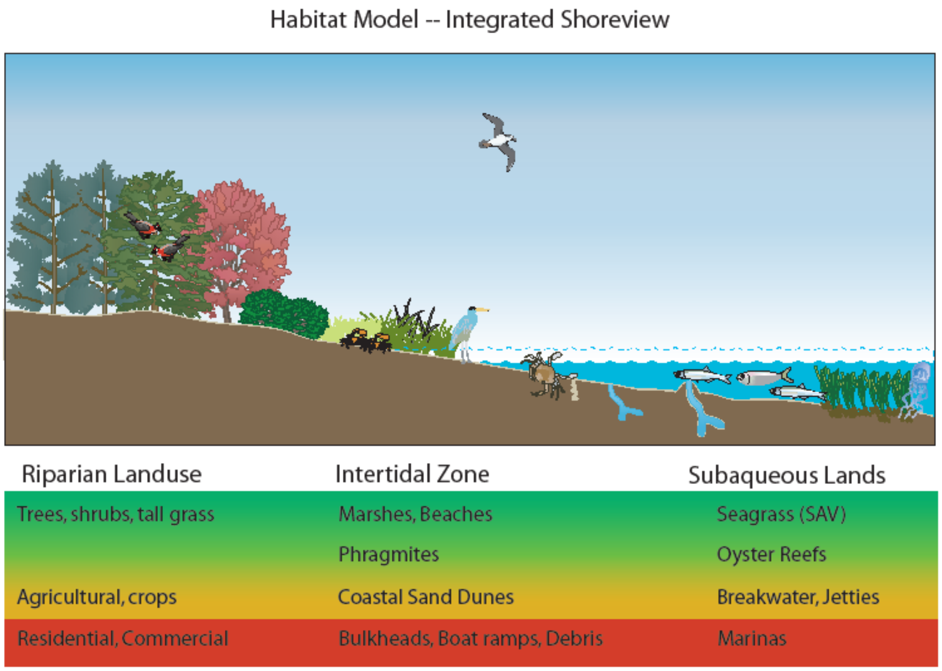
Inclusive of both vegetated and non-vegetated tidal wetlands.

Vegetated wetlands or marshes are extensive, embayed or fringe marshes. Extensive marshes generally occupy significant acreage. Embayed marshes are similar to pocket or headwater marshes and are often fill and surround headwater areas. Fringe marshes are narrow strips of marsh vegetation that extend along the shoreline.

Non-vegetated wetlands encompass the areas between mean high and mean low water which do not support vegetation (e.g. tidal mudflats and sandflats).

Submerged aquatic vegetation (SAV)
Underwater grasses inclusive of vascular macrophyte families and the freshwater macrophytic algal family, the Characeae.

Estuarine Beaches
Unconsolidated sand shores that are subaerial during mean high water. These features are inclusive of both wide and persistent reaches, and very thin lenses of sand.


Habitat Model -- Integrated Shoreview

Riparian Landuse	Intertidal Zone	Subaqueous Lands
Trees, shrubs, tall grass	Marshes, Beaches	Seagrass (SAV)
	Phragmites	Oyster Reefs
Agricultural, crops	Coastal Sand Dunes	Breakwater, Jetties
Residential, Commercial	Bulkheads, Boat ramps, Debris	Marinas

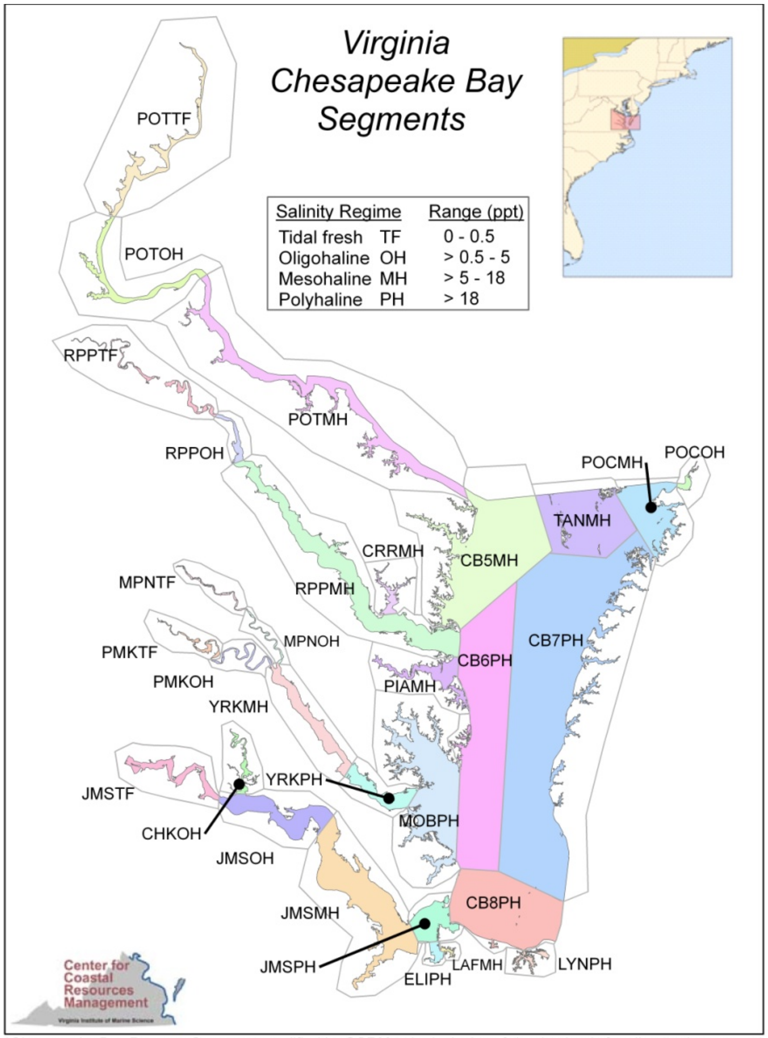
Symbols courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science.

Figure 1. Nearshore environments include subaqueous lands, intertidal zones and riparian habitats. Nearshore ecosystem function can be affected by human activity in any of these zones.

CHESAPEAKE BAY SEGMENTATION

To characterize trends in coastal habitat shifts in an ecologically meaningful way, a modified version of the Chesapeake Bay Program Segmentation Scheme (USEPA 2004) was utilized. The modified version, while retaining the same coding, extends the boundary of some segments inland in order to include all coastal and riparian habitats (Fig. 2). Segments were primarily derived based on salinity regime, a fundamental physical factor influencing habitat and biological organization within an estuarine system.

Trends for each coastal habitat are presented for all tidal Virginia waters and by individual segment.



**Chesapeake Bay Program Segments modified by CCRM to be inclusive of riparian lands for climate change modeling*
Last two letters in Segment label indicate the salinity regmine (e.g. TF = Tidal Fresh)

Segment	System
CB6PH	Chesapeake Bay Western Shore
CB7PH	Chesapeake Bay Eastern Shore
CB8PH	Chesapeake Bay Near Mouth
ELIPH	Elizabeth River
JMSPH	Lower James River
LYNPH	Lynnhaven River
MOBPH	Mobjack Bay
YRKPH	Lower York River
CB5MH	Upper Western Chesapeake Bay
CRRMH	Corrotoman River
JMSMH	Middle James River
LAFMH	Laffayette River
PIAMH	Piankatank River
POCMH	Lower Pocomoke River
POTMH	Lower Potomac River
RPPMH	Lower Rappahannock River
TANMH	Tangier Island
YRKMH	Middle York River
CHKOH	Chickahominy River
JMSOH	Upper James River
MPNOH	Lower Mattaponi River
PMKOH	Lower Pamunkey River
POCOH	Upper Pocomoke River
POTOH	Middle Potomac River
RPPOH	Middle Rappahannock River
JMSTF	Upper James River
MPNTF	Upper Mattaponi River
PMKTF	Upper Pamunkey River
POTTF	Upper Potomac River
RPPTF	Upper Rappahannock River

Figure 2. Virginia tidal water segments (n=30) categorized based on salinity regime.

CLIMATE CHANGE AND SHORELINE HARDENING

Shoreline hardening and land development have had documented adverse effects on nearshore habitats and dependent species (e.g. Beauchamp *et al*. 1994; Jennings *et al*. 1999; Lerberg *et al*. 2000; DeLuca *et al*. 2004; Bilkovic *et al*. 2006; Seitz *et al*. 2006; Bilkovic and Roggero 2008). Climate change will exacerbate the issue by inciting increases in shoreline hardening for protection as sea level rises and storm activity intensifies.

To more accurately anticipate changes to coastal habitats, upland and shoreline development was integrated with climate change stressors (e.g. sea level rise). The availability of shoreline inventories and remotely-sensed land use facilitated efforts to evaluate the combined effects of existing development with projected system changes.

Shoreline and riparian characteristics were extracted from a comprehensive inventory of shoreline condition available for much of Virginia's tidal waters (Fig. 3; http://ccrm.vims.edu/gis_data_maps/shoreline_inventories/index.html). The inventory protocol was specifically developed for Virginia and Maryland coastlines and included a spatially-explicit method for collecting, classifying, mapping, and reporting conditions along the shore. The inventory employed a continuous three-tiered shoreline assessment approach, dividing the shorezone into three regions 1) immediate riparian zone, evaluated for land use; 2) bank, evaluated for height, stability, cover and natural protection; and 3) shoreline, describing the presence of shoreline structures for shore protection and recreational purposes. Data collection was performed in the field from a small, shoal draft vessel, navigating at slow speeds parallel to the shoreline. To the extent possible, surveys took place on a rising tide, allowing the boat to be as close to shore as possible. A complete set of geographically referenced shoreline data was acquired using a pre-programmed data-dictionary in a handheld Trimble GPS GeoExplorer receiver that included a suite of characteristics describing riparian land use, bank condition, and shoreline features. GeoExplorers were accurate to within 10 cm of true position with extended observations and differential correction. Without post processing, these units can achieve accuracies of approximately 1 m. Both static and kinematic data collection was performed. Kinematic data were collected continuously along a pathway (in this case along the waterway) at a rate sufficient to compute a position anywhere along the course (i.e. one observation every five seconds). Land use, bank condition, and linear shoreline structures were collected using this technique. Static surveys used the GPS receiver to pin-point fixed locations, such as piers, based on the average of 6 static observations. GPS field data were converted to GIS spatial coverages which were corrected to reflect true shoreline geometry (for additional details see Berman *et al*. 2007). For a small portion of the modeled area shoreline inventory data were not available (Fig. 3), in these instances land use data (Coastal Change Analysis Program (CCAP 2005)) were substituted within habitat models.

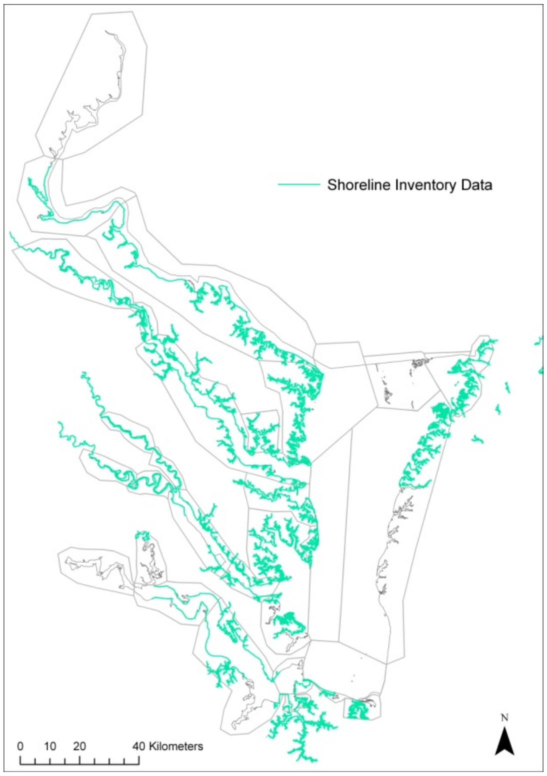
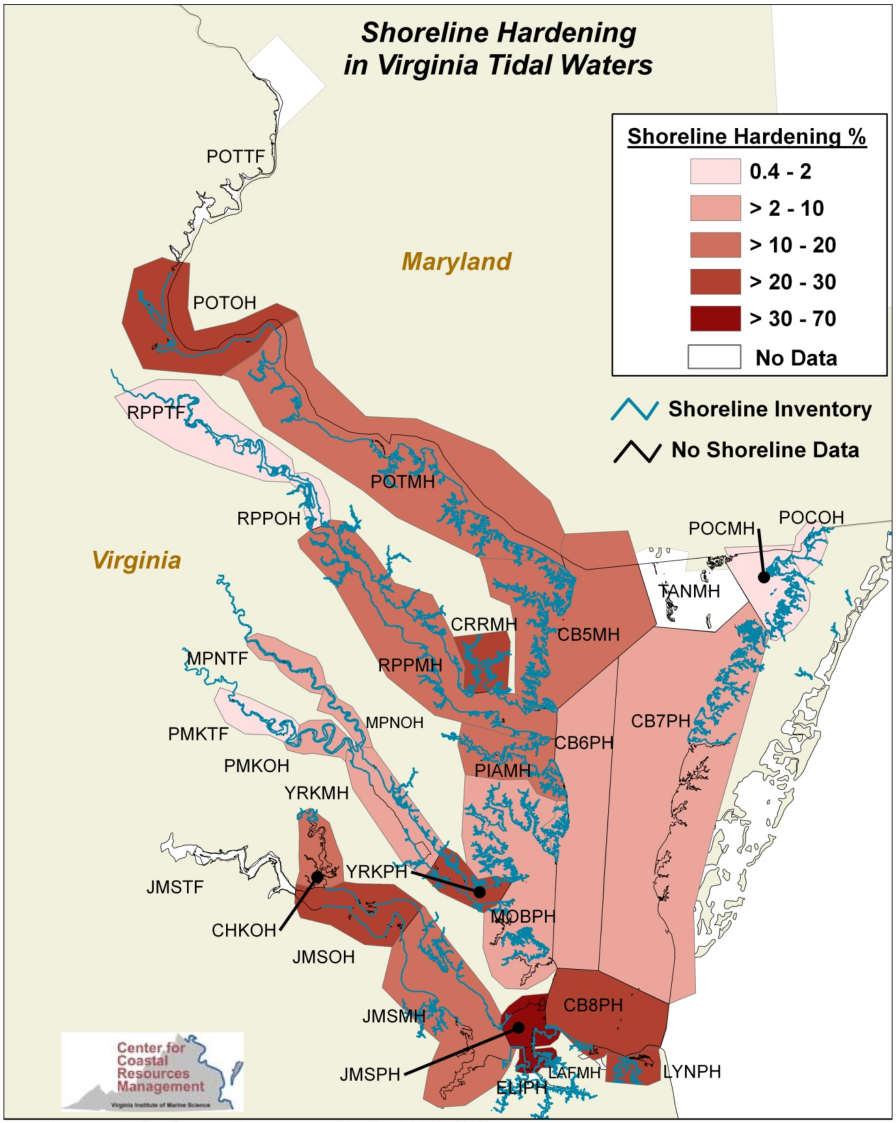


Figure 3. Available Shoreline Inventory data (CCRM-VIMS) as of 2009. Shorelines not shaded were evaluated for the habitat models with alternate datasets (i.e. land use - CCAP 2005).

SHORELINE DEVELOPMENT – EXISTING CONDITIONS

Approximately 11.1% of shoreline inventoried in Virginia tidal waters has been hardened (793 km hardened/7134 km shoreline surveyed). Shoreline alterations, considered a form of hardening, include bulkhead, riprap revetment, marina, seawall, wharf, and unconventional means of hardening. Relatively high proportional amounts of shoreline hardening exist in Hampton Roads (i.e. Lower Bay, Lower York, Lynnhaven, Elizabeth, and Lafayette rivers), upper Potomac River, and Corrotoman River (Fig. 4, Table 1).

Overall, 27% of Virginia tidal riparian lands are developed (Fig. 5). Riparian development in the form of commercial, residential, industrial or paved land use exceeds 20% in the majority of examined Chesapeake Bay Segments. An ecological threshold of ~ 20% development (e.g. residential or commercial land use, impervious surface) has been associated with reduced biotic integrity in fish (Limburg and Schmidt 1990, Wang et al. 1997, Paul and Meyer 2001, Bilkovic and Roggero 2008), benthic (Bilkovic et al. 2006) and bird communities (DeLuca et al. 2004). Similar to shoreline hardening trends, high development regions of concern include Hampton Roads (i.e. Lower Bay, Lower York, Lynnhaven, Elizabeth, and Lafayette rivers), Potomac, Corrotoman and Piankatank rivers. Low development was documented in the upper reaches of the York (Pamunkey and Mattaponi rivers) and Rappahannock rivers, as well as the Eastern Shore (including Pocomoke River) (Fig. 5, Table 1).



**Chesapeake Bay Program Segments modified by CCRM-VIMS to be inclusive of riparian lands for climate change modeling*

Figure 4. Proportion of shoreline hardened (i.e. bulkhead, riprap revetment, marina, seawall, wharf, and unconventional means of hardening) within each Chesapeake Bay Program (CBP) Segment.[1] Overall, 11.1% of shoreline inventoried in Virginia tidal waters was hardened (793 km hardened/7134 km shoreline surveyed).

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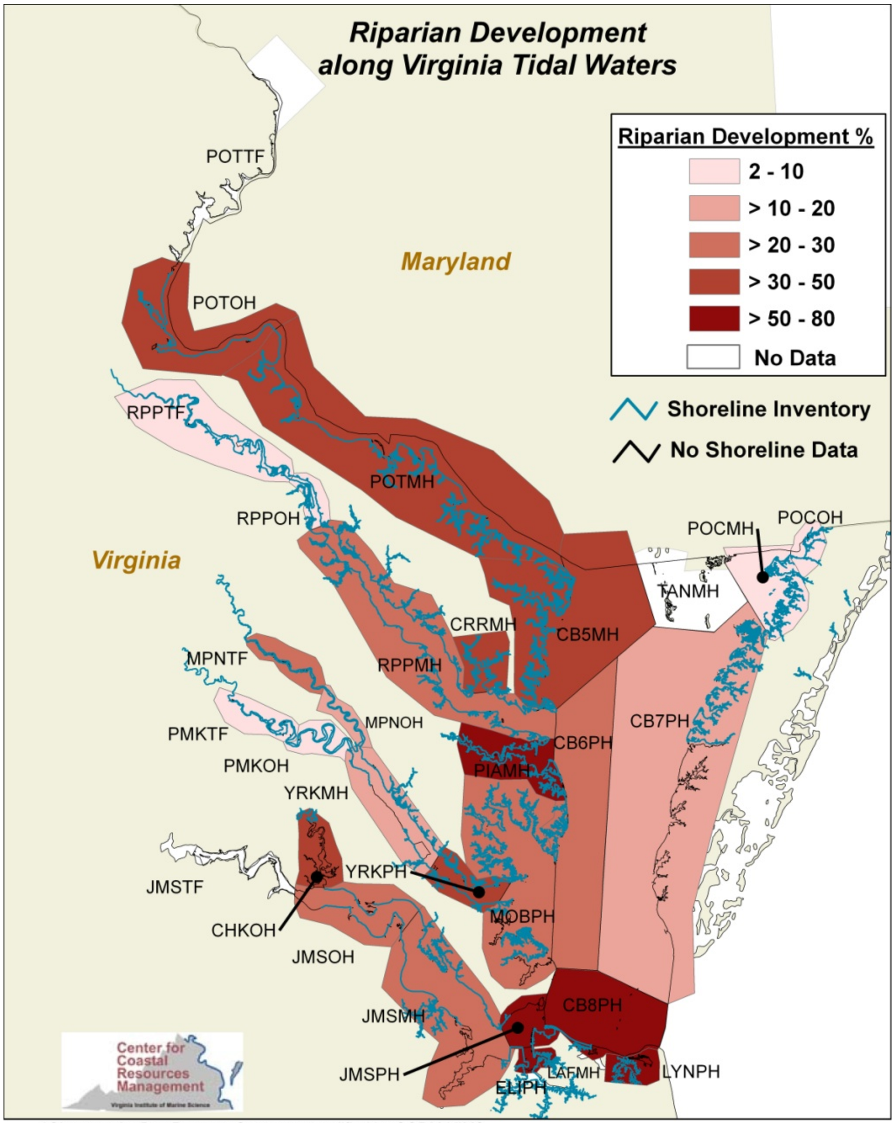
[1] *Shoreline condition data were not available for the upper Potomac River (POTTF), Tangier Island (TANMH), Upper James River (JMSTF), Northampton County (Lower CB7PH), lower Chickahominy River (CHKOH) and sections of the Lower James (JMSPH). The Maryland shore of the Potomac River was excluded from summaries.*



*Chesapeake Bay Program Segments modified by CCRM-VIMS to be inclusive of riparian lands for climate change modeling

Figure 5. Proportion of riparian lands developed (residential, commercial, industrial or paved) within each Chesapeake Bay Program (CBP) Segment. In most segments, in excess of 20% of the shoreline was developed.[1] Overall, 27% of Virginia tidal riparian lands are developed.

[1] *Shoreline condition data were not available for the upper Potomac River (POTTF), Tangier Island (TANMH), Upper James River (JMSTF), Northampton County (Lower CB7PH), lower Chickahominy River (CHKOH) and sections of the Lower James (JMSPH). The Maryland shore of the Potomac River was excluded from summaries.*

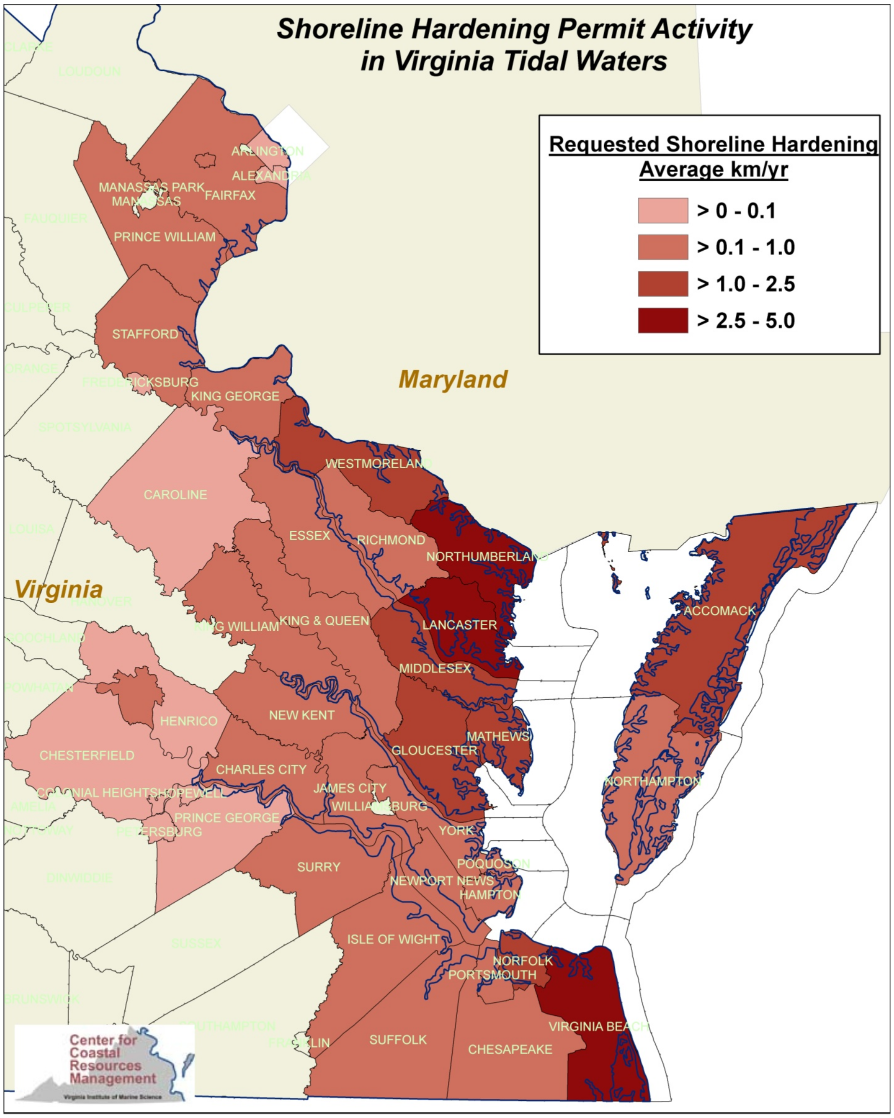
Table 1. Shoreline and riparian conditions within each Chesapeake Bay Program (CBP) Segment extracted from shoreline inventory data (VIMS-CCRM).

					Riparian Land Use					
CBP Segment	Salinity Regime	Total Shl Surveyed (km)	Hardened Shl		Developed		Unmanaged		Agriculture	
			km	%	km	%	km	%	km	%
CB6PH	PH	151.7	5.6	3.7	34.8	22.9	115.8	76.3	1.2	0.8
CB7PH	PH	654.4	17.7	2.7	79.9	12.2	539.7	82.5	34.7	5.3
CB8PH	PH	40.9	10.0	24.4	27.9	68.1	12.3	29.9	0.0	0.0
ELIPH	PH	25.9	17.8	68.7	15.7	60.5	10.2	39.5	0.0	0.0
JMSPH	PH	35.2	18.1	51.6	26.2	74.6	8.9	25.4	0.0	0.0
LYNPH	PH	164.8	46.0	27.9	121.6	73.8	43.2	26.2	0.0	0.0
MOBPH	PH	961.6	61.0	6.3	239.9	24.9	695.7	72.3	26.0	2.7
YRKPH	PH	130.2	35.8	27.5	58.8	45.2	71.0	54.6	0.3	0.2
CB5MH	MH	708.6	111.7	15.8	259.9	36.7	408.0	57.6	40.7	5.7
CRRMH	MH	186.3	43.5	23.3	63.8	34.3	120.7	64.8	1.7	0.9
JMSMH	MH	461.4	51.9	11.2	122.5	26.5	338.9	73.4	0.0	0.0
LAFMH	MH	63.7	28.4	44.5	49.6	77.8	14.1	22.2	0.0	0.0
PIAMH	MH	275.7	54.3	19.7	142.5	51.7	131.9	47.8	1.3	0.5
POCMH	MH	432.5	3.4	0.8	17.6	4.1	411.6	95.2	3.4	0.8
POTMH	MH	672.0	113.9	17.0	288.9	43.0	337.4	50.2	45.7	6.8
RPPMH	MH	907.7	110.3	12.2	202.6	22.3	666.4	73.4	38.6	4.3
TANMH	MH	ND	ND	ND	ND	ND	ND	ND	ND	ND
YRKMH	MH	237.7	11.5	4.8	28.9	12.1	207.0	87.1	1.9	0.8
CHKOH	OH	32.7	4.0	12.2	10.0	30.7	22.6	69.3	0.0	0.0
JMSOH	OH	60.5	13.9	23.0	13.3	22.1	46.5	77.0	0.5	0.8
MPNOH	OH	52.2	1.6	3.1	9.6	18.4	41.1	78.7	0.0	0.0
PMKOH	OH	71.8	2.1	2.9	6.2	8.6	62.4	87.0	3.1	4.4
POCOH	OH	108.1	1.3	1.2	2.5	2.3	93.4	86.4	12.3	11.3
POTOH	OH	104.9	23.7	22.6	34.7	33.1	52.3	49.9	0.3	0.3
RPPOH	OH	209.5	0.8	0.4	4.0	1.9	196.1	93.6	9.4	4.5
JMSTF	TF	ND	ND	ND	ND	ND	ND	ND	ND	ND
MPNTF	TF	61.3	1.9	3.0	13.3	21.7	48.0	78.3	0.0	0.0
PMKTF	TF	76.2	1.3	1.8	4.0	5.2	69.0	90.6	3.2	4.2
POTTF	TF	ND	ND	ND	ND	ND	ND	ND	ND	ND
RPPTF	TF	246.0	1.7	0.7	12.7	5.2	217.4	88.4	15.9	6.5
All Tidal Segments		**7134**	**793**	**16**	**1891**	**27**	**4982**	**70**	**240**	**3**

SHORELINE HARDENING TRENDS

The majority of Virginia localities do not exhibit consistent temporal trends in shoreline hardening for erosion control. While variability may exist among years (e.g. high permit activity following a significant storm event), long-term trends illustrate anticipated futures of shoreline alteration. Based on long-term averages of Virginia shoreline permit application records (1988, 1993-2007), annual increases in shoreline hardening (bulkhead and riprap placement) were estimated for each Virginia tidal water locality (Fig. 6; http://ccrm.vims.edu/perms/newpermits.html). On average, 29 km of shoreline are hardened each year in Virginia. Based on current average rates of shoreline hardening, approximately 9-18% of additional Virginia shoreline will be hardened 50 - 100 years into the future (assuming no shifts in management practices and no accelerated activity due to sea level rise and storm events).

Three localities (City of Hampton, Virginia Beach and Stafford County) exhibited declining shoreline hardening trends over the 14 year time frame. These localities are heavily developed and shoreline structure placement has likely slowed due to the unavailability of natural shorelines in association with residential land use to harden. For instance, comprehensive tidal shoreline inventories in Stafford County (Berman *et al.* 2006) indicated that 36% of the surveyed shoreline was hardened.



*Average annual amount of shoreline hardening is based on permit requests by County from 1989, 1993-2007. Actual constructed shoreline structure may vary from requested or approved activity.

Figure 6. Annual average amounts of requested shoreline hardening by County extracted from Virginia shoreline permit application records (VMRC-VIMS).

CLIMATE CHANGE MODEL COMPONENTS

To project broad-scale climate change effects on the abundance and distribution of coastal habitats, an inundation model based on anticipated relative sea-level rise, temperature and salinity projections, and coastal development were integrated into a GIS modeling framework.

INUNDATION MODEL

A significant challenge to modeling sea level rise in the Commonwealth of Virginia is the lack of comprehensive high resolution topographic and bathymetric data. In the absence of high precision data to facilitate site-specific planning, modeling best-available data allows for the evaluation of projected trends across larger spatial scales.

To accurately assess the future effect of sea level rise and climate change on ecosystems, a merged land/water elevation surface must be created that integrates disparate bathymetric and topographic data. These datasets are collected by different agencies, along varying time frames, and reported in different specifications (e.g. vertical datums). Thus, integration of these data requires a variety of approaches to ensure that the final product consists of the best available data converted to a common geospatial framework (e.g. same vertical and horizontal datum and coordinate system) (Gesch and Wilson 2002). In Virginia, high precision LIDAR (**Li**ght **D**etecting and **R**anging) data are unavailable; therefore, existing topographic and bathymetric data were evaluated for spatial extent and resolution. The best-available data were then extracted for the development of an elevation surface with application in large-scale climate change analyses of shallow tidal Virginia waters.

BATHYMETRY

Bathymetric digital sounding data were extracted from the NOAA's National Ocean Service Hydrographic Database maintained by the National Geophysical Data Center. These data were in the form of soundings collected from the early 1900s to the present. Because these data were taken with different methods throughout history the resolution can be highly variable with soundings ranging from approximately 12 – 60 meters apart in the tidal waters of Virginia, and gaps in coverage also exist (Fig. 7). Bathymetric data are referenced to local tidal datums (e.g. MLW, MLLW); therefore, data must be converted to a standard vertical datum with a fixed benchmark to merge with topographic data. Data conversion between various tidal datums and a fixed datum coordinate system (e.g. NAVD88) can be accomplished with the VDatum tool developed jointly by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS) (http://vdatum.noaa.gov/).

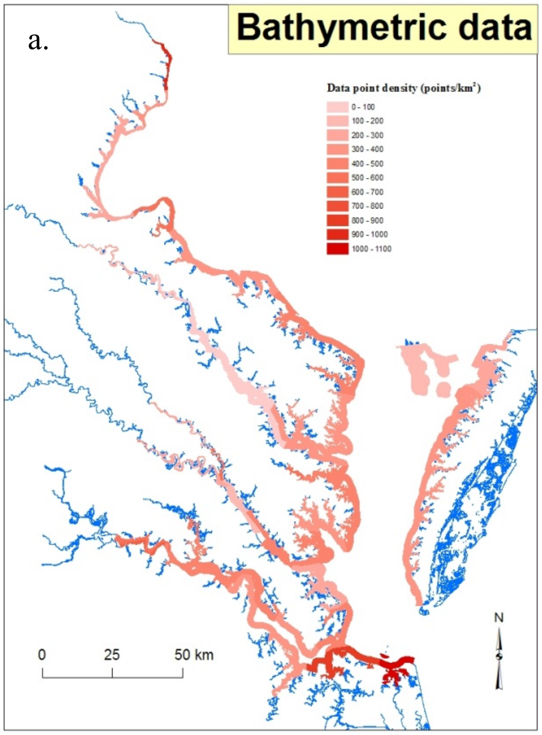
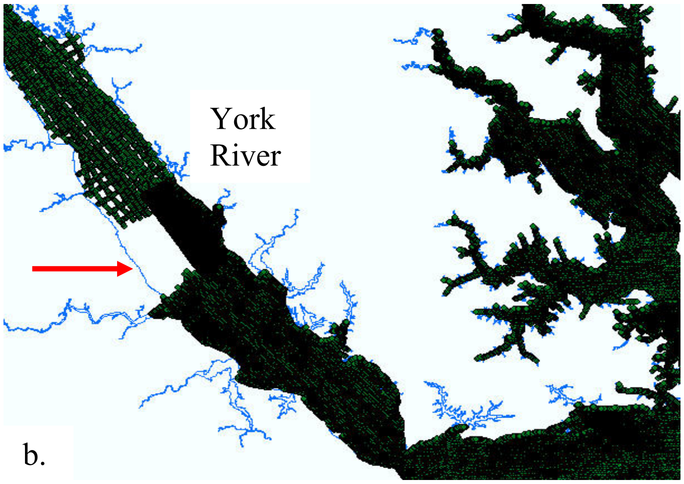


Figure 7. (a) Density of digital bathymetric soundings available for GIS analyses in Virginia tidal waters, (b) Example of deficiencies in bathymetric coverage in upstream areas, as well as adjacent to military installations (Camp Peary, York River).



TOPOGRAPHY

Two topographic datasets are currently available that provide extensive coverage of the Commonwealth: 1) National Elevation Dataset (NED), which is the primary elevation product of the U.S. Geological Survey; and 2) Digital Terrain Model (DTM) from the Virginia Base Mapping Program (VBMP), managed by the Virginia Geographic Information Network (VGIN).

The NED has the advantage of high horizontal resolution (1/3 arc-second (roughly 10 meter) horizontal resolution for the study area). However, the vertical resolution is relatively poor; although it is improving as higher quality data are added. Resolution is variable because of the variety of source data, but the USGS cites an overall root mean square error (RMSE) of 2.44 meters (USGS, Vertical Accuracy of the National Elevation Dataset, URL: http://ned.usgs.gov/ Downloads/documents/NED_Accuracy.pdf). This resolution is likely inadequate for sub-meter sea level rise projections (Gesch *et al* 2009).

The VBMP DTM data has variable horizontal resolution, with an average spacing between elevation sampling points of 9.4 m. Horizontal positional accuracy depends on the scale of the orthophotography (100, 200 or 400 scale) compiled to meet or exceed 2.4, 4.9 or 9.8 foot horizontal accuracy at 95% confidence level in accordance with National

Standards for Spatial Data Accuracy (NSSDA). However, vertical resolution is significantly better than the NED. Vertical resolution varies depending on the pixel resolution from RMSE of 0.5 - 0.6 ft (0.15-0.18 m) to RMSE of 1.0 - 1.2 ft (0.30-0.37m) (Virginia Geographic Information Network (VGIN); *Metadata*: http://gisdata.virginia.gov/Portal/). The DTM also contains 3D break lines and mass points to more accurately define abrupt changes in topography. Therefore, the VBMP provides the highest resolution terrain model available in Virginia. Since any sea level rise analysis is particularly sensitive to the vertical accuracy of the generated digital elevation model, the VBMP DTM was selected for elevation surface production.

SEAMLESS 3-D TOPOGRAPHIC/BATHYMETRIC ELEVATION SURFACE

Geographic coordinate system

Data were projected to UTM NAD83 for horizontal coordinates, and VBMP elevation values were converted from feet to meters for vertical coordinates (referenced to the North American Vertical Datum of 1988 (NAVD88)) to be consistent with the bathymetric data. A NOAA created tool *VDatum* was used to convert bathymetric data values (in mean low water and mean lower low water) into the fixed datum coordinate system used in VBMP topographic data (NAVD88).

GIS Processing

To accommodate faster processing of the extensive modeled area, only data at the land/water interface of the coastal plain were included in the surface (from 600 m landward to 2000 m seaward). Contours were generated for SLR scenarios used in the analysis and overlaid on the surface to verify that habitats of interest were not present inland of the 600 meter landward cutoff.

To generate the seamless surface, bathymetric and topographic data were combined and interpolated into a raster using the “Topo to Raster tool” included in the ArcGIS Spatial Analyst. This tool is based on the ANUDEM program developed by Hutchinson (1989) that was explicitly designed for the creation of hydrologically correct digital elevation models. It is the only ArcGIS interpolator designed to work with 3D feature inputs using this method. To enhance processing speeds, the study area was divided into a large number of arbitrary segments for which surfaces were independently generated. The completed 3-D seamless topographic/bathymetric elevation surface covered the majority of Virginia tidal waters with some exceptions due to deficient data (e.g. digital soundings unavailable for the upper reaches of Chickahominy River) (Fig. 8). Using randomly sampled surface points (n=150), the elevation surface was estimated to have an accuracy at a 95% confidence level of 0.13 ± 0.08 m.

Data Limitations

Sources of potential error to the elevation surface include the variable accuracy of bathymetric data that span a long historic period. Areas without recent bathymetry are likely not accurately portrayed as erosion and sedimentation processes alter those soundings. Additionally, bathymetric data coverage varied significantly across Virginia waters with sparse or no digital sounding data coverage in many upstream reaches. Areas without the necessary digital sounding data required for GIS analyses had to be excluded. As more precise data become available within shallow water (e.g. LIDAR), habitats historically underestimated can be added to future projections. As such, habitat models were structured to elucidate trends across large spatial scales, not at the site-specific level. Projecting overarching shifts in shallow water habitat in response climate change are the necessary first steps in support of forward-looking coastal management.

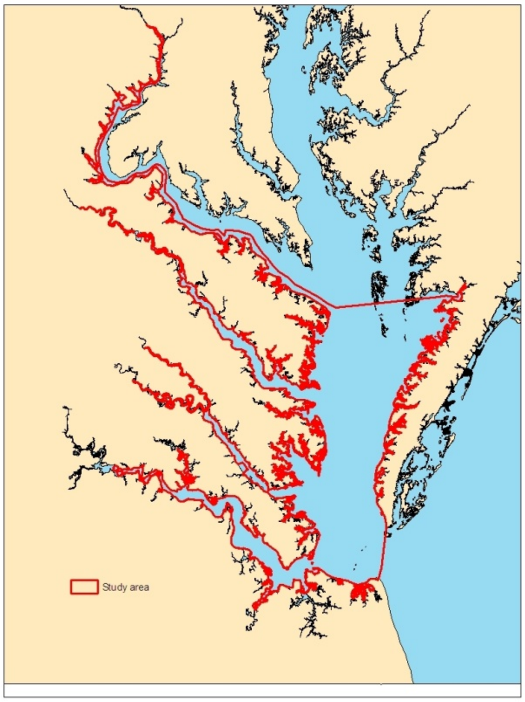


Figure 8. Virginia tidal water area included in the seamless elevation surface of the land/water interface.

SEA LEVEL RISE SCENARIOS

SEA LEVEL RISE IN THE CHESAPEAKE BAY

The Chesapeake Bay is extremely vulnerable to sea level rise, ranking behind only Louisiana and Southern Florida in the United States. In the Chesapeake Bay, rates of relative sea level rise are more than double the global mean and rising (~4.2 mm/yr in Chesapeake vs. 1.7 mm/yr globally) for a total of approximately one foot of sea level rise in the Bay over the past century. Relative sea level rise is the sum of global sea level rise plus localized vertical land movement. The high rates observed in the Chesapeake Bay are due to natural land subsidence caused by glacial isostatic adjustment (the postglacial collapse of a glacial forebulge from the last ice age) and tectonic uplift, as well as anthropogenic influences such as ground-water withdrawal that cause sediment compaction and further land subsidence.

Expected negative effects of sea level rise include intensified coastal flood and storm events, increased shore erosion, inundation of wetlands and low-lying lands, and salt-water intrusion into groundwater (Pyke *et al.* 2008).

MODELED SEA LEVEL RISE SCENARIOS

Two relative sea level rise scenarios (S1 and S2) were modeled and illustrated for the years 2050 and 2100. Scenario 1 elevates sea level 0.2 and 0.6 m, and scenario 2 elevates sea level 0.7 and 1.6 m (2050 & 2100, respectively). Using the present day shoreline contour as a baseline, mean sea level contours (shorelines) on the surface were then generated for each scenario for the time-steps 2050 and 2100 (Fig. 9). The difference between baseline mean sea level and projected shorelines was utilized for estimation of shifts in area of shallow-water habitat, potential tidal wetlands and submerged aquatic vegetation.

SEA LEVEL RISE SCENARIOS

- **Scenario 1 (S1)** represents a conservative estimate of SLR by applying current documented rates of rise (4.2 mm/yr) until the year 2050 with a slightly accelerated rate of 10mm/yr for the years 2051-2100.

- **Scenario 2 (S2)** corresponds to recent estimates specific to the Chesapeake Bay by Pyke *et al*. (2008) that applied regionally-adjusted values to a semi-empirical approach by Rahmstorf (2007) for deriving global sea-level increase.

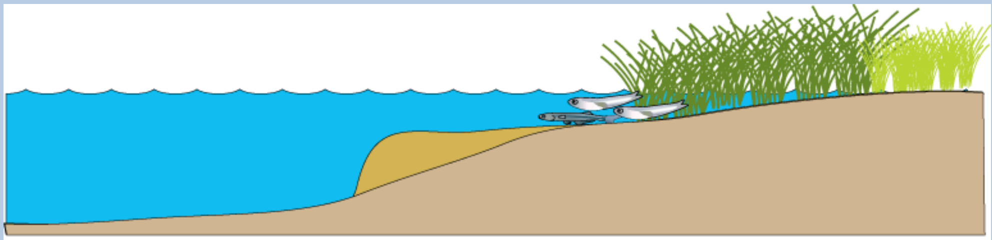
Cumulative relative sea level rise at 2050 and 2100 for two scenarios

	Relative SLR (m)	
Scenario	***2050***	***2100***
S1	0.2	0.7
S2	0.6	1.6

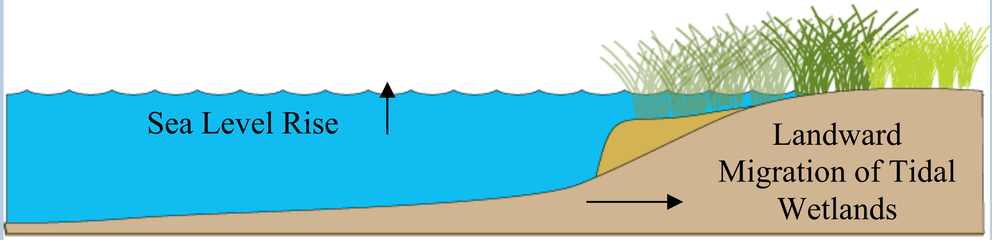
Figure 9. Projected shifts in mean sea level (MSL) by the years 2050 and 2100 in relation to existing tidal wetlands on the Lynnhaven River.

Case Study: Sea Level Rise and Tidal Wetlands

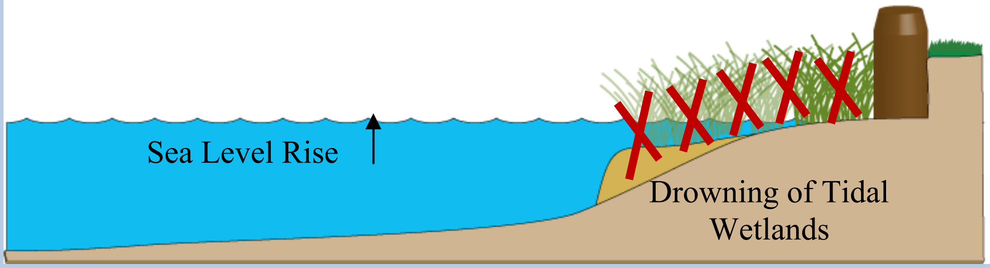
Historically, marshes have kept pace with SLR through sediment accumulation and transgression landward. Rising SLR threatens to outpace marshes ability to vertically accrete sediment and hardened shorelines prevent movement inland. Chesapeake Bay is highly developed with much of its population living on the coasts. Home-owners have traditionally used shoreline armoring techniques such as bulkhead and riprap to prevent erosion of their land. However, shoreline hardening reduces sediment available to marshes for vertical accretion and blocks their landward migration, so they will likely drown in place as SLR continues. The use of living shoreline techniques to protect shorelines from erosion which incorporate natural elements (e.g. marshes) is being promoted in the hopes that these habitats can be protected from SLR.



Historic Conditions
Marshes vertically accrete sediment & transgress landward to keep pace with SLR



Increasing SLR
Reduction in shallow water, intertidal & marsh habitats. Upland transgression may occur.



SLR + Shoreline hardening
Reduction and eventual loss of shallow water, intertidal and marsh habitats

TEMPERATURE AND SALINITY PROJECTIONS

Temperature and salinity interpolations across the survey area (restricted to depths ≤ 2m) were completed using the most comprehensive data available that specifically targets shallow-water:

- DSS - Virginia Division of Shellfish Sanitation Monitoring Survey
- DATAFLOW - Surface Water Quality Mapping System (VIMS, Virginia Estuarine and Coastal Observing System (VECOS))

The DSS dataset ranges from 1984 to present and consists of ~24,000 samples taken each year within the tidal portion of Virginia's mainstem and rivers as well as coastal bays (Fig. 10). Turbidity and fecal coliform counts are measured in addition to water temperature and salinity. Station locations are meant to represent conditions over shellfish beds and are therefore in the nearshore region. Data were obtained from the Virginia Department of Health Office of Environmental Health Services Division of Shellfish Sanitation.

The DATAFLOW monitoring surveys targeted different Chesapeake Bay Program Segments (tributaries) each year (Table 2). Surface water quality (water temperature, salinity, pH, chlorophyll, turbidity, and dissolved oxygen) was mapped with a self-contained compact flow-through system. Depending on river morphology, a number of surveys were run parallel to the shoreline along fixed depth contours to encapsulate conditions along the entire estuary. Further survey data and program information are available on a dedicated Virginia Estuarine and Coastal Observing System (VECOS) webpage http://www2.vims.edu/vecos/default.aspx.

Seasonal averages of long-term surface salinity and temperature data from DSS and DATAFLOW datasets were combined and interpolated with the *ordinary kriging method* in ArcGIS Spatial Analyst to achieve complete coverage of the study area. Summertime (June-August) was the selected focal time-period, since water temperature extremes that have demonstrable affects on Bay flora and fauna are captured within these months.

Temperature Projections

In the Chesapeake Bay, the average, maximum and annual surface water temperatures have increased by more than 1° C over the last four decades (Pyke *et al*. 2008). Temperature projections by Intergovernmental Panel on Climate Change (IPCC) and supported by research in the Chesapeake Bay (Pyke *et al*. 2008) indicate a high likelihood of an increase of 1 to 6°C by 2100. A uniformly applied increase of 1, 3 and 6°C was modeled to illustrate potential shifts in suitable habitat for critical estuarine components (e.g. SAV) (Fig. 11). For example, an elevation of average summertime temperatures by 3°C will result in extensive reaches in the polyhaline exceeding 30°C, which is the maximum temperature to ensure eelgrass survival. An elevation of 6°C will result in dramatic temperature increases throughout the mainstem and tributaries that will extensively affect flora and fauna communities as habitat suitability is lost across much of the Bay. With these projected temperature increases, successful invasions by tropical species will increase as they can tolerate elevations in temperature and salinity and out-compete native species. Likewise, the relied upon cues for spawning and feeding will be altered as climate changes affecting population survival. For example, anadromous fish, such as American shad, rely on changes in water temperature in the spring to initiate spawning runs up tributaries. Recent research by Austin (2002) has indicated average spring water temperature, defined as when temperature first reaches 15° C, is occurring 3 weeks earlier than in the past 50 years. Earlier spawning runs may result in a mismatch with the availability of necessary food items for young fish, which can lead to reductions or failures of year-classes.

Salinity Projections

Salinity variability and the unavailability of precise predictions of precipitation changes make it difficult to project salinity increases, particularly in the tributaries. However, evaluation of Bay mainstem data indicates that an increase in salinity of 1.4-3.2 ppt in conjunction with a sea level rise of 0.7-1.6 m by 2100 may occur (Hilton *et al*. 2008). A uniformly applied increase of 1 and 3 ppt was modeled to illustrate potential shifts in wetland community types (Fig. 12). Since future climate-change induced increases in precipitation and storm events are difficult to predict and may vary dramatically by region, this simplified approach was developed. While this model was not intended to demonstrate precise predictive salinity shifts in response to climate change, it allows for the general assessment of how wetland composition may be affected if average salinity is elevated.

Table 2. Tributary schedule for DATAFLOW surveys

Tributary	Survey Period	CBP segment
Potomac River	2007-2008	POTMH
Rappahannock River	2007-2008	RPPMH
	2007-2008	RPPOH
	2007-2008	RPPTF
Corrotoman River	2007-2008	CRRMH
Pamunkey River	2003-2005	PMKOH
	2003-2005	PMKTF
Mattaponi River	2003-2005	MPNOH
	2003-2005	MPNTF
Chickahominy River	2006-2007	CHKOH
James River	2006-2008	JMSTF
	2005-2006	JMSMH
	2005-2008	JMSOH

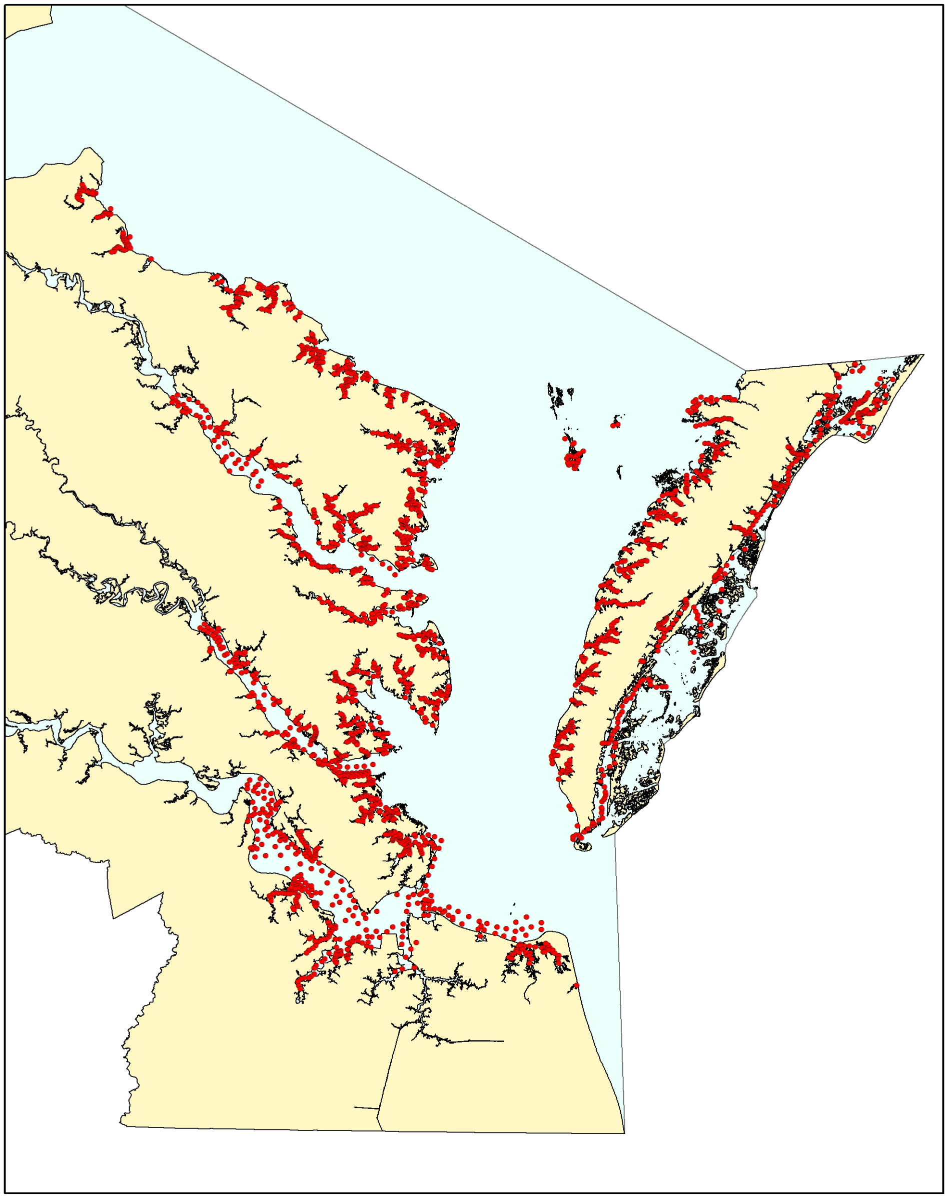


Figure 10. Virginia Division of Shellfish Sanitation Monitoring Survey (DSS) stations.

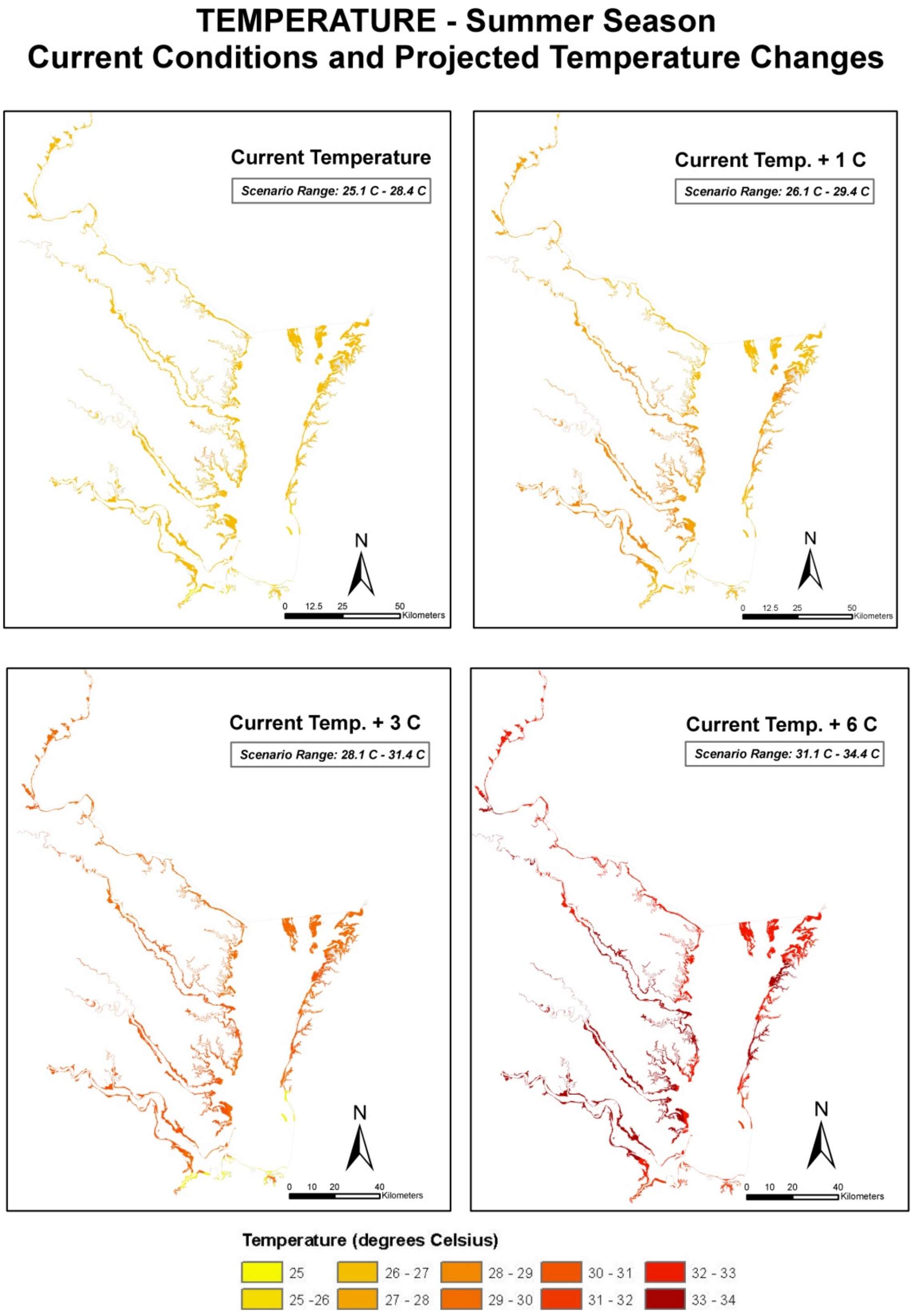


Figure 11. Shifts in surface summer water temperature in shallow waters modeled from uniformly applied elevations in temperature (1, 3 and 6ºC) to historic average summer conditions.

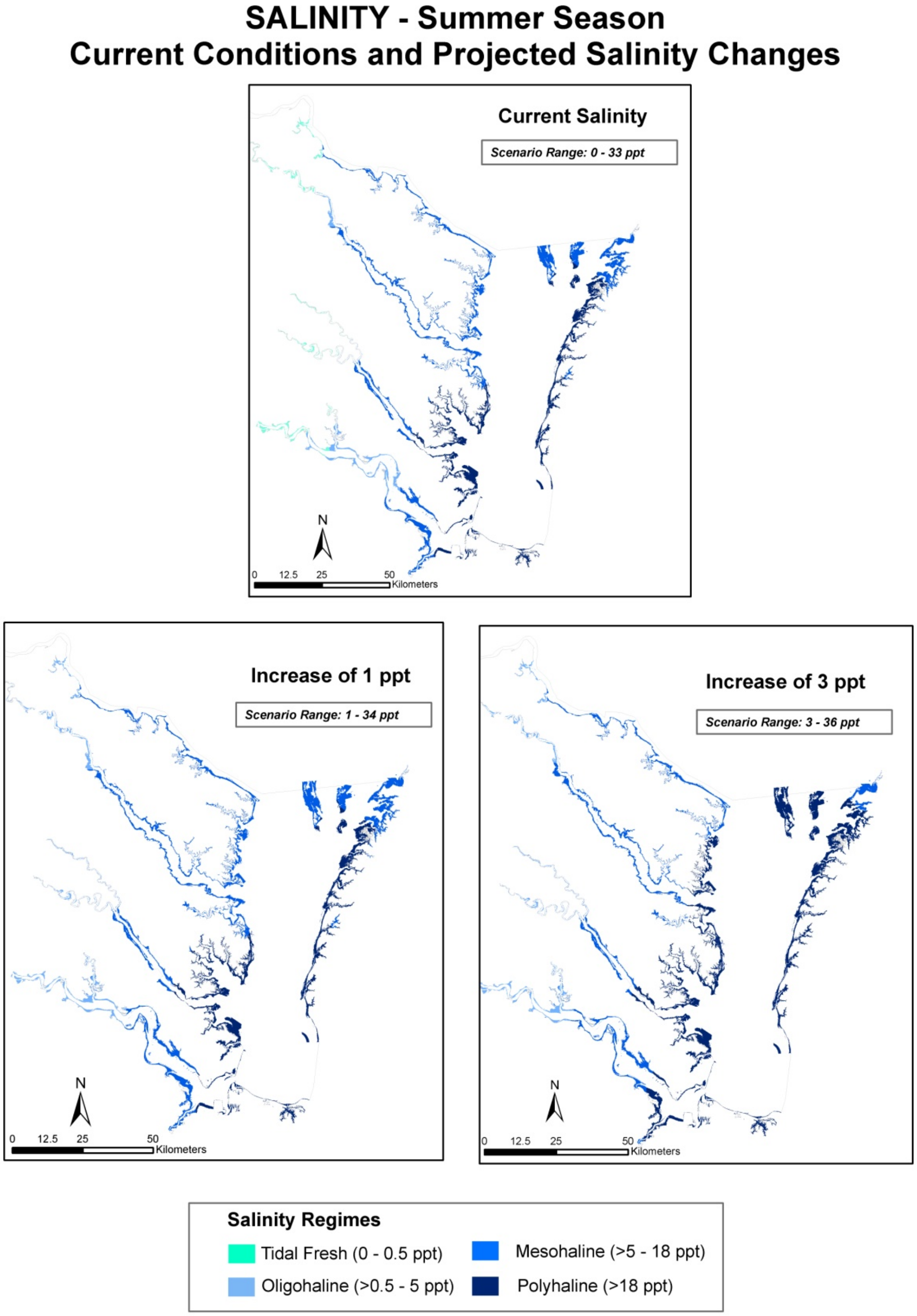


Figure 12. Shifts in surface summer salinity in shallow waters modeled from uniformly applied elevations in salinity (1 and 3ppt) to historic average summer conditions.

COASTAL HABITAT SHIFTS WITH CLIMATE CHANGE

Separate models were developed for each coastal habitat based on available data and known ecological requirements. Conceptual models, associated GIS analysis, and projected trends in habitat are reported by habitat type.

SHALLOW WATER (BETWEEN MLW AND ≤ 2 M DEPTH)

SHALLOW WATER HABITAT

Shallow water habitats are highly productive and established essential nursery areas for nekton, providing protection from predators, and foraging opportunities for numerous fish, shellfish and crustacean species (e.g. McIvor and Odum 1988; Ruiz *et al*. 1993). Numerous studies have documented the utilization of shallow water habitats, tidal creeks and marshes by nekton for nursery areas. For example, shallow water has been described as important nursery habitat for spot, silver perch, spotted seatrout, and Atlantic croaker in the Chesapeake Bay (e.g. Chao and Musick 1977), and subtidal creek habitats may be critical to larval spot, gobies, bay anchovy, and Atlantic croaker (Allen and Barker 1990).

HABITAT MODEL

Shallow water areas were defined for Virginia tidal waters based on each forecasted location of mean sea level. A new 2-m contour was projected separately for each scenario (S1 and S2) and two time-steps (i.e. 2050 and 2100). The new shallow water area (km^2) from MLW and ≤ 2 m depth was estimated for each Chesapeake Bay segment using 3D Analyst in ArcGIS. Land use data (CCAP 2005) were examined in relation to newly defined shifts in shallow water since land development which has the potential to prevent habitat migration. Using the Identity function which computes a geometric intersection of the input features (land use) and identity features (shallow water), area of development coincident with projected shallow water was calculated for each segment. The area of land development (CCAP categories: *Developed – high, medium and low intensity and open space*) that occurred within the projected shift in the shallow water habitat zone was then subtracted from projected shallow water areas. Based on current rates of shoreline and land development, the model likely over-estimates future shallow-water habitat unless management practices are drastically altered.

SHIFTS IN SHALLOW WATER

Overall, shallow water area decreased dramatically over the course of SLR ranging from 10-51% loss of habitat (Table 3). Shallow water habitat loss predominantly occurred in meso-polyhaline segments in all SLR scenarios and gains were observed in oligohaline and tidal fresh segments (Fig. 13, Table 4). Gains in shallow water were representative of conversion of tidal wetland habitat to shallow water and occurred primarily in the oligohaline and tidal fresh reaches of the Mattaponi and Pamunkey. These river reaches notably possess extensive wetland systems which are at risk to conversion to shallow and open water environs. Changes in plant community composition in Sweethall Marsh, Pamunkey River, attributed to eustatic sea level rise, isostatic effects and/or groundwater withdrawal, have been documented over the past few decades, with taller grasses such as Big Cordgrass (*Spartina cynosuroides*) being replaced by the lower elevation plant Arrow Arum (*Peltrandra virginica*), and, in some cases, by mudflats (Perry and Hershner 1999, Perry *et al*. 2009). Additional habitat shifts of this nature are anticipated as sea level rise continues.

Table 3. Estimated shallow-water (≤ 2m depth) based on the forecast location of mean sea level and new projected 2-m contour for each SLR scenario. Projected shallow-water areas coinciding with land development were excluded as potential new shallow water because property owners are likely to protect land from inundation.

Forecast Period	Scenario	Shallow Water Habitat (km^2)	Change in SW (km^2)	Change in SW (%)
Today	------	1,110	--	--
2050	S1	994	(116)	(10)
2050	S2	911	(199)	(18)
2100	S1	867	(243)	(22)
2100	S2	546	(564)	(51)

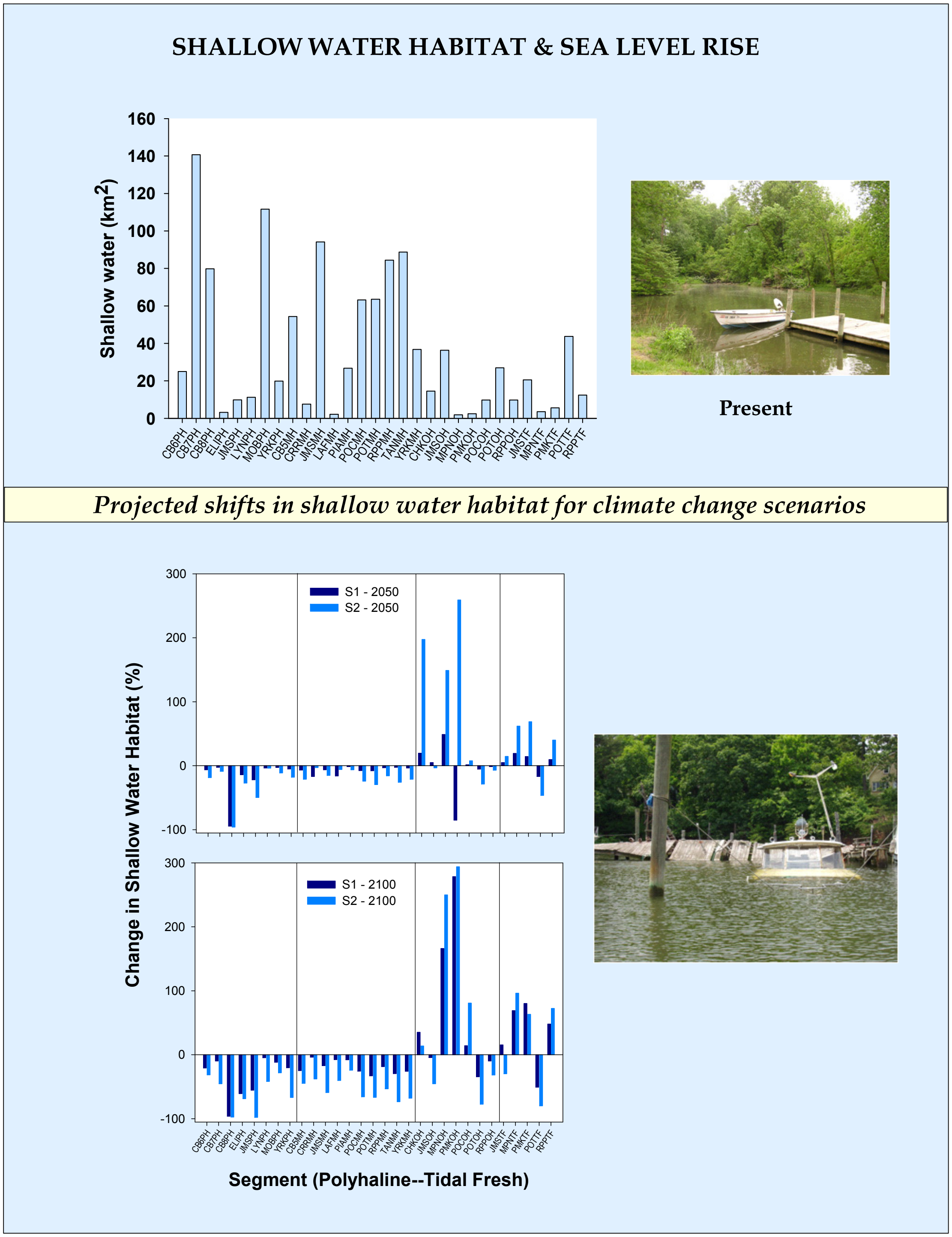


Figure 13. Current shallow water habitat (upper panel) and shifts in shallow water habitat by (a) 2050 & (b) 2100 in response to two SLR scenarios (lower panel).[1] Declines in habitat occurred predominantly in meso-polyhaline salinity regimes with conversion of tidal wetland habitat to shallow water in some tidal fresh-oligohaline areas.

[1] For all graphics, the illustrated sea level rise scenario and time-step are coded as *Scenario – Year*, for example, *S1 – 2050* represents sea level rise Scenario 1 at the year 2050.

Table 4. Projected change in *Shallow-water Habitat* (≤ 2m depth) due to climate change. Estimates based on sea level rise and land development. For some Chesapeake Bay Program (CBP) Segments, bathymetric data do not include those habitats located in headwaters. Therefore, in some cases reported areal extent may be underestimated.

CBP	Salinity	Shallow-Water Habitat Area (km^2)					Change in Shallow-Water Habitat (%)			
Segment	Regime	Present	S1-2050	S1-2100	S2-2050	S2-2100	S1-2050	S1-2100	S2-2050	S2-2100
CB6PH	PH	25.0	23.4	19.8	20.4	17.1	(6.4)	(20.7)	(18.5)	(31.5)
CB7PH	PH	140.7	137.3	126.7	128.4	76.6	(2.4)	(10.0)	(8.7)	(45.5)
CB8PH	PH	79.8	4.5	3.1	3.3	2.0	(94.4)	(96.2)	(95.9)	(97.5)
ELIPH	PH	3.2	2.7	1.3	2.3	1.0	(14.1)	(60.8)	(27.2)	(68.7)
JMSPH	PH	9.8	7.7	4.4	4.9	0.2	(21.9)	(55.4)	(49.7)	(97.9)
LYNPH	PH	11.2	10.8	10.7	10.8	6.5	(3.7)	(4.6)	(3.8)	(41.8)
MOBPH	PH	111.6	108.6	98.5	99.1	80.2	(2.7)	(11.7)	(11.2)	(28.2)
YRKPH	PH	19.9	18.9	15.8	16.3	6.6	(5.0)	(20.4)	(18.0)	(66.8)
CB5MH	MH	54.4	50.7	40.9	42.8	30.0	(6.8)	(24.8)	(21.2)	(44.7)
CRRMH	MH	7.5	6.2	7.2	7.3	4.7	(16.8)	(3.9)	(2.8)	(37.9)
JMSMH	MH	94.2	88.2	78.1	80.0	38.6	(6.3)	(17.1)	(15.1)	(59.0)
LAFMH	MH	2.1	1.8	2.0	2.0	1.3	(16.0)	(7.6)	(5.9)	(40.2)
PIAMH	MH	26.7	26.3	24.6	25.0	20.2	(1.5)	(7.9)	(6.4)	(24.2)
POCMH	MH	63.2	58.3	47.0	47.9	21.7	(7.7)	(25.6)	(24.2)	(65.7)
POTMH	MH	63.6	58.6	42.7	44.8	21.3	(7.8)	(32.9)	(29.5)	(66.5)
RPPMH	MH	84.4	81.8	68.7	71.0	39.4	(3.1)	(18.6)	(15.9)	(53.3)
TANMH	MH	88.7	86.7	62.4	65.7	23.7	(2.3)	(29.7)	(26.0)	(73.3)
YRKMH	MH	36.8	35.4	27.3	29.0	11.8	(3.7)	(25.9)	(21.2)	(67.8)
CHKOH	OH	14.5	17.3	19.6	43.0	16.5	19.5	35.2	197.4	13.9
JMSOH	OH	36.3	38.2	34.7	35.2	19.8	5.2	(4.4)	(3.2)	(45.4)
MPNOH	OH	1.9	2.8	5.0	4.7	6.6	49.0	166.1	149.2	249.8
PMKOH	OH	2.4	0.4	9.2	8.8	9.6	(85.1)	278.5	259.1	293.8
POCOH	OH	9.7	9.9	11.1	10.5	17.6	1.7	14.1	7.7	80.8
POTOH	OH	26.9	25.5	17.7	19.2	6.1	(5.4)	(34.4)	(28.5)	(77.4)
RPPOH	OH	9.7	9.6	8.8	9.0	6.6	(1.4)	(9.7)	(6.9)	(31.6)
JMSTF	TF	20.5	21.6	23.7	23.6	14.4	4.9	15.6	14.8	(29.8)
MPNTF	TF	3.5	4.2	5.9	5.7	6.9	19.5	69.1	61.9	96.4
PMKTF	TF	5.6	6.4	10.1	9.4	9.1	14.3	80.3	68.9	63.4
POTTF	TF	43.8	36.4	21.5	23.4	8.7	(16.9)	(50.8)	(46.4)	(80.0)
RPPTF	TF	12.4	13.6	18.3	17.3	21.3	9.8	48.0	40.1	72.5
All Tidal Waters		**1110.1**	**993.8**	**866.7**	**911.0**	**546.4**	**(10.5)**	**(21.9)**	**(17.9)**	**(50.8)**

SUBMERGED AQUATIC VEGETATION

In the Chesapeake Bay, there are approximately seventeen common species of submerged aquatic vegetation (excluding algae species). Within the high salinity reaches of the Bay, *Zostera marina* (eelgrass), a true seagrass species, dominates. In the Chesapeake Bay, eelgrass is near the southern limit of its distribution on the east coast and summer temperature in excess of 30°C has led to dieback (Moore and Jarvis 2008).

The most commonly observed species in mesohaline--tidal fresh waters are *Ruppia maritima* (widgeon grass), *Vallisneria americana* (wild celery), *Hydrilla verticillata* (hydrilla), *Potamogeton perfoliatus* (redhead grass), *Stuckenia pectinata* (*P. pectinatus*) (sago pondweed), *Myriophyllum spicatum* (Eurasian watermilfoil), and *Ceratophyllum demersum* (coontail). *R. maritima* is tolerant of a wide range of salinities and is often observed growing with eelgrass in high saline waters (Stevenson and Confer 1978, Orth *et al*. 1979, Orth and Moore 1981, 1983, Moore *et al.* 2000).

Cumulative submerged aquatic vegetation (SAV) distribution over 10 years (1998-2007). Annual survey data from the SAV Program at VIMS were merged to represent a composite of current potential SAV distribution. Due to SAV light requirements, anticipated decrease in water clarity from climate change, and known current SAV distribution, the SAV habitat zone was conservatively restricted to 0 - 2 meters depth. While precise seagrass responses to sea level rise are uncertain, a 50 cm increase in water depth has been estimated to reduce light penetration to current seagrass beds by 50% which would have significant effects on seagrass growth (Short and Neckles 1999). Additional factors influencing the ability of SAV to migrate inland as existing suitable habitats are altered include substrate type, shore slope and development, tide range, and nutrient enrichment (Stevenson *et al.* 2002, Short and Neckles 1999). Loss of SAV habitat will have cascading effects on the entire Bay ecosystem as numerous species depend on these habitats for refuge and food, including the young of economically important fish and shellfish, such as blue crabs (Lipcius *et al.* 2005).

Currently, seagrass beds have not been observed in 7 Segments: Middle York River (YRKMH), Lower Mattaponi River (MPNOH), Lower Pamunkey River (PMKOH), Upper Pocomoke River (POCOH), Middle Rappahannock River (RPPOH), Elizabeth River (ELIPH), and Laffayette River (LAFMH).

HABITAT MODELS

Future loss of SAV from climate stressors was estimated separately for

1) Eelgrass beds located in polyhaline waters
2) Mixed SAV species occurring in all other salinity regimes (mesohaline – tidal fresh)

1) Eelgrass Beds – Polyhaline Waters

Known habitat criteria for *Zostera marina*, eelgrass, which predominate polyhaline regions in the Bay allowed for the development of projected loss of eelgrass habitat for future scenarios based on modeled changes in SLR and temperature. Increased frequency and duration of high summertime temperatures, in excess of 30°C, has been associated with intensified eelgrass dieback (Moore and Jarvis 2008); therefore, 30°C was used as a critical threshold for eelgrass survival.

Potential loss of eelgrass habitat was determined for predicted future environments based on

a) Sea level rise (S1 and S2)

Habitats with depths > 2m were considered unsuitable for eelgrass survival

b) Increases in summer water temperature at three levels (1, 3 and 6°C)

Areas ≥ 30°C resulted in eelgrass loss

c) Combination of projected SLR and summer water temperature conditions

Greater than 2m depth OR ≥ 30 °C resulted in eelgrass loss

For each future sea level rise scenario and time-step, the area between 0 and 2 m was extracted from the elevation surface and clipped with the composite SAV coverage to produce coverages of remaining SAV after sea level rise events. High water temperature areas (≥ 30°C) were extracted from the interpolated temperature projections (temperature increases by 1, 3 and 6°C) which were converted from raster to polygons. In order to identify SAV habitat areas where the temperature will be ≥ 30°C, the composite coverage of existing SAV was combined (UNION function) with extracted projected areas of high temperature. The combined effect of sea level rise and temperature elevations was examined by the UNION of individual coverages of remaining SAV for each scenario (S1 and S2) and time-step, with extracted areas of high temperature (≥ 30 °C) for each posited level of temperature increase (1, 3 and 6°C).

2) Mixed SAV species – Mesohaline – Tidal Fresh Waters

Unlike high saline waters that are dominated by one or two species (i.e. *Zostera marina* and *Ruppia maritima*), a large number of species are present in brackish and fresh waters. Because habitat suitability requirements vary from species to species it is difficult to model potential future distributions of mixed-species SAV. However, the majority of the species in the Chesapeake Bay are limited to waters < 2m depth due to water clarity requirements for photosynthesis.

Potential loss of SAV habitat in mesohaline – tidal fresh waters was determined for predicted future environments based on sea level rise (S1 and S2). Habitats with projected depths > 2m were considered unsuitable for SAV. For each future sea level rise scenario and time-step, the area between 0 and 2 m was extracted from the elevation surface and clipped with the composite SAV coverage to produce coverages of remaining SAV after sea level rise events. Because temperature requirements are currently unknown for many of the seagrass species, a maximum temperature could not be ascribed as a criterion. While additions and inland shifts in SAV communities cannot be precisely modeled at this time, estimates of the effects of sea level rise to existing SAV can be achieved (i.e. loss of suitable SAV habitat due to increases in water depths above the 2 m threshold).

Model Limitations

SAV projections represent potential loss of currently existing SAV. The model does not estimate SAV migration to new habitats or native species shifts or non-native species invasions from other salinity regimes or environments. Additional research is needed to determine likelihoods of species-specific survival as not only habitats, but also species complexes are altered with climate change. Therefore, projected SAV losses may overestimate the actual future if 1) other native or non-native SAV species are able to migrate and inhabit areas altered by climate change (i.e. withstand high temperatures and/or deeper waters), or 2) SAV can migrate to new shallows (for eelgrass additional requirements are the temperature remains below 30ºC and water clarity is sufficient).

SHIFTS IN SUBMERGED AQUATIC VEGETATION

1) Eelgrass Beds – Polyhaline Waters

Almost half of Virginia's submerged aquatic vegetation is located in polyhaline waters (46.2%) and beds are typically dominated by eelgrass (*Z. marina*). The modeled effect of climate change pressures (sea level & temperature elevation) on the current distribution of eelgrass beds in higher saline waters indicates potentially dramatic losses. For water temperature increases of 1ºC, eelgrass loss (3-80%) was attributable only to sea level rise, since temperatures remained below 30ºC on average. Water temperature increases of 3ºC resulted in moderate-high losses of eelgrass (65-94%) caused by elevation in both temperature and sea level. With temperature increases of 6ºC, all existing eelgrass beds would be lost due to high temperatures, irrespective of sea-level rise (Fig. 14, Table 5). Unless eelgrass beds are able to migrate to shallower reaches with suitable summertime temperatures and water clarity, these critical nursery habitats may be substantially diminished.

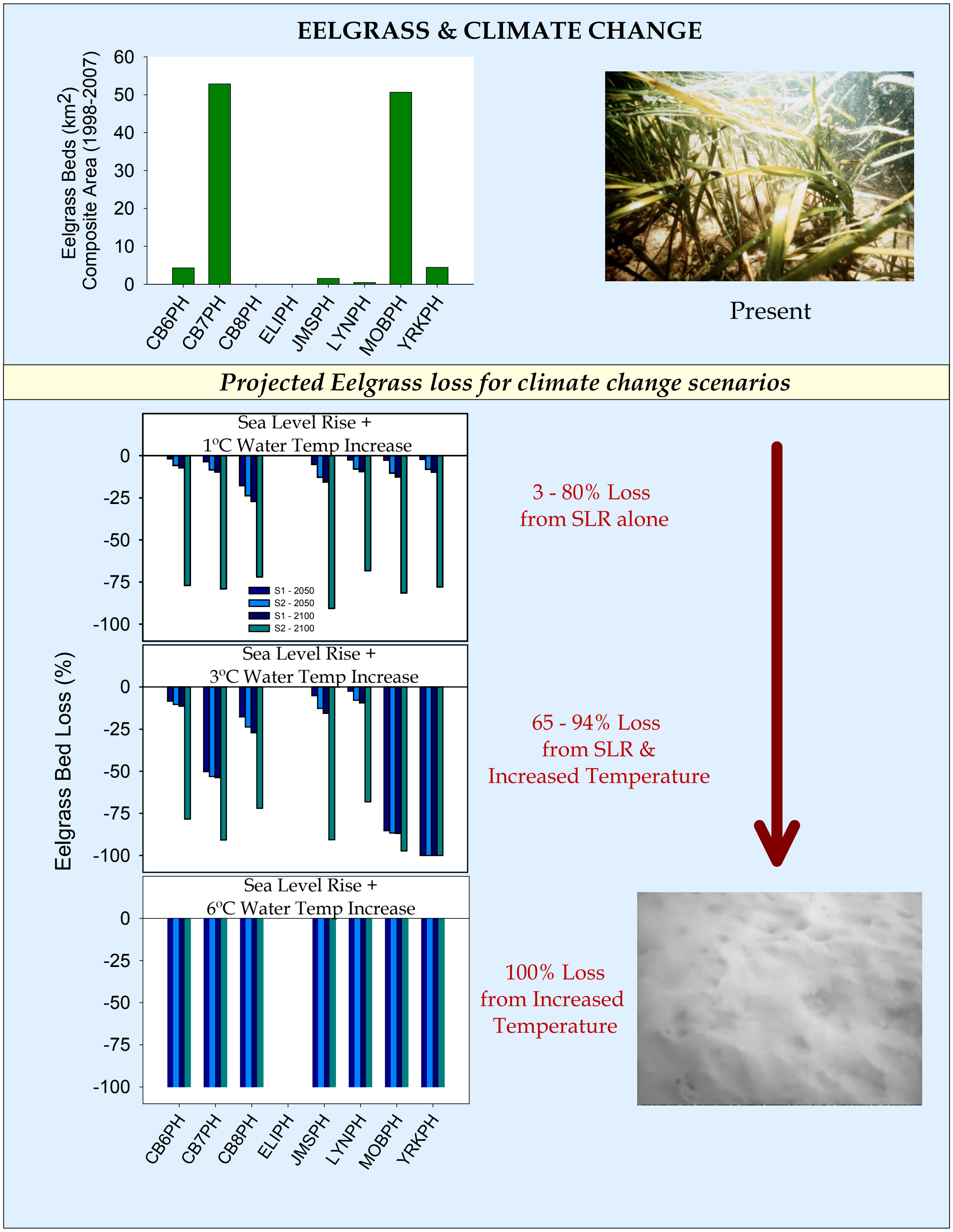


Figure 14. Existing eelgrass beds (upper panel) and shifts in beds by (a) 2050 and (b) 2100 in response to the combined effects of elevated sea level and temperature (2 SLR scenarios & 3 levels of elevated temperature) (lower panel). At 1°C increase, anticipated eelgrass loss is due to SLR alone, 3°C increase with SLR led to 65-94% loss, and 6°C increase eliminated all existing eelgrass beds in polyhaline waters.

Table 5. Projected eelgrass habitat (km^2) and estimated loss (%) in response to elevation in sea-level (S1 and S2) and water temperature (1, 3 and 6ºC). *CBPSEG = Chesapeake Bay Program Segment.*

				Eelgrass Beds - SLR and water temperature + 1°C[a]							
				S1 - 2050		*S1 - 2100*		*S2 - 2050*		*S2 - 2100*	
CBPSEG	**Salinity**	**SAV (km^2)**	**% SAV in VA**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**
CB6PH	PH	4.3	1.7	4.2	(1.8)	4.0	(7.2)	4.0	(5.7)	1.0	(77.1)
CB7PH	PH	52.9	21.4	51.0	(3.5)	47.7	(9.7)	48.4	(8.4)	11.1	(79.1)
CB8PH	PH	0.1	0.0	0.1	(17.8)	0.1	(27.2)	0.1	(23.8)	0.0	(72.0)
JMSPH	PH	1.5	0.6	1.5	(5.2)	1.3	(15.7)	1.3	(12.8)	0.1	(90.6)
LYNPH	PH	0.4	0.2	0.4	(2.5)	0.4	(9.5)	0.4	(7.9)	0.1	(68.2)
MOBPH	PH	50.7	20.5	49.3	(2.6)	44.3	(12.7)	45.4	(10.4)	9.4	(81.5)
YRKPH	PH	4.4	1.8	4.3	(2.2)	4.0	(9.8)	4.1	(8.1)	1.0	(77.9)
TOTAL		***114.3***	***46.2***	***110.8***	***(3.0)***	***101.7***	***(11.0)***	***103.8***	***(9.2)***	***22.7***	***(80.1)***

				Eelgrass Beds - SLR and water temperature + 3°C							
				S1 - 2050		*S1 - 2100*		*S2 - 2050*		*S2 - 2100*	
CBPSEG	**Salinity**	**SAV (km^2)**	**% SAV in VA**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**
CB6PH	PH	4.3	1.7	3.9	(8.4)	3.8	(11.4)	3.8	(10.4)	0.9	(78.4)
CB7PH	PH	52.9	21.4	26.3	(50.2)	24.4	(53.9)	24.8	(53.2)	4.8	(90.9)
CB8PH	PH	0.1	0.0	0.1	(17.8)	0.1	(27.2)	0.1	(23.8)	0.0	(72.0)
JMSPH	PH	1.5	0.6	1.5	(5.2)	1.3	(15.7)	1.3	(12.8)	0.1	(90.6)
LYNPH	PH	0.4	0.2	0.4	(2.5)	0.4	(9.5)	0.4	(7.9)	0.1	(68.2)
MOBPH	PH	50.7	20.5	7.4	(85.3)	6.6	(87.0)	6.7	(86.7)	1.3	(97.3)
YRKPH	PH	4.4	1.8	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
TOTAL		***114.3***	***46.2***	***39.6***	***(65.3)***	***36.5***	***(68.1)***	***37.1***	***(67.5)***	***7.4***	***(93.5)***

				Eelgrass Beds - SLR and water temperature + 6°C[b]							
				S1 - 2050		*S1 - 2100*		*S2 - 2050*		*S2 - 2100*	
CBPSEG	**Salinity**	**SAV (km^2)**	**% SAV in VA**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**
CB6PH	PH	4.3	1.7	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
CB7PH	PH	52.9	21.4	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
CB8PH	PH	0.1	0.0	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
JMSPH	PH	1.5	0.6	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
LYNPH	PH	0.4	0.2	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
MOBPH	PH	50.7	20.5	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
YRKPH	PH	4.4	1.8	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)	0.0	(100.0)
TOTAL		***114.3***	***46.2***	***0.0***	***(100.0)***	***0.0***	***(100.0)***	***0.0***	***(100.0)***	***0.0***	***(100.0)***

[a] *SCENARIO: T +1°C - SAV lost in this scenario is only attributed to SLR*

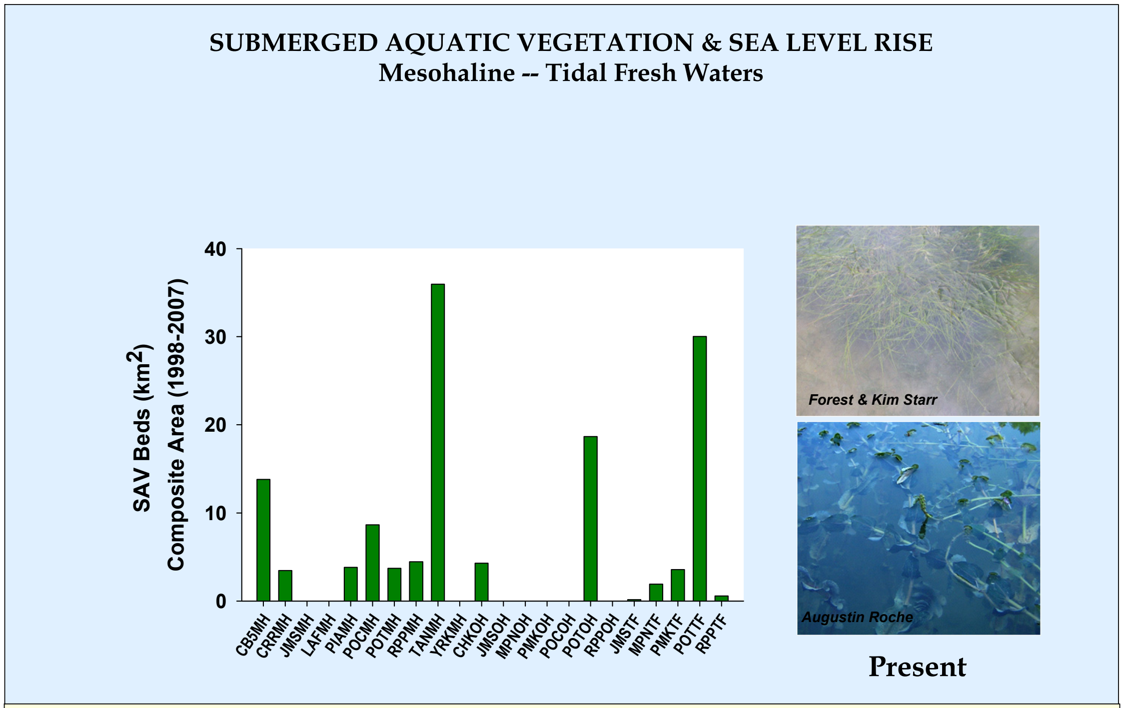
[b] *SCENARIO: T +6°C - All existing SAV beds will be lost under this scenario due to the high temperature that will cover the entire study area*

2) Mixed SAV species – Mesohaline – Tidal Fresh Waters

The majority of mesohaline and tidal fresh waters examined contain SAV, while only a few oligohaline segments have observed beds (~9.3% of Virginia's SAV is in oligohaline waters) (Fig. 15, Table 6). Anticipated SAV loss due to sea level rise ranges from 13-76% for the two climate scenarios (S1 and S2) at 2050 and 2100 (Table 5). The highest initial losses were estimated in tidal fresh systems (~ 28 and 40% loss by 2050 for S1 and S2, respectively). By 2100, oligohaline and tidal fresh were projected to experience similarly high SAV losses (~32 and 82% loss, for S1 and S2, respectively), and mesohaline SAV loss ranged from 17 to 72%. Because SAV species diversity increases as salinity decreases and species habitat requirements vary, there is a possibility that a given species in lower salinity environments may survive or even thrive in projected climate conditions.

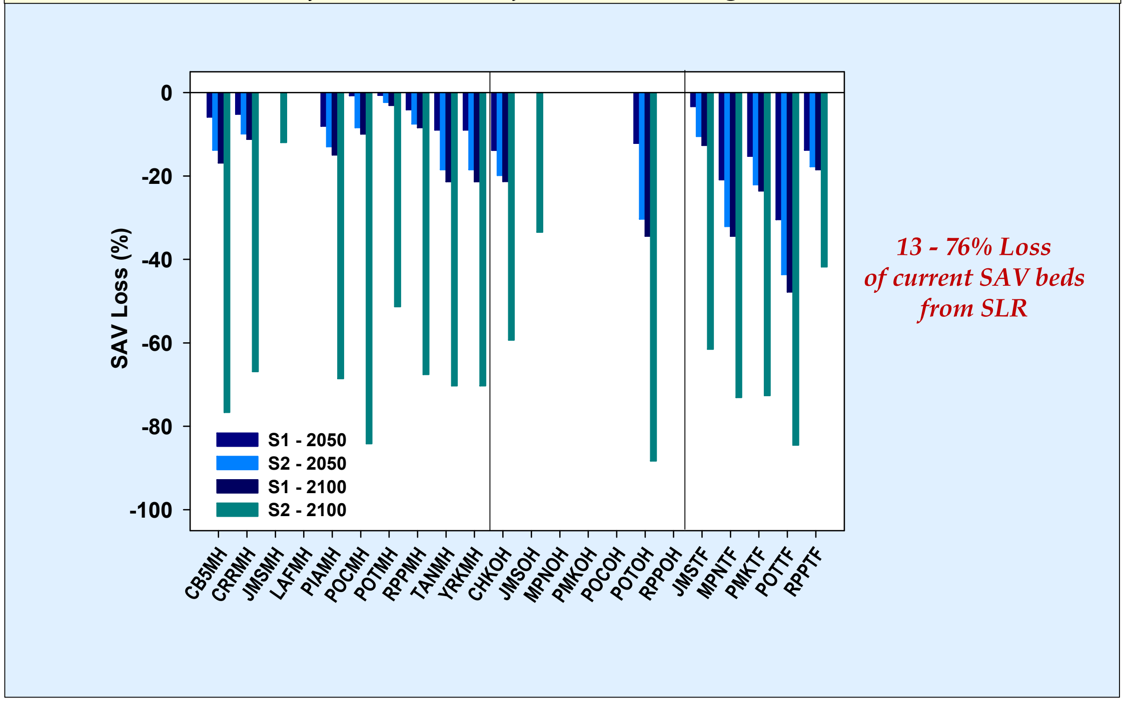
Table 6. Projected SAV habitat (km^2) and estimated loss (%) in response to elevation in sea level (S1 and S2) estimated for 2050 and 2100.

				Mixed SAV Beds - SLR							
				S1 - 2050		*S1 - 2100*		*S2 - 2050*		*S2 - 2100*	
CBPSEG	**Salinity**	**SAV (km^2)**	**% SAV in VA**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**	**km^2**	**% loss**
CB5MH	MH	13.8	5.6	13.0	(5.9)	11.5	(16.9)	11.9	(13.8)	3.2	(76.7)
CRRMH	MH	3.4	1.4	3.3	(5.2)	3.1	(11.2)	3.1	(9.9)	1.1	(66.9)
JMSMH	MH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(12.0)
LAFMH	MH	-	0.0	-	-	-	-	-	-	-	-
PIAMH	MH	3.8	1.5	3.5	(8.1)	3.3	(14.9)	3.3	(13.0)	1.2	(68.6)
POCMH	MH	8.6	3.5	8.6	(0.7)	7.8	(9.9)	7.9	(8.4)	1.4	(84.2)
POTMH	MH	3.7	1.5	3.7	(0.7)	3.6	(3.1)	3.6	(2.3)	1.8	(51.3)
RPPMH	MH	4.5	1.8	4.3	(4.1)	4.1	(8.4)	4.1	(7.5)	1.4	(67.6)
TANMH	MH	36.0	14.5	32.7	(9.0)	28.3	(21.4)	29.3	(18.5)	10.7	(70.3)
YRKMH	MH	0.0	0.0	-	-	-	-	-	-	-	-
CHKOH	OH	4.3	1.7	3.7	(13.8)	3.4	(21.3)	3.4	(19.8)	1.7	(59.3)
JMSOH	OH	0.0	0.0	0.0	0.0	0.0	(0.0)	0.0	0.0	0.0	(33.4)
MPNOH	OH	-	0.0	-	-	-	-	-	-	-	-
PMKOH	OH	-	0.0	-	-	-	-	-	-	-	-
POCOH	OH	-	0.0	-	-	-	-	-	-	-	-
POTOH	OH	18.7	7.5	16.4	(12.2)	12.2	(34.4)	13.0	(30.3)	2.2	(88.3)
RPPOH	OH	-	0.0	-	-	-	-	-	-	-	-
JMSTF	TF	0.1	0.1	0.1	(3.3)	0.1	(12.7)	0.1	(10.5)	0.1	(61.5)
MPNTF	TF	1.9	0.8	1.5	(20.9)	1.3	(34.4)	1.3	(32.1)	0.5	(73.1)
PMKTF	TF	3.6	1.4	3.0	(15.3)	2.7	(23.6)	2.8	(22.1)	1.0	(72.6)
POTTF	TF	30.0	12.1	20.9	(30.4)	15.7	(47.8)	16.9	(43.6)	4.6	(84.5)
RPPTF	TF	0.6	0.2	0.5	(13.8)	0.5	(18.5)	0.5	(17.8)	0.3	(41.8)
All Segments		***133.1***	***53.8***	***115.2***	***(13.4)***	***97.4***	***(26.8)***	***101.4***	***(23.8)***	***31.4***	***(76.4)***


SUBMERGED AQUATIC VEGETATION & SEA LEVEL RISE
Mesohaline -- Tidal Fresh Waters

Present

Projected SAV loss for climate change scenarios



13 - 76% Loss
of current SAV beds
from SLR

Figure 15. Composite SAV bed area (km^2) observed from 1998-2007 (upper panel) in mesohaline to tidal fresh waters, and projected SAV loss for sea level rise scenarios (S1 and S2) at years 2050 and 2100 (lower panel).

TIDAL WETLANDS

TIDAL WETLANDS

Wetlands can be vegetated or non-vegetated. The presence and structure of vegetation is primarily dictated by physical factors such as waterlogged soils, salinity, and exposure. Non-vegetated wetlands include sand and mud flats, which have varying productivity that is partially determined by the character of adjacent habitats. For example, adjacent marshes may provide organic material to mud flat microbial populations which are essential for nutrient cycling in the Bay. Tidal flats, which sustain high abundance of invertebrate prey, are critical foraging areas for migrating shorebirds. Loss of flats could result in habitat limitations for foraging birds leading to reduction in populations (Galbraith *et al.* 2002).

HABITAT MODELS

Future distribution of tidal wetland habitat under climate change pressures was projected for Virginia tidal waters in two primary ways.

The ***first model*** was developed to estimate potential tidal wetland habitat area (inclusive of vegetated and non-vegetated wetlands) in relation to sea level rise and land development.

The ***second model*** assessed the vulnerability of existing tidal marshes to anticipated sea level rise over the next 100 years based on landscape conditions including shoreline and riparian land development.

1) Potential Tidal Wetland Habitat (vegetated & non-vegetated wetlands)

Potential tidal wetland habitat was defined as the area between MLW (mean low water) and the landward elevation at twice the tidal range (MLW to MHW). Existing and projected *Potential tidal wetland habitat* area (based on sea level rise scenarios) was estimated for each Chesapeake Bay segment using 3D Analyst in ArcGIS. Following a similar approach as shallow water habitat models, land use data (CCAP 2005) were examined in relation to newly defined shifts in tidal wetland habitat, since land development has the potential to prevent habitat migration. Using the GIS Identity function which computes a geometric intersection of the input features (land use) and identity features (tidal wetlands); area of development coincident with projected tidal wetland habitat was calculated for each segment. The area of land development (CCAP categories: *Developed – high, medium and low intensity and open space*) that occurred within the projected shift in the tidal wetland habitat zone was then subtracted from projected tidal wetland areas. Again, based on current rates of shoreline and land development, the model likely over-estimates future tidal wetland habitat unless management practices are drastically altered

The habitat zone of tidal wetlands was initially modeled to extend from mean low water to an elevation above MLW equal to 1.5 times the mean tide range which simulates jurisdictional boundaries (Code of Virginia § 28.2-1300). However, upon examination of tidal marshes (TMI) distribution in relation to tidal datums derived from the digital elevation models (using both VBMP and LIDAR), it was observed that wetlands often extended well above that zone (Fig. 16). To accommodate a higher percentage of existing wetlands, the potential wetland habitat zone was extended from mean low water to double the tidal range. Notably, some wetlands still extend above this modeled zone, indicating that wetland habitat limitations should be reexamined especially in reference to jurisdictional boundaries.

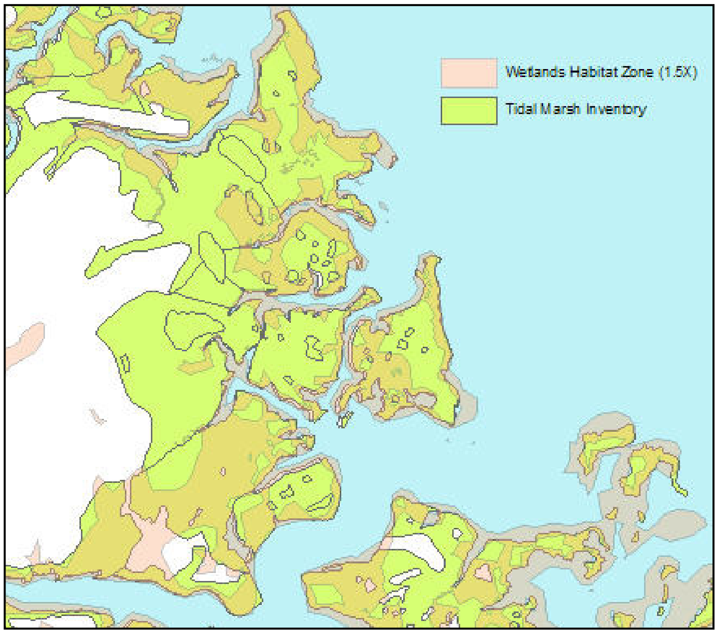


Figure 16. Guinea Marshes, Virginia. Distribution of existing tidal marsh in relation to estimated tidal wetlands habitat zone (1.5 X tidal range). Tidal marsh extends beyond the estimated habitat zone in some locations, indicating wetland jurisdictional boundaries may underestimate tidal wetland habitat.

2) Tidal Marsh Vulnerability (Vegetated Wetlands)

Tidal marsh vulnerability from sea level rise was evaluated in relation to the landscape setting. Lands adjacent or coincident with each tidal marsh (n= 17,093) were examined for the presence of obstacles to landward transgression: 1) shoreline structures (riprap or bulkhead), 2) riparian development (residential, commercial, industrial, or paved), and/or 3) high bank height. Vegetated wetlands within a landscape setting that contains shoreline hardening, upland managed lands, or high bank height are more vulnerable to sea level rise due to their inability to migrate landward. Vegetated wetlands within a landscape setting that contains low bank height, unmanaged uplands and unaltered shoreline have the highest probability of surviving sea level rise through migration and accretion.

- High risk marshes are those entirely adjacent to hardened shoreline, riparian land development (e.g. residential, commercial, industrial, paved) and/or banks > 5 ft in height.

- Moderate risk marshes are those adjacent to mixed land use conditions (e.g. partial association with shoreline hardening or riparian development).

- Low risk marshes are those entirely adjacent to natural lands, a shoreline without structures (riprap or bulkhead), and banks < 5ft

Tidal marsh distribution and areal extent were extracted from the Tidal Marsh Inventory (TMI). The TMI database is a digital compilation of tidal marsh inventories conducted in individual Virginia counties produced by Virginia Institute of Marine Science from 1972 until 1988. Tidal wetlands data were collected through site visits to all tidal marshes in Virginia in conjunction with aerial photography for verification. Digitized marsh polygons are coded for marsh or community type, marsh number, and county location. Individual inventories can be viewed from the webpage http://ccrm.vims.edu/publications/tidal_marsh_inventories.html. Shoreline and riparian characteristics were determined with the VIMS-CCRM comprehensive inventory of shoreline condition (*detailed on p. 5*).

For a small section of the modeled area, shoreline inventory data were not available (Fig. 3). These areas were evaluated based on land use data from the Coastal Change Analysis Program (CCAP 2005). Classification criteria were the proximity to and intensity of upland development (CCAP categories: *Developed – high, medium and low intensity and open space*) surrounding each tidal wetland. A 100 m buffer was delineated around each tidal marsh and marsh vulnerability was categorized based on land use within the buffer (excluding water) (Table 7).

Table 7. Marsh vulnerability classification criteria for reaches without shoreline inventory data. Developed lands were extracted from CCAP (2005) within a 100m buffer of each tidal marsh.

Vulnerability	Criteria
High Risk	> 75% developed lands
Moderate Risk	25 – 75% developed lands
Low Risk	< 25% developed lands

Tidal Wetlands Model Limitations

Tidal wetland sustainability during sea level rise is dependent on the ability of the wetland to vertically accrete and/or horizontally migrate. Vertically accretion, the accumulation of sediment and plant organic matter, equal to or in excess of sea level rise rates allows for the wetland to maintain its position in the landscape. However, vertical accretion rates vary depending on the geomorphic settings, tide and wave energy climates, sediment supply, as well as the plant community structure (Cahoon *et al.* 2009). Since, detailed vertical accretion rates are unknown for the entire study area, and anticipated sea level rise in this region dramatically exceeds historic rates, the assumption was made that wetlands were susceptible to loss (conversion to open water) unless horizontal migration was possible.

The assessment of shifts in wetland distribution was intended to provide landscape-scale estimates of wetland susceptibility to climate change. Model output can be used to determine areas at high risk to wetland habitat conversion, as well as potential opportunities for wetland preservation where upland conditions currently allow transgression. The exclusion of local influences such as current and future vertical accretion rates, sediment supply, and dominant plant species, reduces the reliability of site-specific predictions.

Output from the two tidal wetland models (*Potential Tidal Wetland Habitat* and *Tidal Marsh Vulnerability)* cannot be directly compared due to limitations in the data utilized for the *Potential Tidal Wetland Habitat* areal estimates. The lack of definitive wetland zone boundaries (i.e. MLW to 1.5 X tidal range) and bathymetric data in upstream areas reduced the precision and areal coverage of projected estimates (e.g. headwater areas could not be modeled). The *Tidal Marsh Vulnerability* model assessed all marshes measured in the TMI survey, including upstream areas that could not be modeled for *Potential Tidal Wetland Habitat.* Therefore, in some segments the *Potential Tidal Wetland Habitat* area will appear to be less than the existing vegetated wetland area. *Potential Tidal Wetland Habitat* estimates are most reliable in mainstem and downstream areas with robust bathymetric data (Fig. 7).

SHIFTS IN TIDAL WETLANDS

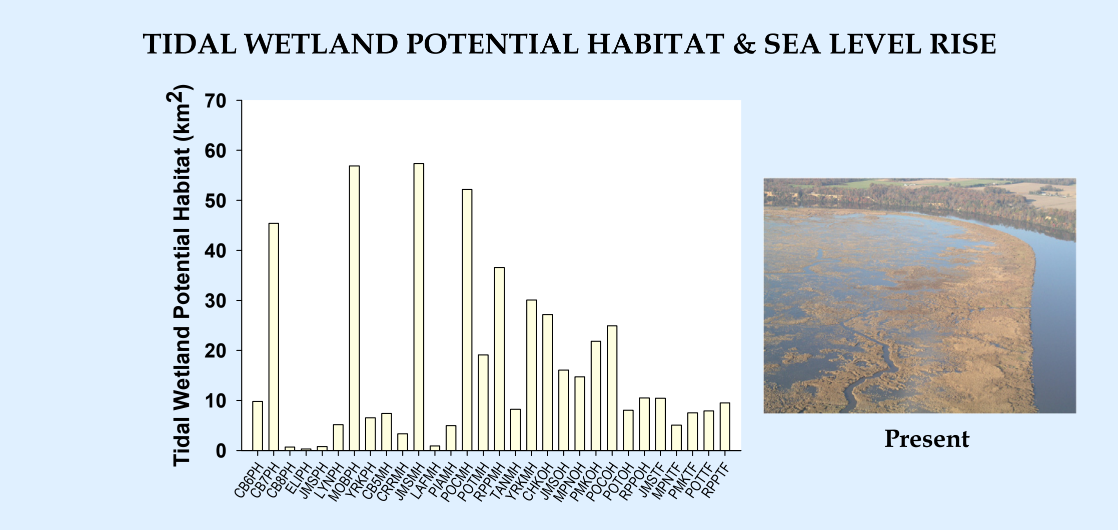
Projected future distribution of tidal wetland habitat in Virginia indicates the potential for relative declines in wetland habitat up to 52%, with tidal marsh habitat in the meso-polyhaline reaches of the Bay at the highest risk due to land development and sea level rise pressures.

1) Potential Tidal Wetland Habitat (vegetated & non-vegetated wetlands)

Potential tidal wetland habitat in Virginia waters were projected to experience overall declines by 12 – 52% under the two SLR scenarios (Table 8). Decreases in habitat occurred in all salinity regimes with the exception of a few select segments (e.g. Mobjack Bay (MOBPH), Piankatank River (PIAMH)) in which increases in potential habitat were modeled where opportunities for wetland landward transgression may exist (Fig. 17, Table 9).

Table 8. *Potential Tidal Wetland Habitat* (includes vegetated and non-vegetated wetlands) under sea level rise scenarios determined by estimating the area between MLW (mean low water) and the elevation at twice the tidal range (MLW to MHW) that does not coincide with developed lands.

Forecast Period	Scenario	Tidal Wetland Habitat (km^2)	Change in TW (km^2)	Change in TW (%)
Today	------	397	--	--
2050	S1	348	(49)	(12)
2050	S2	311	(86)	(22)
2100	S1	302	(95)	(24)
2100	S2	191	(206)	(52)



TIDAL WETLAND POTENTIAL HABITAT & SEA LEVEL RISE

Projected shifts in tidal wetland potential habitat for climate change scenarios

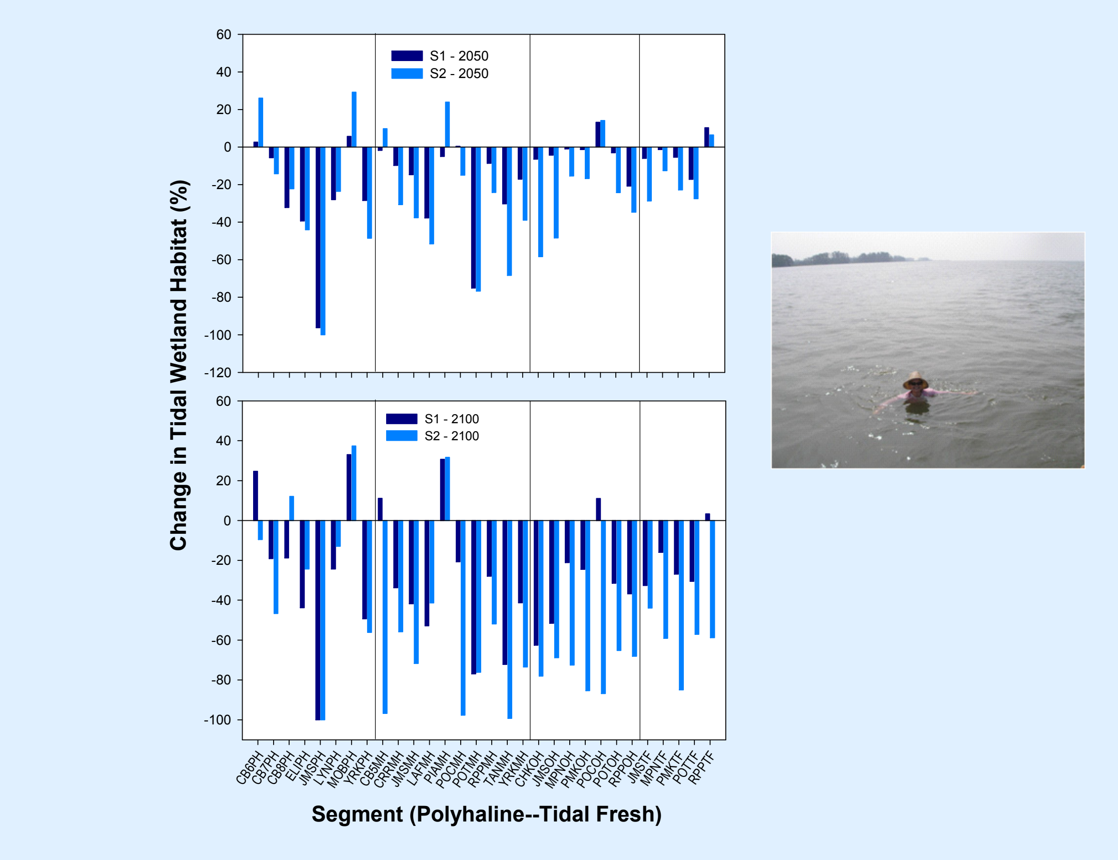


Figure 17. Existing *Potential Tidal Wetland Habitat* (vegetated and non-vegetated) (upper panel) and change in habitat by (a) 2050 and (b) 2100 in response to sea level rise and land development (lower panel). Declines in habitat occurred in all salinity regimes with the exception of a few select segments (e.g. Mobjack Bay (MOBPH), Piankatank River (PIAMH)) where opportunities for wetland landward transgression exist.

Table 9. Projected change in *Potential Tidal Wetland Habitat* based on sea level rise and land development. For some Chesapeake Bay Segments, tidal wetland estimates do not include those habitats located in headwaters. Therefore, in some cases reported areal extent may be underestimated.

CBP	Salinity	Tidal Wetlands Habitat Area (km2)					Change in Tidal Wetland Habitat (%)			
Segment	**Regime**	**Present**	**S1-2050**	**S1-2100**	**S2-2050**	**S2-2100**	**S1-2050**	**S1-2100**	**S2-2050**	**S2-2100**
CB6PH	PH	7.6	7.8	9.5	9.6	6.9	2.7	24.7	26.1	(9.6)
CB7PH	PH	47.0	44.3	38.0	40.3	25.1	(5.7)	(19.2)	(14.2)	(46.6)
CB8PH	PH	2.3	1.5	1.9	1.8	2.6	(32.2)	(18.9)	(22.2)	12.1
ELIPH	PH	1.2	0.8	0.7	0.7	0.9	(39.3)	(43.8)	(44.0)	(24.3)
JMSPH	PH	3.0	0.1	0.0	0.0	0.0	(96.2)	(100.0)	(100.0)	(100.0)
LYNPH	PH	7.2	5.2	5.5	5.5	6.3	(28.0)	(24.4)	(23.6)	(12.9)
MOBPH	PH	51.2	54.1	68.1	66.1	70.3	5.7	33.1	29.2	37.4
YRKPH	PH	5.6	4.0	2.8	2.9	2.4	(28.5)	(49.3)	(48.6)	(56.2)
CB5MH	MH	9.6	9.5	10.7	10.6	0.3	(1.8)	11.2	9.8	(96.8)
CRRMH	MH	2.4	2.2	1.6	1.7	1.1	(9.8)	(33.8)	(30.7)	(55.8)
JMSMH	MH	36.5	31.1	21.2	22.7	10.3	(14.7)	(41.8)	(37.7)	(71.8)
LAFMH	MH	1.6	1.0	0.7	0.8	0.9	(37.8)	(52.8)	(51.6)	(41.4)
PIAMH	MH	5.8	5.5	7.6	7.2	7.7	(5.0)	30.7	23.9	31.7
POCMH	MH	18.9	19.0	15.0	16.0	0.4	0.4	(20.7)	(15.0)	(97.7)
POTMH	MH	32.2	8.0	7.4	7.5	7.7	(75.1)	(77.0)	(76.7)	(76.1)
RPPMH	MH	22.2	20.2	15.9	16.8	10.7	(8.7)	(28.0)	(24.2)	(51.9)
TANMH	MH	17.2	12.0	4.8	5.4	0.1	(30.3)	(72.3)	(68.4)	(99.3)
YRKMH	MH	11.7	9.7	6.8	7.1	3.1	(17.1)	(41.3)	(39.0)	(73.6)
CHKOH	OH	13.1	12.3	4.9	5.5	2.9	(6.4)	(62.6)	(58.4)	(78.1)
JMSOH	OH	15.9	15.2	7.7	8.2	5.0	(4.3)	(51.5)	(48.4)	(68.8)
MPNOH	OH	6.4	6.4	5.1	5.4	1.8	(1.0)	(21.2)	(15.5)	(72.6)
PMKOH	OH	9.5	9.3	7.1	7.9	1.4	(1.4)	(24.6)	(16.8)	(85.4)
POCOH	OH	13.6	15.4	15.1	15.5	1.8	13.3	11.0	14.2	(86.9)
POTOH	OH	3.3	3.2	2.3	2.5	1.2	(3.1)	(31.5)	(24.3)	(65.2)
RPPOH	OH	4.0	3.2	2.5	2.6	1.3	(20.7)	(36.8)	(34.7)	(68.1)
JMSTF	TF	10.9	10.2	7.3	7.8	6.1	(6.1)	(32.7)	(28.8)	(44.0)
MPNTF	TF	7.2	7.1	6.0	6.3	2.9	(1.3)	(16.0)	(12.5)	(59.1)
PMKTF	TF	9.1	8.6	6.6	7.0	1.4	(5.4)	(26.9)	(22.9)	(85.0)
POTTF	TF	7.2	6.0	5.0	5.2	3.1	(17.2)	(30.6)	(27.5)	(57.1)
RPPTF	TF	13.8	15.3	14.3	14.7	5.7	10.4	3.3	6.5	(58.8)
All Segments		**397.3**	**348.2**	**302.2**	**311.3**	**190.7**	**(12.4)**	**(23.9)**	**(21.6)**	**(52.0)**

2) Tidal Marsh Vulnerability (vegetated wetlands)

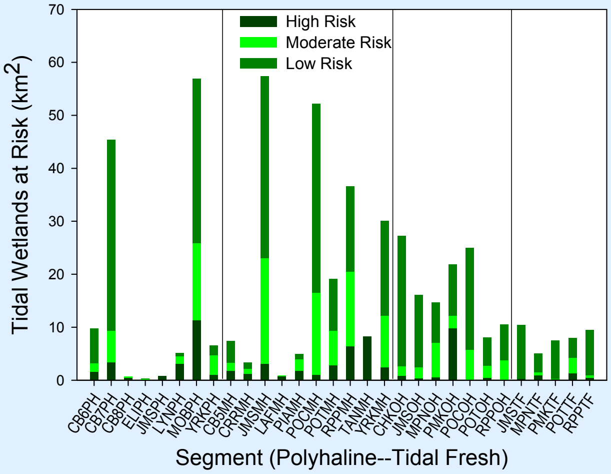
The relative proportion of marshes at high risk was typically highest in meso-polyhaline salinity regimes. High risk indicates no/minimal opportunity to transgress landward in the face of SLR (Fig. 18, Table 10). Although 38% of existing marshes are moderately-highly vulnerable to SLR due to adjacent development, 62% of marshes may have opportunities for landward transgression. Preserving landscapes that allow for the transgression of the Bay's essential shallow-water habitats should be a high conservation priority. The loss of these habitats will significantly alter the character of the Chesapeake Bay from a highly productive shallow-water estuary that provides crucial spawning and nursery habitat for numerous species to a deep open-water system.

Tidal Marsh Shifts Due to Salinity Changes

Tidal freshwater environments are uniquely tidal and fresh, sustaining a species-rich and structurally diverse system (Odum *et al.* 1984, Odum 1988, Perry *et al.* 2009). These systems are highly susceptible to climate change, as a minimal elevation in salinity will dramatically alter the ecosystem structure and function. Tidal freshwater marshes are comprised of plants that are intolerant of sustained saline waters. If average salinity increases, tidal freshwater marshes will likely convert to a brackish marsh community with the possibility of invasion by the aggressive non-native *Phragmites australis*. This could compromise the ecosystem functions of the marsh, as *P. australis* colonization has been documented to reduce plant diversity with yet uncertain ecological consequences (e.g. Chambers *et al.* 1999, Hershner and Havens 2008).

VEGETATED TIDAL WETLANDS & SEA LEVEL RISE

Marsh vulnerability to sea level rise



Total Tidal Wetlands
Evaluated = 510 km^2

Risk Level	Tidal Wetland Habitat at Risk (km^2)	Tidal Wetlands at Risk (%)
High	66.6	13.1
Moderate	126.8	24.9
Low	316.2	62.1

High Risk Marsh

Low Risk Marsh

Figure 18. *Tidal Marsh Vulnerability* from anticipated sea level rise in relation to landscape settings (e.g. developed lands, hardened shoreline). High risk marshes have no/minimal opportunity to transgress landward in the face of SLR. Low risk marshes are associated with unmanaged uplands and unprotected shorelines allowing for preservation of habitat during SLR through landward migration.

Table 10. *Tidal Marsh Vulnerability* to climate change. Estimates based on sea level rise, shoreline hardening, bank conditions, and land development. Approximately 510km^2 of marshes documented in the Tidal Marsh Inventory (TMI, 1972-1988) were evaluated within the study area. Present tidal marsh area may vary due to loss or gain of marsh habitat since inventories were completed.

			Marsh (km^2) Vulnerability			Marsh (%) Vulnerability		
CBP Segment	Salinity Regime	Current Tidal Marshes (km^2)	High Risk	Mod Risk	Low Risk	High Risk	Mod Risk	Low Risk
CB6PH	PH	9.8	1.5	1.7	6.6	15.8	17.2	67.0
CB7PH	PH	45.4	3.4	6.0	36.0	7.5	13.2	79.3
CB8PH	PH	0.7	0.4	0.2	0.0	64.0	35.1	1.0
ELIPH	PH	0.3	0.0	0.2	0.0	12.2	77.8	10.0
JMSPH	PH	0.8	0.8	0.0	0.0	100.0	0.0	0.0
LYNPH	PH	5.2	3.1	1.5	0.6	59.5	28.9	11.6
MOBPH	PH	56.9	11.3	14.5	31.1	19.9	25.4	54.7
YRKPH	PH	6.5	1.1	3.6	1.9	16.6	55.0	28.4
CB5MH	MH	7.4	1.8	1.5	4.1	24.0	20.5	55.6
CRRMH	MH	3.3	1.2	1.0	1.1	36.4	29.2	34.3
JMSMH	MH	57.4	3.1	20.0	34.3	5.3	34.8	59.8
LAFMH	MH	0.9	0.7	0.2	0.0	81.8	17.7	0.5
PIAMH	MH	5.0	1.8	2.2	1.0	36.8	43.9	19.3
POCMH	MH	52.2	1.0	15.5	35.7	1.9	29.7	68.3
POTMH	MH	19.1	2.8	6.5	9.8	14.9	33.8	51.3
RPPMH	MH	36.6	6.4	14.1	16.2	17.4	38.4	44.2
TANMH	MH	8.3	8.3	0.0	0.0	100.0	0.0	0.0
YRKMH	MH	30.1	2.5	9.7	17.9	8.2	32.2	59.6
CHKOH	OH	27.2	0.8	1.8	24.6	2.9	6.6	90.4
JMSOH	OH	16.1	0.3	2.1	13.6	2.1	13.2	84.7
MPNOH	OH	14.7	0.6	6.5	7.6	3.8	44.4	51.8
PMKOH	OH	21.8	9.8	2.3	9.7	45.1	10.6	44.3
POCOH	OH	24.9	0.0	5.7	19.2	0.0	22.9	77.1
POTOH	OH	8.0	0.5	2.2	5.3	6.1	27.5	66.4
RPPOH	OH	10.5	0.1	3.7	6.7	0.9	34.8	64.3
JMSTF	TF	10.5	0.2	0.0	10.2	2.3	0.0	97.6
MPNTF	TF	5.1	1.0	0.6	3.5	19.1	11.6	69.4
PMKTF	TF	7.5	0.2	0.1	7.2	2.4	1.7	95.9
POTTF	TF	7.9	1.3	2.9	3.7	16.8	36.9	46.4
RPPTF	TF	9.5	0.5	0.5	8.5	5.1	5.3	89.6
All Segments		**509.6**	**66.6**	**126.8**	**316.2**	**13.1**	**24.9**	**62.1**

ESTUARINE BEACHES

ESTUARINE BEACH HABITAT

Estuarine beaches support diverse and productive ecosystems at the land-margin. Species groups that utilize this unique estuarine habitat include migratory waterfowl, feeding shorebirds, meiofauna inhabiting the sand substratum, bivalve and snail species, as well as many species of crustaceans, such as isopods and amphipods and beach plants. Beaches also serve as a natural buffer from winds and waves, potentially protecting uplands.

HABITAT MODEL

Beach vulnerability was evaluated based on the assumption that without an enduring sediment source the habitat becomes unsustainable under accelerated sea level rise. Current beach distribution was extracted from VIMS-CCRM Shoreline Inventories and VIMS-Shoreline Studies Program Surveys (Fig. 19). Merging these datasets provided the most comprehensive inventory of beaches within tidal Virginia waters.

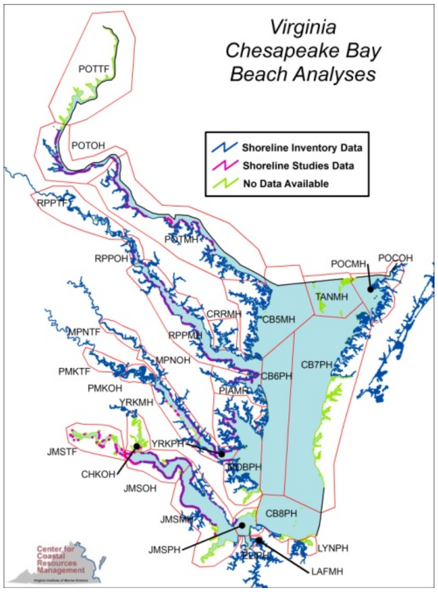


Figure 19. Spatial distribution of beach data sources merged to create a comprehensive dataset of existing beach habitat in Virginia tidal waters.

Each dataset while providing similar positional and size (length) estimates of beaches had different reporting protocols; therefore, criteria for vulnerability assessment varied depending on the source data available for a shoreline reach. When riparian data were available from Shoreline Inventories (VIMS-CCRM), criteria based on land development and bank conditions were applied. The beach dataset was unioned with riparian land use data from the Shoreline Inventory to query adjacent conditions. If riparian data were absent, descriptors of beach stability were extracted from the Shoreline Studies Survey (Table 11).

Beaches considered low risk were coincident or adjacent to erosional banks (sediment source) and unmanaged/agricultural riparian lands (allow migration of beaches landward). Beaches considered to be at high-moderate risk were associated with developed riparian lands and altered shorelines that reduce sediment supply and prevent landward transgression.

Table 11. Estuarine beach vulnerability criteria assessed with shoreline inventory data

Vulnerability	Shoreline Inventory Criteria	Shoreline Studies Survey Criteria
High Risk (Unsustainable)	Associated with developed lands (Industrial, Residential, Commercial, Paved)	*Stability* descriptor = Erosional
Moderate Risk (Unknown)	Associated with unmanaged or agricultural lands and/or are not adjacent or coinciding to an eroding bank	*Stability* descriptor = Stable
Low Risk (Sustainable)	Coincide with or are adjacent to an eroding bank & unmanaged or agricultural lands	*Stability* descriptor = Accretionary or Stable-Accretionary

ESTUARINE BEACH VULNERABILITY MODEL LIMITATIONS

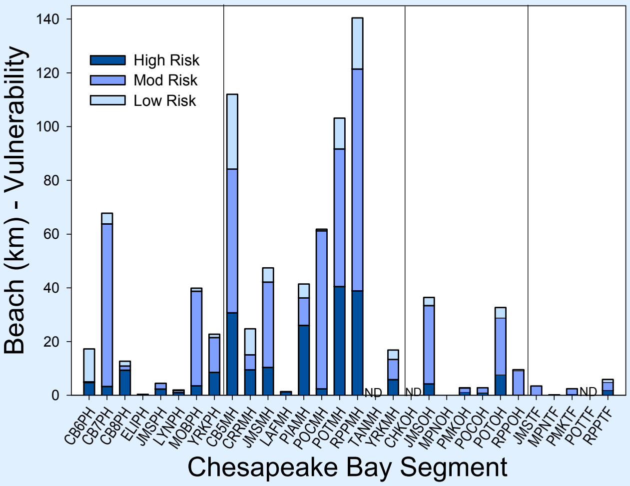
An assumption of the beach vulnerability model was that beaches would not be nourished in the future. Additionally, localized sediment accumulation, storm events or variable fetch were not incorporated into the initial model. Future iterations may include these variables as more data become available on the magnitude and importance of contributing factors at local levels.

SHIFTS IN ESTUARINE BEACHES

Over 7134 km of surveyed shoreline within tidal Virginia, 812 km of beach habitat exists. With the exception of select public beaches, most estuarine beach habitat is not maintained (subsidized with sand) and is subject to sea level rise. The majority of estuarine beach habitat occurs in poly-mesohaline reaches (716 km (88.2%)) (Fig. 20, Table 12). Of existing beaches, ~ 85% are at high-moderate risk from sea level rise (26.5% high risk and 59.8% moderate risk).

BEACHES & SEA LEVEL RISE

Beach vulnerability to sea level rise



Total Beaches
Surveyed = 812 km

Risk Level	Beach Habitat at Risk (km)	Beach Habitat at Risk (%)
High	215.1	26.5
Moderate	485.8	59.8
Low	111.3	13.7

High Risk Beach

Low Risk Beach

Figure 20. Estuarine beach vulnerability to sea level rise. There are approximately 812 km of beach habitat within 7134 km of surveyed shoreline in tidal Virginia. The highest abundance of beaches occurs within mesohaline reaches, and more than 85% of existing beaches are at high-moderate risk to sea level rise.

Table 12. Estuarine beach vulnerability to sea level rise based on developed lands and potential sediment sources.

CBP Segment	Salinity Regime	Current Beaches (km)	Beach (km) Vulnerability			Beach (%) Vulnerability			Incomplete Beach Information
			High Risk	Mod Risk	Low Risk	High Risk	Mod Risk	Low Risk	
CB6PH	PH	17.2	4.7	0.3	12.2	27.4	1.6	71.0	
CB7PH	PH	67.7	3.3	60.5	4.0	4.8	89.3	5.9	*No Data for Northampton County*
CB8PH	PH	12.7	9.3	1.6	1.8	73.7	12.4	13.9	*No Data for Mainstem Chesapeake*
ELIPH	PH	0.3	0.3	0.0	0.0	98.8	1.2	0.0	
JMSPH	PH	4.4	2.3	2.1	0.0	52.0	48.0	0.0	*No Data for Hampton County*
LYNPH	PH	2.0	1.0	0.8	0.1	51.7	41.9	6.5	*No Data for Broadbay*
MOBPH	PH	39.9	3.5	35.3	1.1	8.7	88.4	2.8	*No Data for Hampton County*
YRKPH	PH	22.7	8.5	13.0	1.2	37.2	57.4	5.4	
CB5MH	MH	112.0	30.7	53.5	27.8	27.4	47.7	24.9	
CRRMH	MH	24.7	9.5	5.6	9.7	38.2	22.6	39.1	
JMSMH	MH	47.4	10.3	31.8	5.3	21.8	67.1	11.1	*Incomplete-Suffolk & Isle of Wight Co*
LAFMH	MH	1.4	1.2	0.1	0.0	90.5	9.5	0.0	
PIAMH	MH	41.5	26.0	10.2	5.2	62.7	24.7	12.7	
POCMH	MH	61.8	2.4	58.9	0.5	3.8	95.3	0.9	
POTMH	MH	103.2	40.5	51.2	11.5	39.2	49.6	11.2	
RPPMH	MH	140.4	38.8	82.6	19.0	27.6	58.8	13.5	
TANMH	MH	-	-	-	-	-	-	-	*No Data for segment TANMH*
YRKMH	MH	16.8	5.8	7.5	3.5	34.7	44.4	20.8	
CHKOH	OH	-	-	-	-	-	-	-	*No Data for Chickahominy River*
JMSOH	OH	36.4	4.2	29.1	3.1	11.6	80.0	8.4	
MPNOH	OH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PMKOH	OH	2.8	1.3	1.4	0.1	44.8	51.2	4.0	
POCOH	OH	2.8	1.0	1.8	0.0	35.0	65.0	0.0	
POTOH	OH	32.6	7.7	21.1	3.8	23.7	64.7	11.6	*< 5% incomplete - Prince William Co*
RPPOH	OH	9.5	0.3	8.9	0.4	2.8	93.5	3.7	
JMSTF	TF	3.4	0.0	3.4	0.0	0.0	100.0	0.0	
MPNTF	TF	0.2	0.2	0.0	0.0	100.0	0.0	0.0	
PMKTF	TF	2.4	0.5	2.0	0.0	19.2	80.8	0.0	
POTTF	TF	-	-	-	-	-	-	-	*No Data for segment POTTF*
RPPTF	TF	5.9	1.9	3.0	1.0	32.2	50.8	16.9	
Total		**812.2**	**215.1**	**485.7**	**111.3**	**26.5**	**59.8**	**13.7**	

ADDITIONAL INFORMATION ONLINE

To assist in the identification of coastal habitats at risk or possible conservation targets, select examples of model outputs were highlighted and illustrated for individual Chesapeake Bay Segments.

- Shallow Water and Tidal Wetland Habitat Shifts with Climate Change
- Tidal Marsh Vulnerability
- Estuarine Beach Vulnerability
- Submerged Aquatic Vegetation Shifts with Climate Change
- Developed Lands

Map outputs for each Chesapeake Bay Segment can be viewed digitally on a companion website, and downloaded from associated Map Appendices I-V. Additionally, an interactive map interface served on the webpage allows for the creation of user-specified depictions of existing and future coastal habitat conditions (http://ccrm.vims.edu/research/climate_change/index.html).

All map and model products were not intended for use at the local-level, but to illustrate general trends and conditions across larger spatial scales (i.e. Chesapeake Bay Segment). Once additional high resolution data become available, refinement of estimates and increased precision will become possible for future model iterations.

Example products for each model output are described below.

SHALLOW WATER AND TIDAL WETLAND HABITAT SHIFTS WITH CLIMATE CHANGE

Model output illustrates potential shifts in shallow water and tidal wetland habitat due to sea level rise (Fig. 21). Individual Chesapeake Bay segments are depicted with a relative rise in sea level of 0.6 m by 2050 and 1.6 m by 2100. Estimates of shallow-water and tidal wetland habitat excluded development areas as potential habitat at the Chesapeake Bay Segment level, not the site-level. Therefore, map portrayals do not distinguish areas excluded due to land development and shoreline hardening and likely overestimate the opportunities for retention of shallow-water and tidal wetlands habitat due to landward migration.

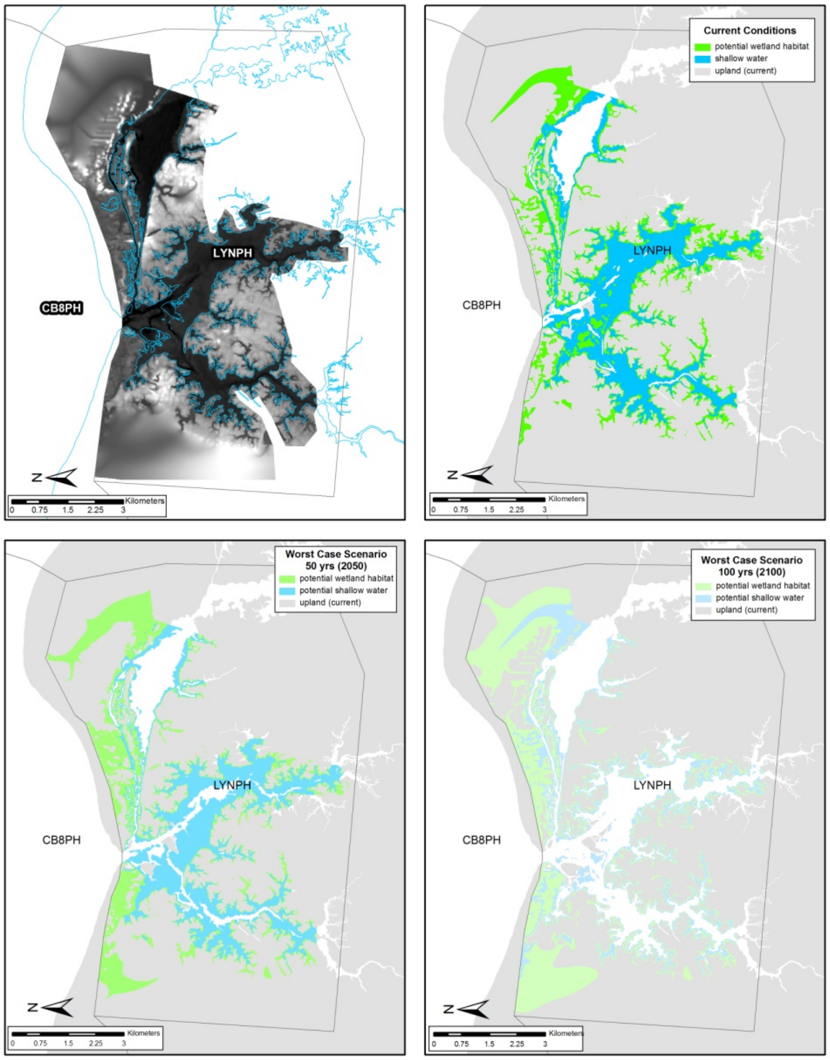


Figure 21. Generalized trends in shallow-water and tidal wetland habitat conversions within Lynnhaven Bay due to sea level rise.

TIDAL MARSH VULNERABILITY

Illustration of landscape settings with the potential to support transgression of tidal marshes in response to sea level rise can assist coastal management goals to preserve ecosystem integrity (Fig. 22). Tidal marshes at high and moderate risk are associated with upland development, shoreline hardening and/or high banks. These marshes will likely drown as sea-level rises and personal properties are protected preventing landward transgression. *Tidal Marsh Preservation Opportunities* represent marshes along estuary reaches that are associated with unmanaged upland and natural shoreline with potential to survive sea level rise by migrating landward. This model output was an initial prioritizing of marsh conservation potential. Future iterations can refine targeting as wetland inventories are updated, accretion rates are defined, and high precision elevation data become available.

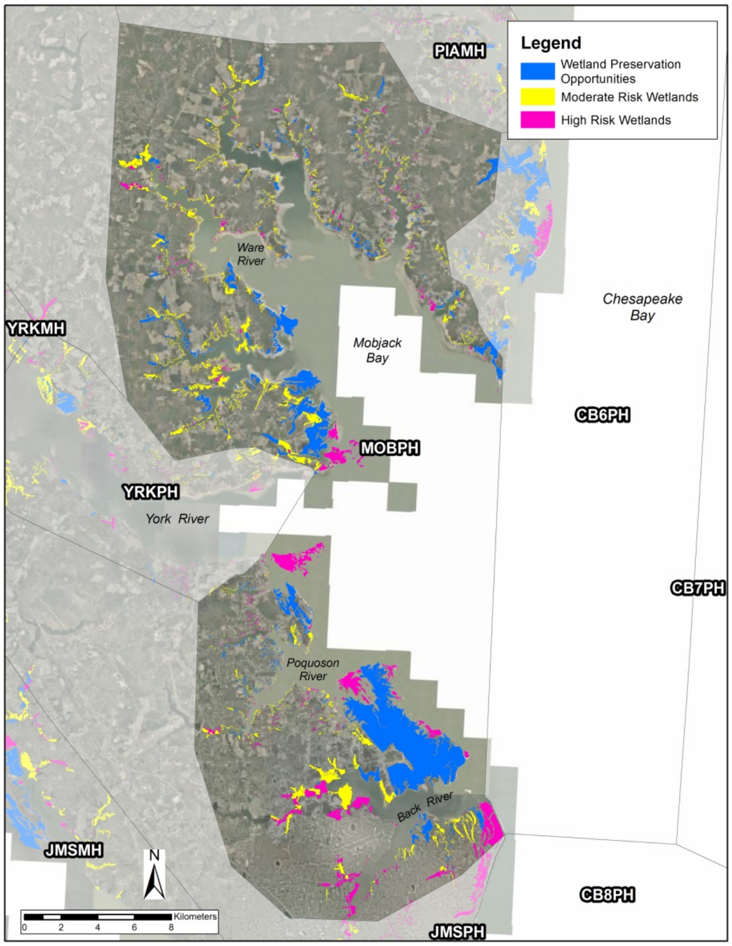


Figure 22. Potential tidal marsh preservation opportunities and marshes at high-moderate risk from sea level rise within Mobjack Bay and Poquoson and Back rivers.

ESTUARINE BEACH VULNERABILITY

Model output depicts the vulnerability of existing estuarine beaches to inundation from projected sea level rise within 50-100 years. Sustainable beaches are associated with potential sediment sources, such as steep eroding banks observed on the Rappahannock River (mesohaline) in McKans Bay. Beaches likely to be unsustainable are associated with hardened shorelines and developed lands which remove sediment sources required to maintain beaches in the long-term (Fig. 23).

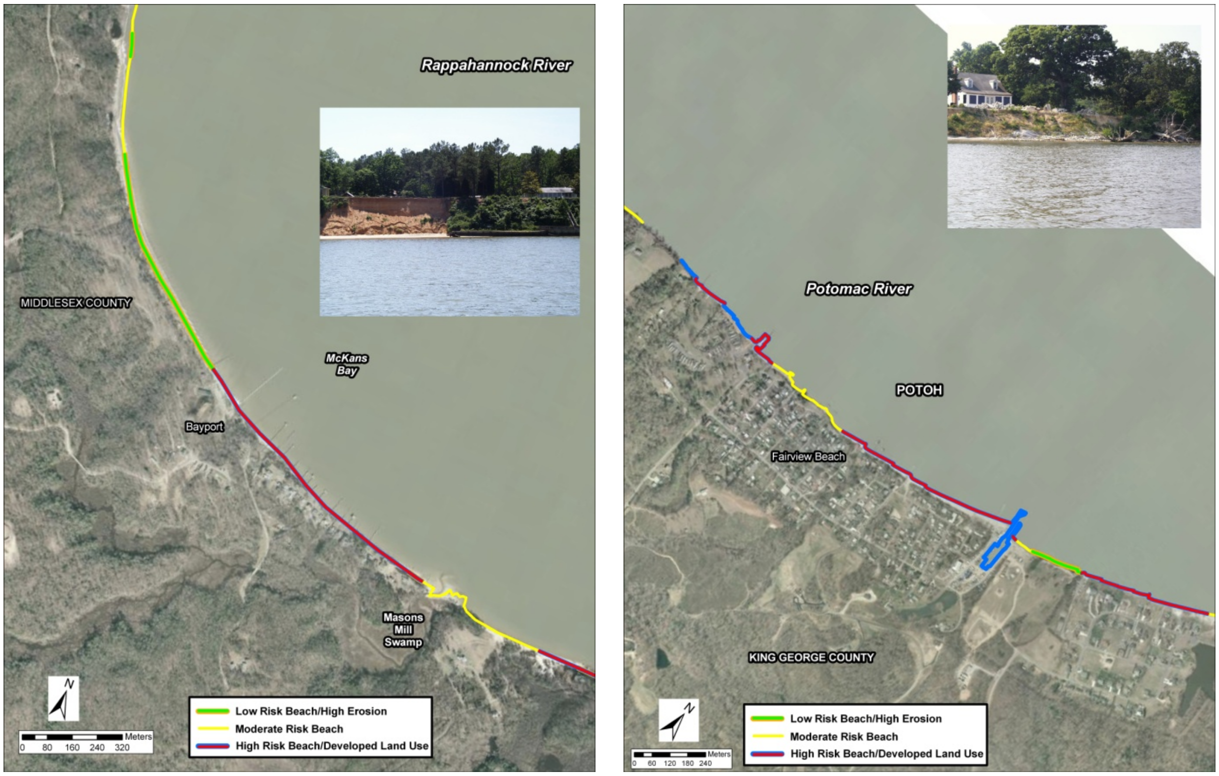


Figure 23. Examples of beach habitat characterization within (a) Rappahannock River-mesohaline, sustainable beaches associated with an existing sediment source (eroding bank); and (b) Potomac River-oligohaline, highly vulnerable beaches associated with shoreline and land development.

SUBMERGED AQUATIC VEGETATION

The potential for reduction of existing SAV beds due to sea level rise and temperature elevation illustrates the extent that present ecosystem will be affected. Individual Chesapeake Bay segments were depicted with a relative rise in sea level of 0.6 m by 2050 and 1.6 m by 2100. SAV beds in polyhaline (PH) segments are predominantly comprised of eelgrass, which have known susceptibility to elevated temperatures. Therefore, polyhaline segment illustrations depict projected loss of eelgrass from the combination of sea level rise and elevated temperature (1, 3 and 6°C). Increases in summertime temperatures of 6°C result in complete loss of eelgrass. Enhanced research is needed on the potential effects of the loss of seagrass bed ecosystems on Bay productivity, as well as the probability that alternate aquatic plant species may provide similar ecosystem functions.

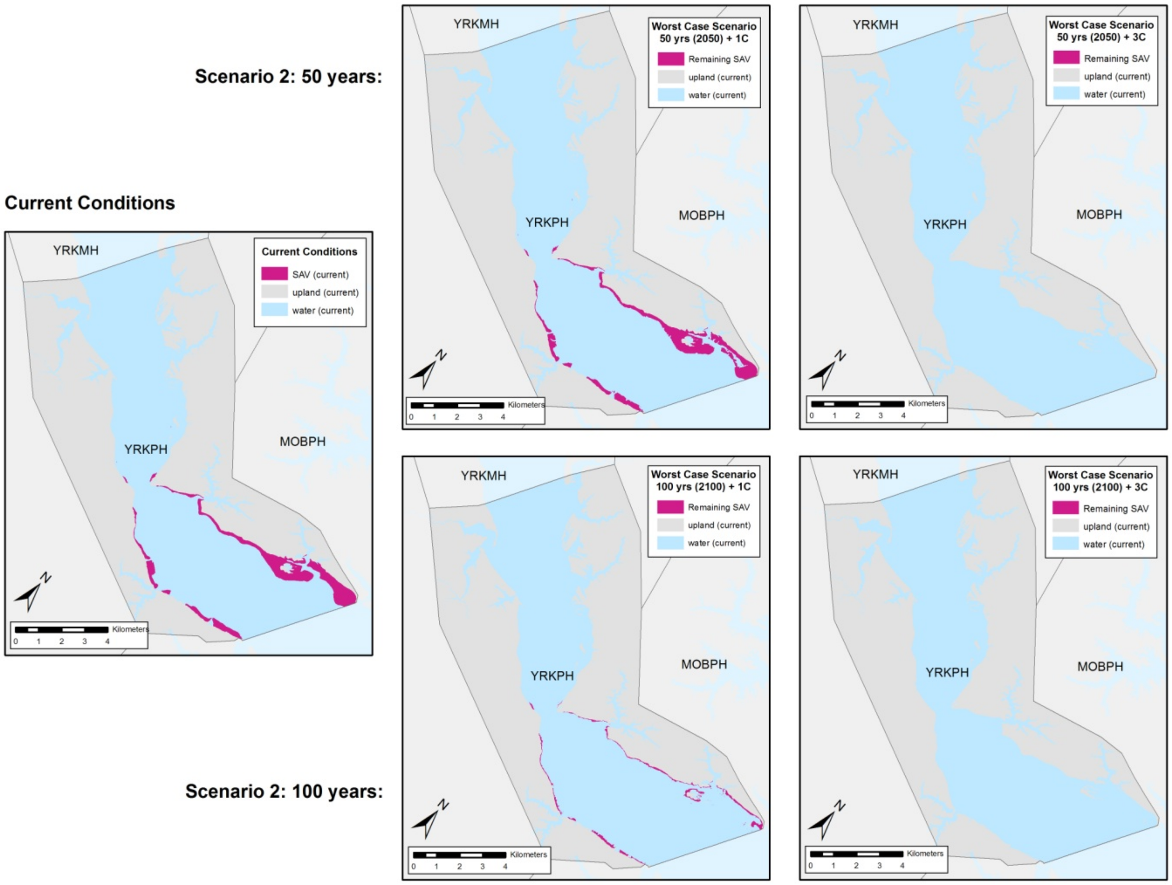


Figure 24. Potential loss of eelgrass beds within the lower York River due to sea level rise and temperature elevation.

VULNERABLE DEVELOPED LANDS

Of economic importance, information on the vulnerability of developed lands within the created elevation surface (within 600 m landward) can be examined for regional trends and areas of concern (Fig. 25). Many low-lying segments are in danger of losing high percentages of infrastructure and residences near the coastline in the next 50-100 years (e.g. Mobjack Bay (51%), Tangier Island (99%), Middle York River (37%)) (Fig. 26).

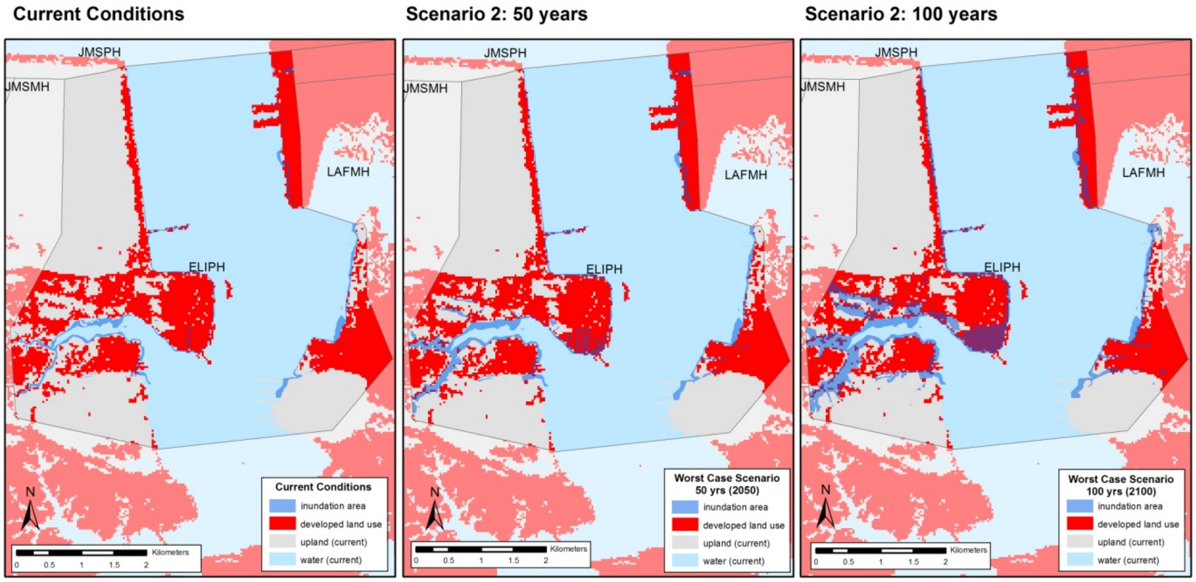


Figure 25. Coastal developed lands vulnerable from sea level rise by the years 2050 and 2100 (7 and 19% vulnerable, respectively) within Elizabeth River.

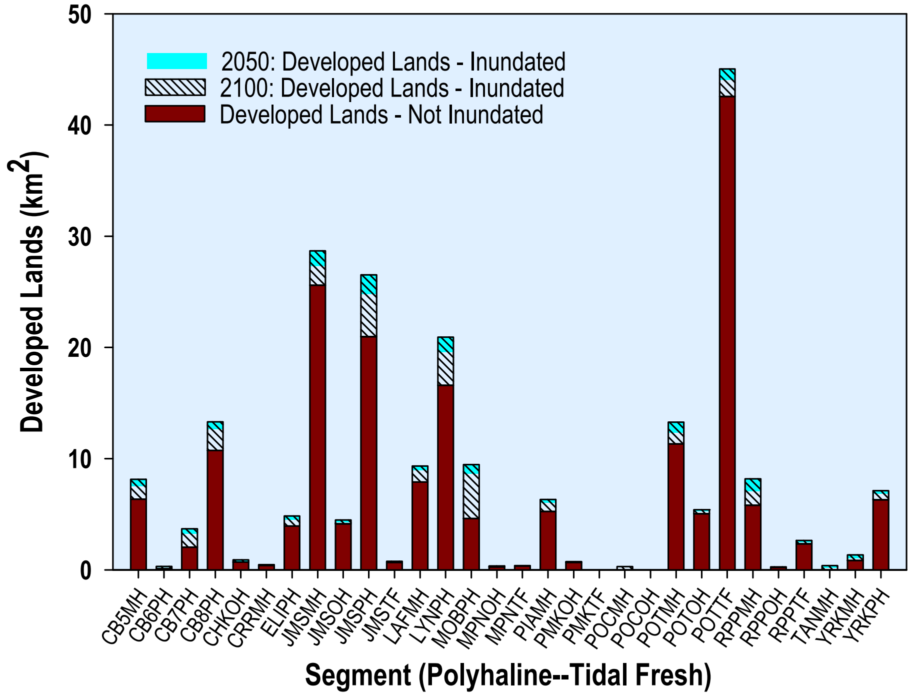


Figure 26. Coastal developed lands vulnerable to inundation by the years 2050 and 2100 for each Chesapeake Bay Segment.

SUMMARY

This effort was an essential first step to enhance understanding of shallow water system responses to climate change. Existing information was integrated with the best current understanding of system processes, to produce a clear and practical assessment of potential futures for Virginia's estuarine shallow water environments.

Several key findings can be incorporated into future strategies

- Within Virginia tidal waters, approximately 11.1% of shoreline has been hardened and 27% of riparian lands are developed. Shoreline hardening continues at an average rate of 29 km/yr. Alternative approaches to erosion control, such as living shorelines, and restricted riparian development will promote ecosystem resilience in the face of sea level rise.

- Coastal habitats were estimated to experience significant reductions under forecasted climate change. Preserving landscapes that allow for the transgression of the Bay's essential shallow-water habitats should be a high conservation priority.

- Data limitations currently prevent precise prediction of sea level rise effects. Effective management of resources is hindered by the lack of high precision bathymetric and topographic data, as well as the need for updated inventories of critical coastal habitats (e.g. tidal wetlands).

- Modeled shifts in coastal habitat features can provide the basis for an ecosystem-based evaluation of ecological consequences of climate change (e.g. effects of tidal marsh loss on fish productivity).

These and similar spatial analyses can be used to inform forward-looking management efforts to identify and protect areas where habitat complexes are most likely to be sustainable, as well as preserve opportunities for migration of habitat elements in an evolving system.

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