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Evolution of Tidal Marsh Distribution under Accelerating Sea Level Rise

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Evolution of tidal marsh distribution under accelerating sea level rise

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Abstract

Tidal marshes are important ecological systems that are responding to sea level rise-driven changes in tidal regimes. Human development along the coastline creates barriers to marsh migration, moderating tidal marsh distributions. This study shows that in the Chesapeake Bay, an estuarine system with geographic and development variability, overall estuarine tidal marshes are projected to decline by approximately half over the next century. Tidal freshwater and oligohaline habitats, which are found in the upper reaches of the estuary and are typically backed by high elevation shorelines are particularly vulnerable. Due to their geological setting, losses of large extents of tidal freshwater habitat seem inevitable under sea level rise. However, in the meso/poly/euhaline zones that (in passive margin estuaries) are typically low relief areas, tidal marshes are capable of undergoing expansion. These areas should be prime management targets to maximize future tidal marsh extent. Redirecting new development to areas above 3m in elevation and actively removing impervious surfaces as they become tidally inundated Results in the maximum sustainability of natural coastal habitats. Under increasing sea levels and flooding, the future of tidal marshes will rely heavily on the policy decisions made, and the balance of human and natural landscapes in the consideration of future development.

Key Words

Tidal marsh; sea level rise; marsh migration; ecological conflicts

1 Introduction

Tidal marsh loss is a significant issue throughout the United States and there is growing concern about accelerating sea level rise and the impact it will have on marsh persistence. Significant marsh loss may dramatically change coastal and estuarine functions and potentially impact global nutrient/biogeochemical cycles (Chmura, 2013; Coverdale et al., 2014). Marsh loss associated with sea level rise, erosion and human activity has been documented throughout the United States (e.g. Nyman et al., 1994; Hartig et al., 2002; Bromberg & Bertness, 2005; Mitchell et al., 2017).

Tidal marsh extents are defined by the interaction of landscape elevations and tidal regime. As sea levels rise and the maximum extent of tidal inundation reaches higher elevations, tidal marshes are induced to migrate inland to maintain their place in the tidal frame. In areas with low coastal elevations, tidal marshes can expand or maintain their size as they migrate across the landscape, resulting in a potential future gain of tidal marshes (e.g., Kirwan et al., 2016). However, in areas with higher elevations or where migration paths are blocked by shoreline structures or impervious surfaces, marsh loss has been documented (Mitchell et al., 2017). Tidal marshes along shorelines with high banks (steep slopes) or stabilized shorelines and those comprising marsh islands have limited migration potential and are at particular risk of reduction under sea level rise. Although elevation is the primary control on marsh migration potential, as marshes migrate inland they also conflict with development, particularly impervious surfaces. This conflict is likely to increase in importance since coastal zones are not only more densely populated than inland areas but also show a trend of increasing population growth and urbanization (Neumann et al., 2015). Within the coastal zone, populations tend to be clustered in the lowest elevation areas (Small & Nicholls, 2003), which are prime areas for marsh migration and expansion. Development patterns in urbanizing areas are a controlling factor in habitat loss (Bierwagen et al., 2010). In coastal areas, future development patterns may intersect with marsh migration corridors, affecting the persistence of tidal marsh ecosystems.

In addition to human land use patterns affecting the expansion of the landward edges of marshes, high erosion rates lead to accelerated seaward edge marsh loss. Shoreline erosion rates are predicted to increase with sea level rise, exacerbating marsh loss (Leatherman et al., 2000). On high energy, moderate gradient slopes, high erosion rates have the potential to outpace landward migration, resulting in shrinking marsh extent. High erosion rates are also associated with proliferation of shoreline stabilization structures designed to protect developed areas but these can actively block marsh migration pathways. Shoreline hardening currently occurs on 14% of the U.S. coastline (Gittman et al., 2015) and in the Chesapeake Bay, approximately 18% of all tidal shorelines are already hardened (Bilkovic & Mitchell, 2017).

The question of future marsh persistence is incomplete without consideration of changes in the types of marsh habitat and their position in the landscape. Many marsh functions (e.g., enhanced shoreline stabilization, Shepard et al., 2011; provision of nekton refuge habitat, Minello et al., 2012) are reliant on a wide-spread distribution of marshes along shorelines, while some (e.g., modifiers of nutrient loads from upland, Valiela & Cole, 2002) require their persistence in the upper portion of the estuary where they can effectively intercept groundwater and overland flow (Arheimer et al., 2004). Furthermore, freshwater marshes support unique floral and faunal communities that are not replicated in higher salinity marshes.

This study uses shorelines from the Virginia portion of the Chesapeake Bay (henceforth “CBVA” as opposed to “Chesapeake Bay” which refers to the entire system) to model potential changes in marsh area, habitat provision and location under accelerating sea level rise. The

Chesapeake Bay is the largest estuary in the United States. Its long, crenulated shoreline means there are marshes of all shapes and sizes along the edges of the Chesapeake Bay and its tributaries. CBVA coastal areas include both rural and highly urbanized waterfronts -and cover a wide range of erosive energy and geomorphic settings (CBVA population is slightly more than 5.5 million people, 86% of which live in one of 2 urban coastal regions; 2017 population statistics, US. Census data). Recent rates from around the Chesapeake Bay are in the range of 4-6 mm/yr (Ezer & Atkinson, 2015; Boon & Mitchell, 2015) exceeding the rate of recent global sea level rise (based on satellite altimetry), which is around 3.2 mm/yr (Church & White, 2011; Ezer, 2013). This extreme rate is attributed to multiple factors including changes in global sea level in combination with regional and local land subsidence (Boon, 2012; Eggleston & Pope, 2013) and shifts in the Gulf Stream Current location and speed (Ezer, 2013). With these high rates of relative sea level rise, and with evidence that those rates are accelerating (Boon & Mitchell, 2015; Boon et al., 2018), the CBVA is a perfect laboratory for investigating the balance between forces affecting tidal marsh persistence into the future.

Sea level rise has led to an increase in flooding (Ezer & Atkinson, 2014; Sweet & Park, 2014) and an interest in flooding adaptations that reduce impacts to human infrastructure. The desire to protect infrastructure from flooding can constrain the potential space for marsh migration, affecting future marsh distributions (e.g., Feagin et al., 2010). To explore the balance between the geographically-controlled capacity of marshes to migrate landward with rising sea levels and the constraints of adjacent human land use, we project the movement of tidal marsh elevations across the landscape under an accelerating sea level rise scenario, allowing examination of how different factors impact future marsh distributions.

2 Data and Methods

The CBVA is generally representative of regional tidal estuaries, containing a diverse array of tidal marsh types and ecologies, geologic settings, and human settlements. The CBVA estuary (Figure 1) consists of the mainstem bay (with long fetches and flat, coastal plain shorelines) and estuarine rivers (with variable topography and fetches). It possesses a wide range of salinities from approximately 35 ppt near the mouth of the CBVA, to 0 ppt in the upper reaches of the estuarine rivers and in the small tributary creeks found along their edges. Currently, there are approximately 761 km^2 of tidal marshes, with a mix of salinity types consisting of about 25% tidal freshwater marsh, 15% oligohaline marshes, 30% brackish and 30% salt marsh (TMI; CCRM, 2017). Marshes are spread extensively along the shoreline, with concentrated pockets of salt marsh areas in some bay-front localities and tidal freshwater marsh areas in the upper tributaries. The tributary rivers split the landscape into four peninsulas, creating corridors of development that expand outward from old harbors. Because of this, areas of concentrated development are predominately in the Hampton Roads region (comprised of Newport News and Hampton on the lower Peninsula, and Norfolk, Virginia Beach, Chesapeake, and Portsmouth on the lower Southside) and the Northern Virginia region (comprised of Alexandria, Arlington, Fairfax, Prince William and Stafford on the upper reaches of the Northern Neck). Future development is expected to continue in these and nearby areas, sprawling north and west in the southern part of the CBVA and south in the northern part of the CBVA (U.S. EPA, 2010).

2.1 Movement of the tidal frame across the landscape

The goal of this project was to look at large patterns of change in marsh extent, location and habitat type and elucidate potential conflict with development. To do this, we used an approach similar to the Sea Level Over Proportional Elevation (SLOPE) model that has been used in the Gulf of Mexico (US) to examine the impact of sea level rise on tidal freshwater forests (Doyle et al. 2010). Because this approach makes no assumption about accretion rates, plant productivity, or erosion activity (all of which exhibit high variability around the CBVA and for which comprehensive datasets do not exist) it is suitable for a broad scale assessment of marsh change.

Modeling of the tidal marsh extent was based on a digital elevation model (DEM) derived from high-resolution, bare earth, lidar data of the CBVA localities (USGS 2010, 2011a, 2011b, 2012, 2013, 2015) using ArcGIS software (ESRI, v 10.4.1). DEM grid cell vertical resolution is 0.15 m and horizontal resolution is 0.76 m.

In this approach, we modeled changes in tidal marsh elevations under sea level rise out to 2100 (Table 1) and used those tidal marsh elevations to delineate the extent of tidal marsh at 0.15 m increments of sea level rise. For each elevation step of 0.15 m, the total area of tidal marsh was calculated for each locality, giving a measure of how tidal marsh distribution is projected to change throughout Virginia, based solely on elevation. For the model, starting tidal marsh elevations were 0 m – 0.61 m NAVD88 (Table 1, Time step 1), which was considered to be the approximate tidal frame for 2010. The model went through 13 steps, to finish with tidal marsh elevations of 1.83 m – 2.44 m NAVD88, projected to occur in approximately 2100.

Vegetated tidal marshes in the CBVA region fall within the elevation range between MSL and HAT. The exact vertical range of the tidal marshes varies somewhat around the estuary, with variations in tidal amplitude. To select an appropriate range for the model, we examined NOAA tide gauge datums at three disparate locations along the estuarine gradient (shown in Fig 1). These tide gauges gave a mean vertical range for tidal marsh elevation of 0.621 m. This was estimated in the model using 0.61 m, since we were constrained by the 0.15 m (precisely 0.1524 m) vertical resolution of the model to a multiple of that value. To test the assumption that a 0.61 m tidal frame is a reasonable approximation of tidal marsh area, predicted 2010 modeled tidal marsh areas (step 1, 0 m – 0.61 m NAVD88) were extracted from 25 subwatersheds along the mainstem York River, VA. These areas were compared to the areas of tidal marshes from a ground-verified, aerial photograph-derived inventory conducted in 2010 in the same watersheds (methods described in Mitchell et al., 2017) using a regression (JMP 10).

Estimates of projected dates for each time range were taken from published data on historic relative sea level trends in at Sewell’s Point, Virginia over the past 50 years (Boon & Mitchell, 2015), extrapolated out to 2100. Years are approximate and estimated from the MSL trend curve. Sea level rise trends vary minimally across the Virginia portion of the Chesapeake Bay (Ezer & Atkinson, 2015) and the resulting estimations of years should be broadly applicable across the modeled region.

Table 1. Scenarios used for analysis with their elevations and approximate time frames (based on Boon & Mitchell, 2015).

Scenario step number	Projected vertical tidal marsh elevations (NAVD88)	Approximate year
1	0 m - 0.61m	2010
2	0.15 m – 0.76 m	2020
3	0.30 m – 0.91 m	2030
4	0.46 m – 1.07 m	2040
5	0.61 m – 1.22 m	2050
6	0.76 m – 1.37 m	2058
7	0.91 m – 1.52 m	2062
8	1.07 m – 1.68 m	2070
9	1.22 m – 1.83 m	2078
10	1.37 m – 1.98 m	2082
11	1.52 m – 2.13 m	2090
12	1.68 m – 2.29 m	2095
13	1.83 m – 2.44 m	2100

2.2 Evaluating the impacts of current and development on tidal wetland migration potential

Developed/impervious areas cannot convert to wetland without either 1) removal of the impervious surface, or 2) significant burial of the impervious surface by sediment. In addition, developed areas have economic value, making them likely areas for protection measures that would prevent wetland migration. To examine the importance of developed areas on future marsh migration capacity, current impervious surfaces that are located in the tidal marsh elevation range were identified at each time step. This gives a “best case scenario”, assuming no future development into coastal areas.

In the analysis, Virginia 1m Land Cover dataset (VGIN, 2016) was used to categorize the type of land in the tidal frame for each step as "Developed (with impervious, turf grass and barren areas) and "Undeveloped" (all other categories, e.g., wetland, pasture, forest, agricultural). Areas of marsh within each category were summed by locality and time period.

2.4 Salinity distribution

Salinity distribution in the CBVA varies seasonally and annually; for a generalized salinity distribution, we used the Chesapeake Bay Program's salinity assignments (shown on Figure 1). No attempt was made to project changes in salinity due to the difficulty of balancing sea level rise-induced upstream salinity migration with the potential increases in river flow due to changing precipitation under current projections.

3 Results

3.1 Tidal marsh frames as an indicator of tidal marsh extent

A comparison of the 2010 modeled tidal marsh areas (step 1, 0 m – 0.61 m NAVD88) with surveyed tidal marshes (digitized from aerial photography and then field-verified; Mitchell et al. 2017) showed that the model effectively identified tidal marshes (Figure 2, R^2=0.89), with overestimation in a few watersheds and minor underestimation in other watersheds.
Examination of mapped extents showed that, in general, the model slightly underestimated marsh extents in extensive marshes. This is not unexpected, since in the York River, HAT is 0.69 m above MSL. This issue should be minimal in the lower parts of the estuary, where the tidal marsh frame is closer to the 0.61 m used in the model. The model also slightly overestimated marsh extents at the tops of some creeks. In these cases, land use frequently indicated that the areas

were treed/forested—suggesting that these might be tidal swamp areas (which would not be captured in the TMI dataset) or forested areas transitioning to tidal marsh.

3.2 Projected changes in marsh area and distribution

In the 2010 tidal frame elevation range there were 850 km^2 of potential tidal marsh in the CBVA. This number declines slowly over time steps to a minimum of 331 km^2 at Time Step 9 (approximately 2078; Figure 3, entire bars). The tidal area then recovers slightly, ending with a net loss of 379 km^2 of tidal marshes in 2130, or 43% of the starting tidal marsh area. Most of the tidal marsh loss will be realized relatively early, by 2050-2080. Following that time period, total tidal marsh extent should remain fairly constant or even expand slightly.

However, the geographic distribution of the marsh area will change over time (Figure 4). In the 2010 time frame (Step 1), 38% of total tidal marsh area is in Accomack and Northampton Counties (composing Virginia's Eastern Shore of the Chesapeake Bay), while only 27% of tidal marshes are found in the Southside region (Norfolk, Chesapeake, Virginia Beach). By the final time step, this has shifted so that the Southside region (particularly Chesapeake and Virginia Beach) has 53% of all tidal marshes, while the Eastern Shore region has only 11% of the remaining tidal marshes. A similar shift in marsh distribution can be seen between the lower and upper parts of the York River (shown in Figure 4 insets). This means that upland areas in localities where marsh expansion is likely are the most critical preservation targets to ensure marsh migration.

3.3 Impervious surfaces in migration pathways

Under current development conditions, 2-36% of the area in each time step's tidal elevation range is developed (Figure 3a, hatched portion of bars). The proportion of developed area in the tidal frame increases over time as the tidal frame migrates upland, limiting the likely area of tidal marsh. The proportion of impervious surface varies by location as well as through time (Figure 5a and b). In the low elevation urban localities (e.g., Hampton), there are ample lands in the future tidal elevation range for marsh migration. However, the majority of those lands are already developed. Only a small fraction of the appropriate elevations are currently natural lands. In the low elevation rural localities (e.g., Mathews), the percentage of impervious surface currently in the projected tidal elevation ranges is low. If future coastal development is discouraged, tidal marsh areas will be essentially consistent over time in these localities.

3.4 Marsh salinity distributions

Concurrent with an overall decline in marsh area, there is an increase in the dominance of salt marsh communities (mesohaline and poly/euhaline areas) and a reduction in the proportion of oligohaline and tidal freshwater marshes (Figure 6). In the first time step (i.e., 2010), 36% of marsh acreage is tidal freshwater/oligohaline, and 64% is salt marsh. By 2050 (step 5), only 23% of the remaining marsh acreage is tidal freshwater/oligohaline, while 76% of marsh acreage is salt marsh. This translates to a greater than 50% loss in both tidal freshwater and oligohaline marsh area compared to current marsh extent. Because this study did not include upstream salinity migration, this shift is entirely driven by the expansion/enhanced persistence of ocean and bay-front marshes (which are dominated by saltmarsh communities) and the loss of tributary marshes (dominated by tidal freshwater and oligohaline marsh communities).

4 Discussion

When planning for the future, it is important to understand the distribution of natural resources, how they will change and which changes will be affected by management decisions. It is clear from this analysis that tidal marsh area in the CBVA will tidal marsh area will decline over time (assuming no vertical accretion and thus inevitable loss of existing wetlands that occur at elevations below future intertidal elevations), and that much of this decline is likely to occur within this century. In addition, there will be shifts in the distribution of tidal marshes leading to an increase in salt marshes and a decline in the oligohaline and tidal freshwater marshes that will alter ecological connections and functions. However, management decisions, particularly in the low elevation areas can maximize future tidal marsh extent. Although this study was conducted in the Virginia portion of the Chesapeake Bay, its results are applicable to many estuarine systems, where elevations rise and salinities decline with distance from the coast.

Our study shows that predicted patterns of future marsh expanse vary spatially with differences in geomorphology and land use (Mitchell et al., 2017). Although, this study shows an overall decrease in tidal marsh extent throughout the CBVA, marsh extents in localities on the main stem of the CBVA will increase. These results are broadly consistent with analyses of historic marsh migration (Schieder et al., 2018), which found significant marsh expansion on lower the main stem of the Chesapeake Bay since the 1800s, but marsh contraction in marshes backed by higher elevations. Lower main stem localities in the Chesapeake Bay have low elevations which provide ample land for marsh expansion, coupled with the currently low human development in many of these areas. Hampton, Norfolk and Virginia Beach are exceptions with their high development, and the cost of this development is evident in the low amount of natural lands available for future marsh migration.

In addition to changes in the distribution of marsh extent, the pattern of topography in the Chesapeake Bay region is predicted to drive a shift in the distribution of marsh ecotypes over time. As bay-front marshes expand, oligohaline and tidal freshwater marshes (particularly those in headwater systems) contract. This is likely to have significant ecological impacts due to a decline in important tidal marsh habitats and a reduced potential for groundwater interception and filtering at the heads of the estuaries as marsh acreage in these areas declines. This study did not attempt to project sea level rise-induced changes in salinity; however, it is important to note that upstream migration of salinity is predicted in the Chesapeake Bay (Hong & Shen, 2012) and that this will further reduce the proportion of tidal freshwater marshes in projected distributions unless increased precipitation is sufficient to counter the salinity migration.

4.1 Interaction of sea level rise, accretion and erosion

Factors not explicitly considered in this analysis that can impact marsh persistence include marsh accretion and erosion rates. These factors could cause the model to over- or underestimate the rate of future marsh changes in locations where they are of importance (e.g., areas of high erosion or large potential sediment loading). Both marsh erosion and accretion rates are known to vary around the Chesapeake Bay; since there are no comprehensive data sets on these rates for CBVA marshes or future projections of how those rates will change under sea level rise, they could not be quantitatively included in the analysis. However, their critical parameters are discussed in this section.

The contribution of marsh accretion to future marsh extent is still an open question. Marsh accretion is a factor of both in situ organic production rates and allocthonous sediment retention. It is the hardest variable to project into the future, since climatic shifts can affect plant productivity (e.g. C3 plant production under increased CO_2; Drake, 2014) and sediment supply (e.g. sediment erosion under increased precipitation intensity; Williams et al. 2017). Marsh plant production rates and local sediment supply are highly variable, but a geographically expansive survey suggests that there is a theoretical limit to sediment accretion of 5 mm yr^{-1}, suggesting that current rates of sea level rise on the Atlantic coast are already at a level that will lead to eventual marsh drowning (Morris et al., 2016). The sea level rise trend in the CBVA over the past 30 years has exceeded 5 mm yr^{-1} (5.86 mm yr^{-1}at the mouth of the Bay; Ezer & Atkinson, 2015) and is predicted to accelerate (Boon & Mitchell, 2015). During the same time period, sediment loads to the Chesapeake Bay (a potential source of allochthonous sediment contribution to marshes) have declined due to management actions (Gellis et al., 2004). Explicit TSS reduction goals for the Chesapeake Bay (http://www.epa.gov/chesapeake-bay-tmdl) are designed to continue aggressive sediment management into the future. These reductions in sediment supply coupled with the predicted acceleration in sea level rise could constrain marsh accretion potential, impacting future marsh persistence. Even in areas with high sediment supply, rates of relative sea level rise above 10.2 mm $yr^{-1}$are predicted to be unsustainable for marshes (Morris et al., 2002). Under current rates of acceleration (0.119 mm yr^{-2}; Boon et al., 2018), relative sea level rise in the CBVA will exceed those values within 60 years. However, previous studies in the Chesapeake Bay have shown a time lag between the time when sea level rise rates exceeded local accretion rates and the subsequent marsh loss (Kearney et al., 2002), suggesting that tidal marsh loss in the next couple decades will be controlled more by erosion rates than drowning due to sea level rise.

It is important to note, that even in a region with high rates of sea level rise and declining sediment supply, such as CBVA, there are marshes where progradation of the shoreline has been observed over the past 30 years (Mitchell et al., 2017). This emphasizes the point that sediment supply can be localized, and in some areas is sufficient to compensate for changes in the tidal frame elevation. Although these marshes are unusual compared to the marshes in the entire study area of Mitchell et al. (2017), it is reasonable to assume that they, and marshes in areas of similarly high sediment supply, will maintain their extent longer than predicted in this study. This is also broadly in agreement with Schieder et al. (2018), which found that some marshes in the upper tributaries contracted and some expanded over the historic period studied.

Erosion rates are highly variable along CBVA shorelines, even sometimes within close geographic proximity. Although relatively stable over the past 60 year (Kirwan et al., 2016), erosion rates are predicted to increase with accelerating sea level rise, potentially resulting in huge coastal losses (Leatherman et al., 2000; Mariotti & Fagherazzi, 2010). On average, localities on the main stem of the CBVA experience low to moderate (0.3-1.5m yr^{-1}) erosion on 30% of their shorelines (Milligan et al., 2012). Exceptions are heavily stabilized shorelines such as those in Norfolk. Main stem CBVA marshes are considered one of the more stable CBVA shoreline environments, eroding at 0.54 – 0.66 m yr^{-1}, depending on the underlying substrate

(Rosen, 1980). Rates on the tributaries are generally lower (e.g., York River marshes are eroding at 0.21 m yr^{-1}; Byrne & Anderson, 1978) and erosion in the creeks is generally negligible. Given these rates, the marshes where erosion rates will most affect marsh acreage are located in the same localities where much of the marsh expansion is projected (e.g., Gloucester, Mathews). The balance between marsh erosion and marsh migration will vary over time depending on their relative trends (i.e., linear vs. accelerating rise), and the impact to marsh acreage will be highly dependent on the slope of the shoreline (Figure 7). However, it is expected that erosion will result in the loss of some of the projected marsh acreage; therefore, the numbers in the study may be overestimating future marsh extent, particularly where there are narrow, fringing marshes that could erode before having the opportunity to migrate significantly.

Shoreline stabilization placed at the front edge of a marsh will reduce or eliminate erosion, while allowing marsh migration. However, where shoreline stabilization is placed landward of the marsh, erosion of the marsh will continue while marsh migration will be blocked until the elevation of the stabilizing structure is topped. This may lead to a temporary loss of marsh in heavily stabilized areas, even with low gradient shorelines, or longer-term loss if stabilization structures are tall. Tidal marshes should re-establish following overtopping of stabilization structures by the tidal frame, but the ecological structure and ecosystem services associated with those marshes may be difficult to re-establish, particularly if the new plant community differs from the original.

4.2 Management Implications

Maximizing future tidal marsh extent will require prioritization of undeveloped land preservation in low elevation lands contiguous to the shoreline. A clear policy consideration resulting from this study is that a uniform state-wide management policy will not maximize future tidal marsh extent unless that policy is specifically tied to elevations (e.g., minimizing development in lands below 0.91 m (3 ft) NAVD88). In localities with shallow shoreline elevation gradients, passive measures (such as the preservation of undeveloped lands) can be a powerful management action, assuming that extensive undeveloped lands exist. However, in localities with steep shoreline gradients, tidal marsh persistence will require more active measures and may eventually be futile. Active management in these areas may include the construction of "living shorelines" to replace or expand dwindling marsh extents or thin-layer deposition to help existing marshes maintain their elevation in relative to rising sea level (Wigand et al., 2017).

In highly developed/urban areas, tidal marshes may be of particular ecological importance since they are often scarce and therefore the remaining marshes represent critical refuges for faunal marsh residents. In the Chesapeake Bay, many of the localities with shallow shoreline elevation gradients are also highly urbanized and expanding. In these localities, tidal marshes have the capacity to expand and become less fragmented under sea level rise. However, that endpoint requires aggressive preservation of remaining undeveloped lands in tidal marsh migration corridors and consideration of the active removal of impervious surfaces as they become inundated to allow marsh development. This type of activity is contrary to the actions taken by many urban areas under pressure from flooding and sea level rise. Rising water levels are frequently met with shoreline hardening and coastal barriers, which can preserve or improve property values (Jin et al., 2015). Less frequently used, managed retreat/realignment and rolling easements, where development is gradually moved out of the water's path, is the adaptation that is most in line with the goal of maximizing future tidal marsh extents. However, this option is challenging to implement and requires collaboration between property owners and all levels of government to align private and public economic and resiliency goals. Other adaptations that allow a balance between protection of human infrastructure and tidal marshes include storm surge barriers (which allow natural tidal action except during storm events) and the use of natural features (such as beach nourishment or marsh creation) to alleviate storm-associated flooding.

5 Conclusions

Overall, tidal marsh extent is predicted to decline significantly in the Chesapeake Bay over the next 50-60 years due to sea level rise. However, the future distribution of tidal marsh complexes depends on their location within the geological and human landscape. In low elevation areas, significant marsh expansion is possible. While in urbanized areas, rising sea levels and increased flooding will create additional pressures to shoreline ecosystems, and may conflict with local efforts to protect their infrastructure. Where low elevation areas overlap with urban shorelines, current and future policy decisions will be a critical determinant of future tidal marsh extent.

The future of tidal marsh complexes is highly dependent on their location within the geological (elevation) and human (impervious surface) landscape. Not all areas of the Chesapeake Bay have land elevations suitable for marsh retreat/migration. Low salinity areas, where fresh and oligohaline marshes are found, are particularly likely to sustain substantial marsh losses in the future. The loss of marsh extent from these locations have the potential to impact the entire estuarine ecology. These losses will be difficult to mitigate, so it is important to understand the greater ramifications of this change.

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Figures

Figure 1. Virginia portion of the Chesapeake Bay (referred to in the text as "CBVA"). Localities are labeled. Approximate split between fresh and brackish water is shown.

Figure 2. Comparison of predicted marsh area to field-verified marsh area (m^2) in 25 subwatersheds on the mainstem York River, VA.

Figure 3. Predicted changes in area (m^2) within the tidal marsh elevation frame over time. Scenario steps are 0.61m in range and move up 0.15m in elevation with each step. The time steps can be related to sea level rise projections using the information in Table 1. Solid portions of the bars indicate areas that are pervious (natural lands) in the projected tidal elevations. Hatched portions of the bars indicate areas that are currently impervious surfaces. These areas would have to be remediated to allow tidal marshes to establish through migration.

Figure 4. Changing distribution of marshes in Chesapeake Bay, VA between current tidal envelope and predicted tidal envelope for 2100. Insets show two areas with different prognosis based on elevation.

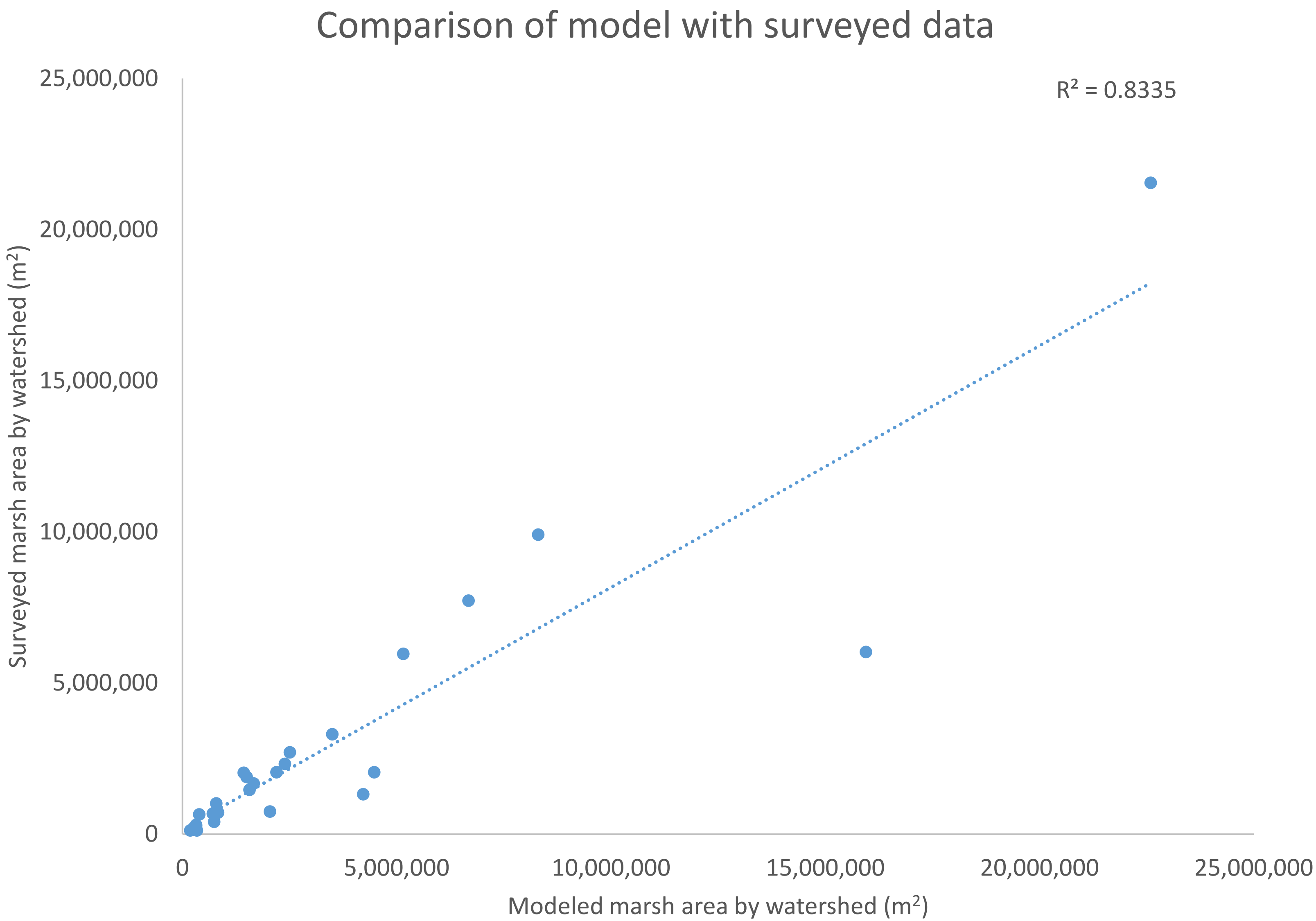
Figure 5. Total projected marsh area over time in two low elevation localities (a) Hampton (urban) and (b) Mathews (rural). Solid portions of the bars indicate areas that are pervious (natural lands) in the projected tidal elevations. Hatched portions of the bars indicate areas that are currently impervious surfaces. These areas would have to be remediated to allow tidal marshes to establish through migration. Scenario steps are 0.61m in range and move up 0.15m in

elevation with each step. The time steps can be related to sea level rise projections using the information in Table 1.

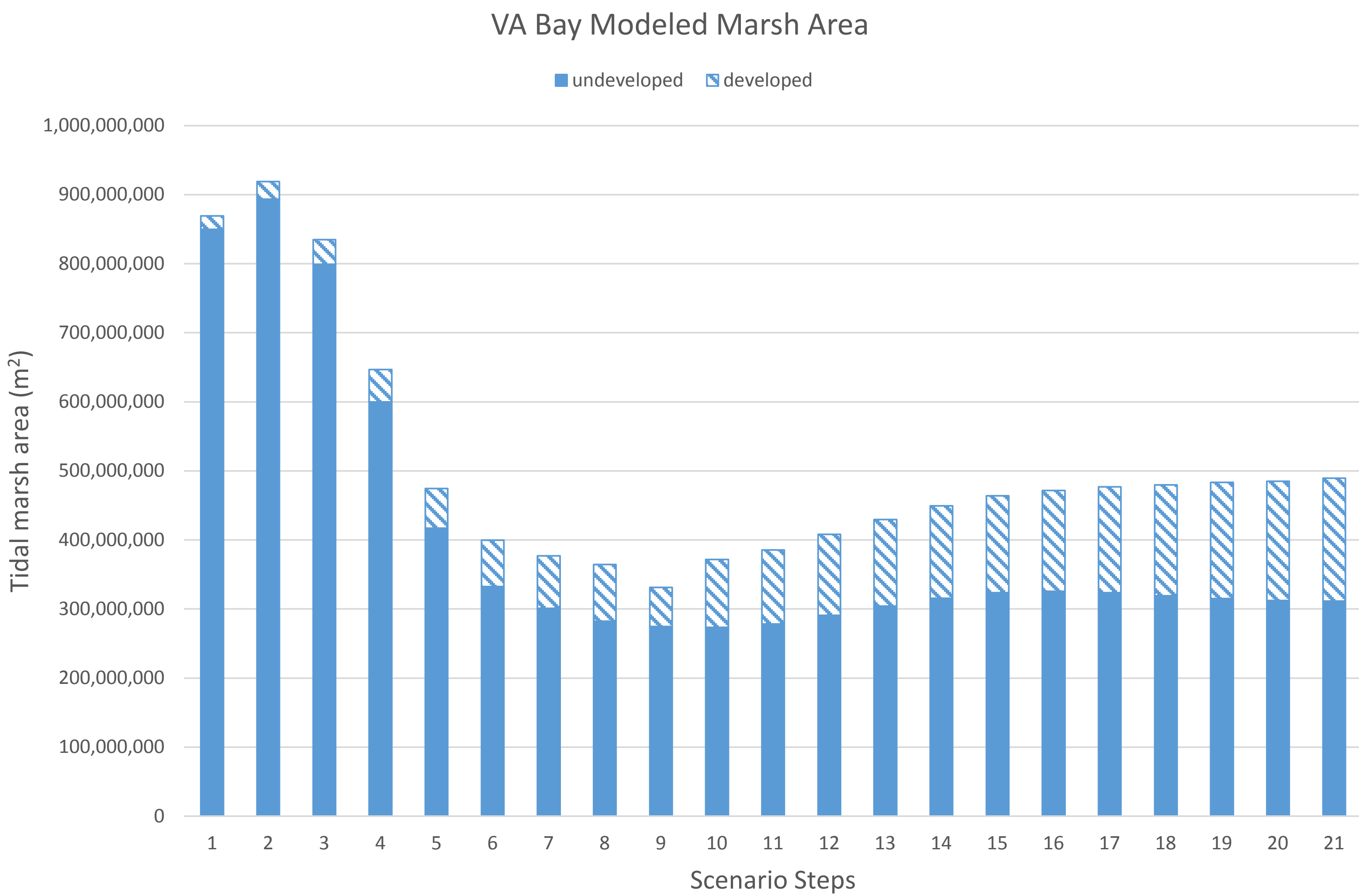
Figure 6. Projected changes in marsh area by salinity type over time. Scenario steps are 0.61m in range and move up 0.15m in elevation with each step. The time steps can be related to sea level rise projections using the information in Table 1.

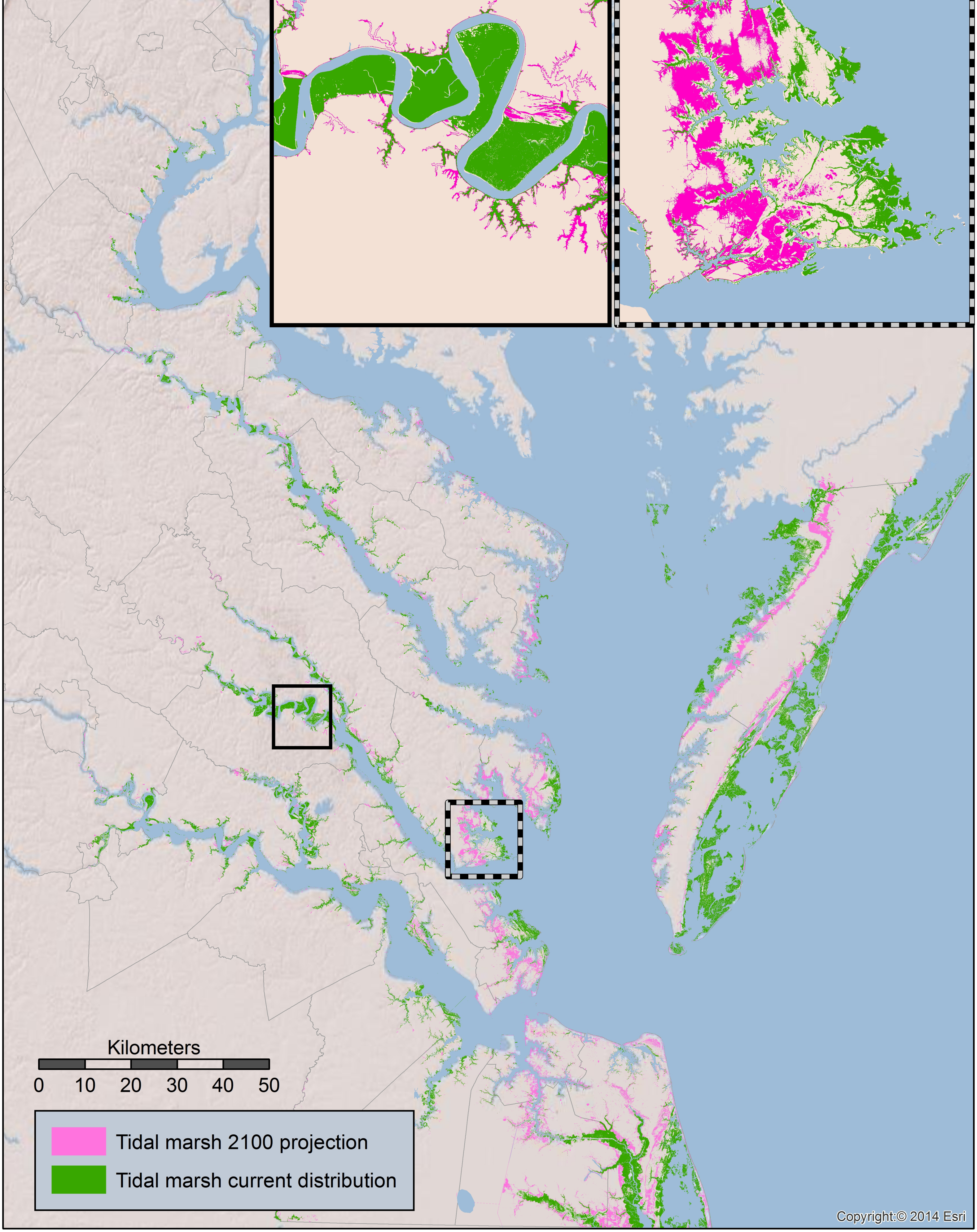
Figure 7. A conceptual graph showing the importance of slope in determining the dominant process determining affecting marsh size over time. The figure considers the balance between steady erosion and accelerating sea level rise-driven marsh migration. This figure assumes a steady erosion rate of 0.6 m yr^{-1} (Rosen 1980) and a sea level rise rate of 5.11 mm yr^{-1}, accelerating at 0.0169 mm yr^{-2} (Boon and Mitchell 2015). On steep slopes, erosion is the dominant force controlling marsh change; however, on gradual slopes, migration becomes the dominant force as sea level rise acceleration increases rise rates.

Loudoun
Arlington
Alexandria
Fairfax
Prince William
Stafford
King George
Spotsylvania
Westmoreland
Caroline
Richmond
Northumberland
Essex
Hanover
King William
King and Queen
Lancaster
Middlesex
New Kent
Henrico
Gloucester
Mathews
Chesterfield
Charles City
James City
Northampton
Accomack
Chesapeake Bay
Petersburg
Prince George
York
Poquoson
Newport News
Dinwiddie
Surry
Hampton
Norfolk
Isle of Wight
Portsmouth
Virginia Beach
Suffolk
Chesapeake
New Jersey
Maryland
West Virginia
District of Columbia
Delaware
Virginia
ATLANTIC OCEAN
North Carolina
Copyright:© 2014 Esri
Coastal localities
Salinity zone
tidal fresh
oligohaline
mesohaline
polyhaline or euhaline
Kilometers
0 10 20 30 40 50
Copyright:© 2014 Esri

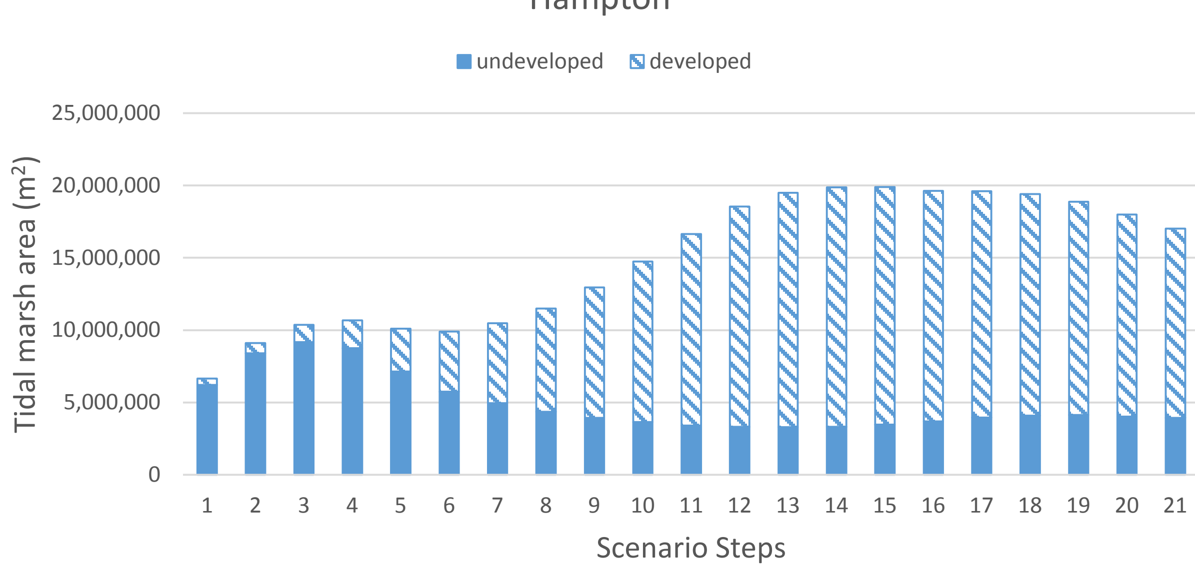


Comparison of model with surveyed data
R² = 0.8335
25,000,000
20,000,000
15,000,000
10,000,000
5,000,000
0
Surveyed marsh area by watershed (m²)
0
5,000,000
10,000,000
15,000,000
20,000,000
25,000,000
Modeled marsh area by watershed (m²)

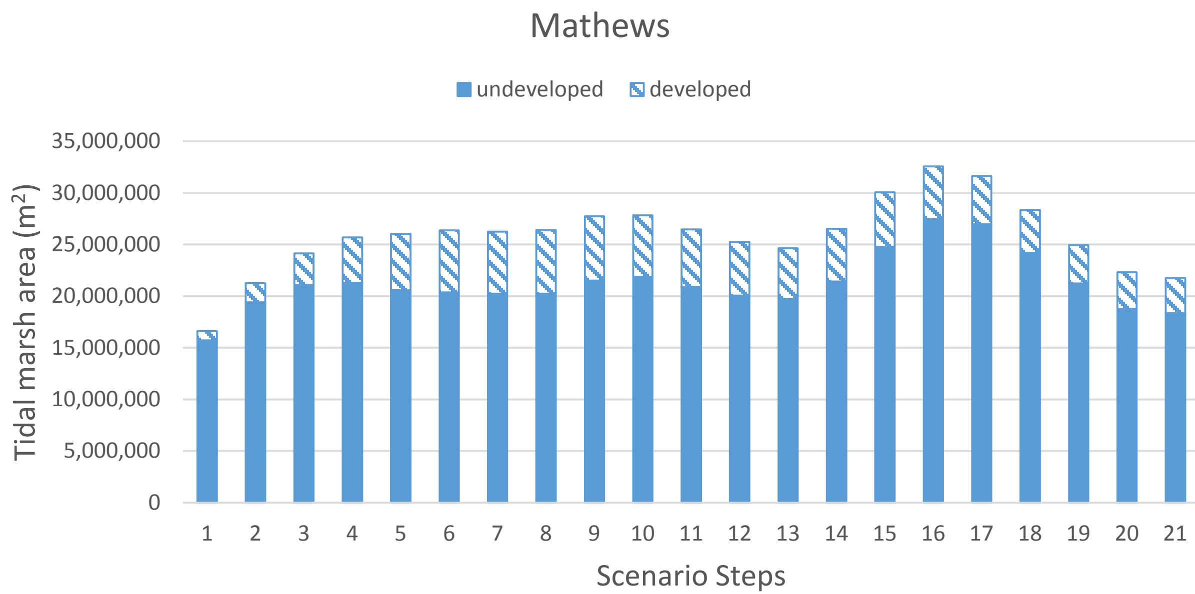

VA Bay Modeled Marsh Area
undeveloped
developed
Tidal marsh area (m2)
1,000,000,000
900,000,000
800,000,000
700,000,000
600,000,000
500,000,000
400,000,000
300,000,000
200,000,000
100,000,000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Scenario Steps

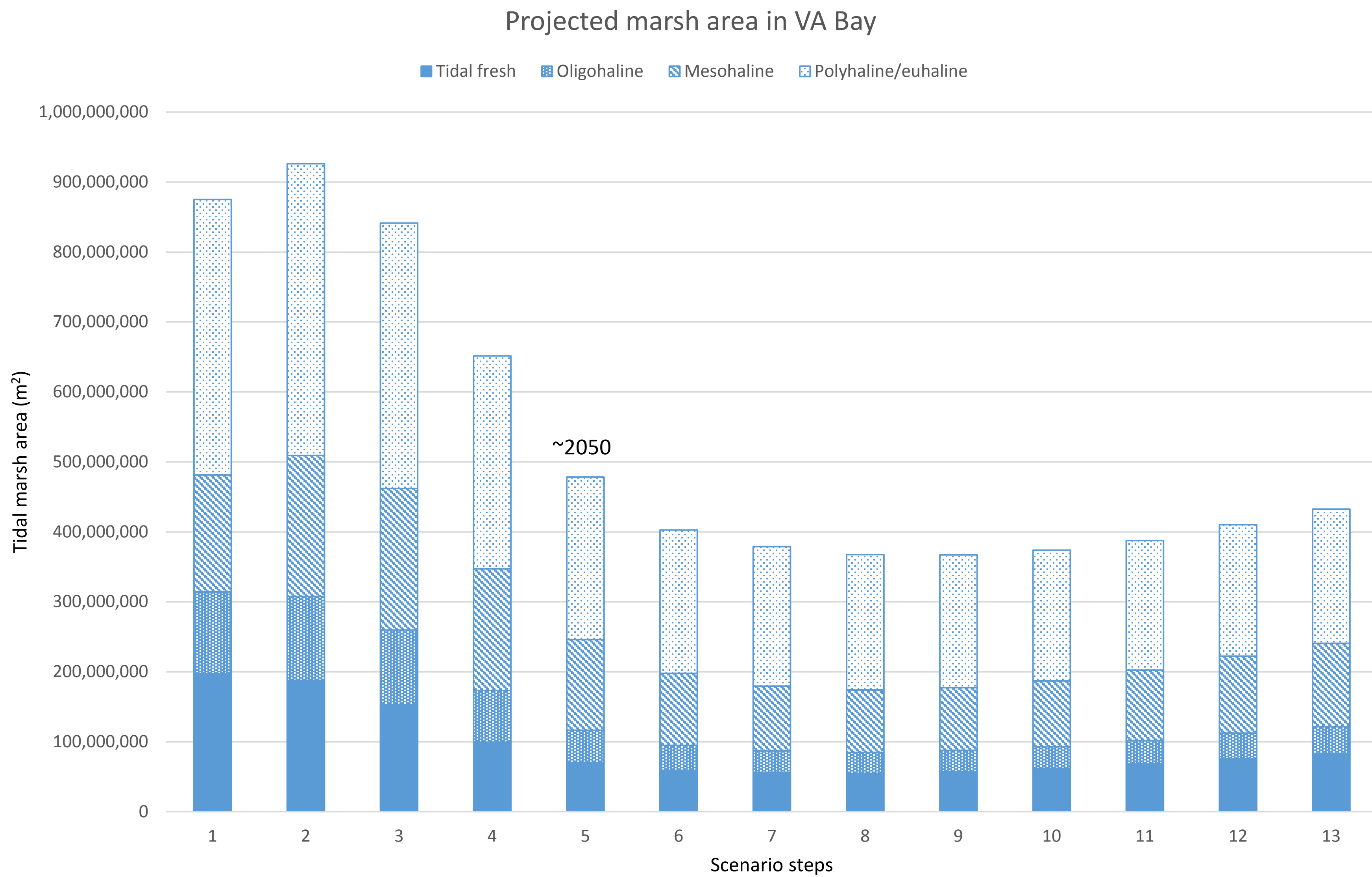

Kilometers
0 10 20 30 40 50
Tidal marsh 2100 projection
Tidal marsh current distribution
Copyright:© 2014 Esri

a)

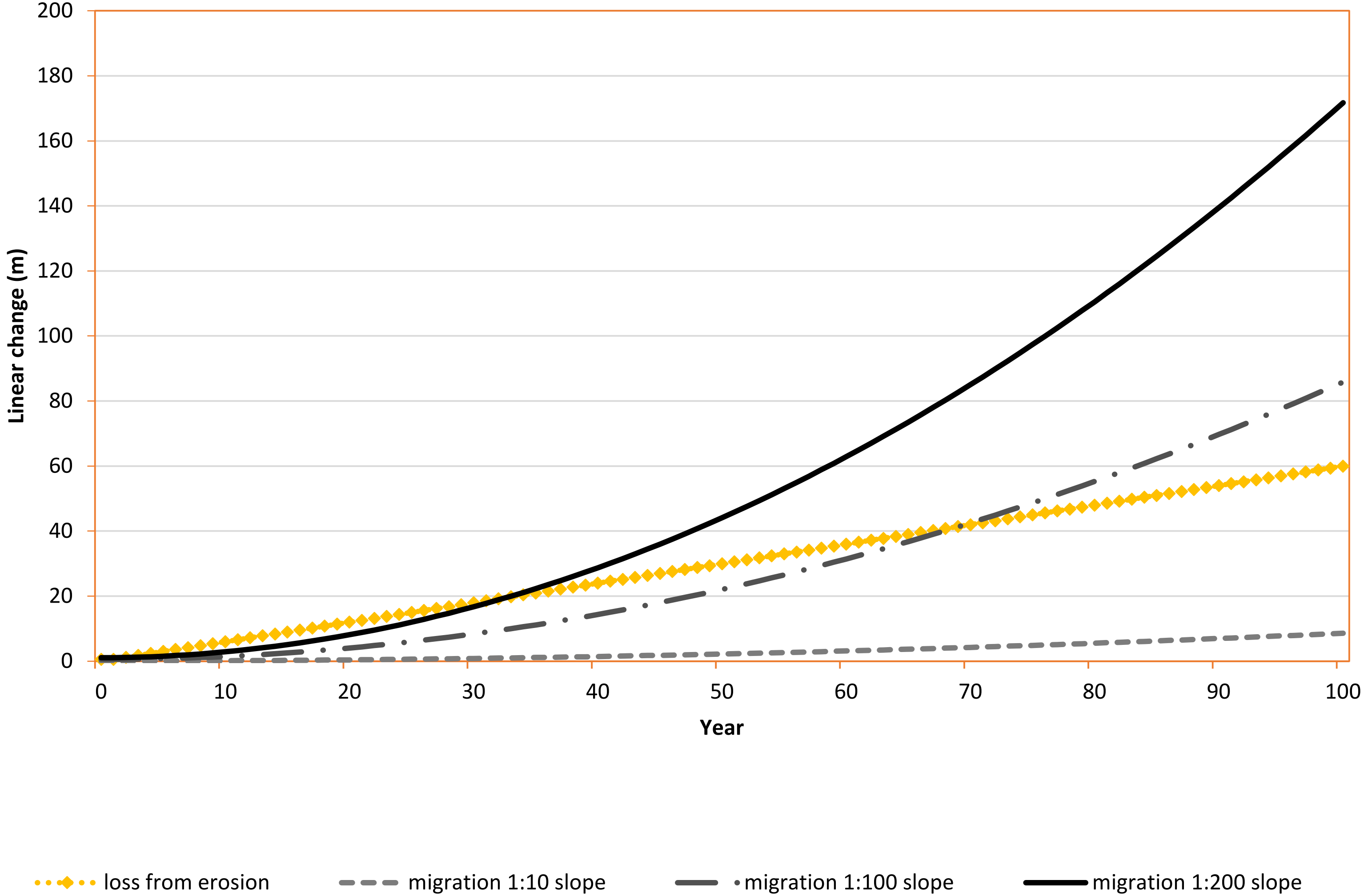

Hampton
undeveloped
developed
25,000,000
20,000,000
15,000,000
10,000,000
5,000,000
0
Tidal marsh area (m²)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Scenario Steps

b)


Mathews
undeveloped
developed
35,000,000
30,000,000
25,000,000
20,000,000
15,000,000
10,000,000
5,000,000
0
Tidal marsh area (m²)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Scenario Steps



Projected marsh area in VA Bay
Tidal fresh
Oligohaline
Mesohaline
Polyhaline/euhaline
Tidal marsh area (m2)
1,000,000,000
900,000,000
800,000,000
700,000,000
600,000,000
500,000,000
400,000,000
300,000,000
200,000,000
100,000,000
0
~2050
1
2
3
4
5
6
7
8
9
10
11
12
13
Scenario steps



200
180
160
140
120
100
80
60
40
20
0
Linear change (m)
0
10
20
30
40
50
60
70
80
90
100
Year
loss from erosion
migration 1:10 slope
migration 1:100 slope
migration 1:200 slope