Modeling Shoreline Change and Resulting Wetland Response Due to Erosion and Sea-Level Rise: A Case Study in Dorchester County, Maryland

Mirtha Karinna Nunez
College of William and Mary - Virginia Institute of Marine Science

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Modeling Shoreline Change and Resulting Wetland Response Due to Erosion and Sea-Level Rise: A Case Study in Dorchester County, Maryland

A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William & Mary in Virginia

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science

by
Mirtha Karinna Nunez
2010
This Thesis is submitted in partial fulfillment of
the requirements for the degree of

Master of Science

Mirtha Karinna Nunez

Approved by the Committee, October 2010

Carl H. Hershner, Ph.D.
Committee Chairman

Mark J. Brush, Ph.D.

Robert J. Byrne, Ph.D.

Carl H. Hobbs, III, Ph.D.
This thesis is dedicated to
my grandmother Ita
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ABSTRACT

The present study was focused on developing a shoreline change forecast and wetland response model for Dorchester County, MD, to evaluate the vulnerability of wetlands to shoreline erosion and inundation due to relative sea level rise. The model considers the following forces involved in wetland stability and sustainability: inundation (as a function of topography and sea-level rise), shoreline erosion, vertical accretion and horizontal migration. To predict the long-term risk to nearshore wetlands and the potential habitat zone for wetlands in the next 50 years, shoreline change due to inundation and erosion/accretion was assessed within the frameworks of two-dimensional and three-dimensional analyses. To that end, three different scenarios were taken into account in the shoreline change forecast. The first (conservative) scenario estimated the future shoreline positions based on historic sea-level rates of change and historic erosion/accretion rates. The other two scenarios employed accelerated rates of sea-level rise and accelerated rates of shoreline erosion/accretion in the shoreline forecast. Two different approaches were employed to spatially analyze and combine the outputs of the projections based on inundation and erosion. A Maximum Change approach and a Characterization of the Inundation Forecast were carried out in each scenario. The future location of the shoreline was defined as the wetland-water boundary. The wetland-upland boundary was defined based on current topography (elevations at 2 times the tidal range above mean low water), and the potential wetland habitat was restricted to areas that are not presently developed and/or not behind a shoreline defense structure. The outputs of this model allow identification of potential future wetland habitats where wetland protection and restoration strategies can be directed. This model approach can serve as a prototype for expanded investigations in other coastal habitats.
Modeling Shoreline Change and Resulting Wetland Response Due to Erosion and Sea-Level Rise: A Case Study in Dorchester County, Maryland
INTRODUCTION

Wetlands are important habitats due to the variety of ecological services they provide (e.g. shoreline stabilization, storm surge protection, habitat for fish, invertebrates, waterfowl, and other wildlife, and water quality control, among many others). As a result of the critical role wetlands play, protection and restoration of coastal wetlands as well as development of management strategies have been receiving substantial attention in the recent years.

Extensive wetlands along the mainstem of the Chesapeake Bay are showing decreased areas of vegetative cover as a consequence of inundation and erosion (Najjar et al., 2010) Specifically, inundation due to sea-level rise is one of the most direct threats confronted by coastal wetlands in the Chesapeake Bay region (Pyke et al., 2008). Coastal and estuarine marshes are especially susceptible to accelerated sea-level rise since their vertical accretion rates are limited and, as a result, they may drown. In many cases, this impact will be aggravated by on-going land use change and associated shoreline hardening, which directly reduce the availability of upland sediment sources as well as interfere with the natural landward migration of the wetlands as water levels rise.

There are several management challenges concerning the preservation of wetlands given rising sea level and increased anthropogenic stressors. The extent of the impacts that sea-level rise will have over these habitats is difficult to estimate due to the inherent uncertainty associated with sea level rise projections. The range and magnitude of these impacts will vary among different regions in accordance with site-specific characteristics.
Interdisciplinary efforts are therefore necessary to better understand how shoreline and surrounding habitats will evolve in the future, as well as to develop adaptive management strategies to prepare for changing conditions.

One of the most effective approaches for examining the cumulative effects of natural processes and anthropogenic activities on shoreline change and its adjacent habitats is to study the patterns and extent of shoreline change over time (Hennessee et al. 2003). This approach not only documents how a particular shoreline has changed through time, but also provides an estimate of how it might respond in the future. Knowing the future position of a shoreline and surrounding conditions allows us to map and estimate potential change in habitat extent and distribution.

The purpose of this Master of Science thesis research was to develop a shoreline change forecast and wetland response model for Dorchester County, MD, to evaluate the influence that relative sea-level rise and shoreline erosion have on long-term wetland stability and sustainability. The model flow diagram is shown in Figure 1. This study proposes GIS-based methodologies for combining the outputs from a two-dimensional erosion model and a three-dimensional static inundation model to forecast the potential response of Dorchester’s shoreline to three different sea-level rise scenarios.

Each of the three scenarios was projected out 50-years from the present. In each scenario, the future position of the shoreline and the long-term risk to nearshore wetland habitats were defined by projecting shorelines based on sea-level rise estimates and
calculated historic erosion rates for the area. Hence, the current shoreline was repositioned by the estimated shoreline erosion/accretion rates (erosion forecast) or the current topography (inundation forecast). The outputs of the two forecasts were spatially analyzed in each sea-level rise scenario using different approaches. In addition, anthropogenic stressors (i.e. areas that are currently developed and/or present shoreline defense structures) were assessed due to the impact that they exert in constraining the natural ability of wetlands to migrate landward under rising sea level conditions.

This study is designed to advance the quality of the analyses currently available to inform shoreline and wetland management. Combining inundation projections with erosion/accretion estimates in a framework that considers uncertainty is one means of using the best available information even when it is of variable resolution in space and time. This type of conditioned future analysis can help managers make informed risk assessments in the effort to sustain wetland ecosystem services in a changing system.
LITERATURE REVIEW

Sea-level rise

There are two basic types of sea-level changes: relative and absolute. Relative sea level is the local apparent change in sea level and it varies through time depending upon changes in the absolute sea level and vertical movement of the land (i.e. uplift or subsidence). Absolute sea level is the eustatic or global sea level, which varies in response to changes in the volume of water on the ocean, and on a larger time scale, to the volume of the ocean basins. Eustatic sea level changes are primarily a result of climate change and plate tectonics. Climate change affects sea level through seasonal or other short-term fluctuations, as well as through long-term changes (Davis and FitzGerald, 2004).

There is a universal consensus that global sea levels will rise at an increased rate from those in the recent past (Cazenave and Nerem, 2004; Rahmstorf, 2007). Even though changes in sea level have significant implications for future evolution of coastal ecosystems, these changes are difficult to estimate. The Intergovernmental Panel on Climate Change (2007) expects a continuous increase in the sea level average as a result of thermal expansion and melting of glaciers and ice sheets.

In the Mid-Atlantic coastal region, sea level has risen approximately 0.3 m in the last century, and due to a combination of climate change and regional land subsidence, sea level is expected to rise another 0.6 to 0.9 m by the year 2100 (Leatherman et al.,
1992). Along Maryland's shoreline, the average rate of sea-level rise has been 3-4 mm/yr (Johnson, 2000). These rates are practically twice those of the global average (1.8 mm/yr) (Church et al., 2004; Church and White, 2006), which are most likely a consequence of land subsidence.

Maryland's shoreline involves a diverse variety of landscapes, and for that reason, the magnitude of impact from sea level rise will vary from region to region depending on the physical characteristics of the site (Johnson, 2000). Similar conditions are being experienced in Hampton Roads, which is another example of sea level rising relative to the land (like most of the east coast). In this region, the rate of sea level rise is 4.25 mm per year (data based on 73-year record between 1930 and 2004) (Boon, 2004).

The major impacts of sea-level rise are coastal erosion, coastal flooding, and salt-water intrusion. Sea-level rise influences and exacerbates on-going coastal processes, making coastal areas more vulnerable to extreme events. The effects of sea-level rise might decrease or eliminate coastal habitats (Carter 1992; Brown and McLachlan, 2002). Lands that are low in elevation will be highly susceptible to inundation (Gornitz, 1991). Marshes, sandy beaches, barrier islands, and tidal estuaries could be significantly impacted. Considerable reductions in wetland areas and the corresponding increase in open water habitats can happen if rates of sea-level rise increase considerably (Orson et al., 1985). In fact, a strong correlation has been found between past marsh loss and relative sea-level rise within the Blackwater Wildlife Refuge on the Eastern Shore of Maryland (Lower Dorchester County). Studies conducted by the University of Maryland
have shown that approximately 1400 hectares of Blackwater’s marsh were converted to open water between 1938 and 1989 (Johnson, 2000).

During episodes of slow sea-level rise, salt marshes can keep pace with the rising water levels by trapping sediments and their own organic detritus (Leatherman, 1991). This raises the bottom, offsetting the rise in water level, and providing the plant species time to adjust to the change by moving progressively landward. If the sea-level rises considerably faster than the rate at which the marsh can respond, the marsh will drown and be lost.

A well-known example of how sea-level rise is affecting marshes can be observed in Virginia’s Pamunkey and Mattaponi Rivers. Scientists have hypothesized that rising sea level in combination with local subsidence has exceeded the marshes’ capacity to accumulate surface material fast enough to sustain their position in the intertidal zone (Hershner, 2002). As a result, a transition in plant communities has been observed in this area, with plants very tolerant of inundation, such as *Peltandra virginica*, replacing less tolerant marsh plants, such as *Spartina alternifolia* and *S. cynosuroides* (Perry and Hershner, 1999; Davies, 2004).

In the era of globally rising sea level, understanding the response of shorelines to changes in sea level is a major scientific objective. Nevertheless, there is still plenty of scientific information describing both the complexity of the linkages between sea-level
rise and shoreline response, and the comparative lack of understanding of these linkages (Cooper and Pilkey, 2004).

**Sea-level rise Inundation Models**

A variety of approaches have been used to model inundation due to sea-level rise. Studies conducted in the Chesapeake Bay have mostly relied on elevation alone to estimate shoreline inundation. For instance, Titus and Richman (2001) focused on the Chesapeake Bay shorelines of Virginia and Maryland. Based on Digital Elevation Models (DEMs), they estimated that about 2,500 km² of land is below the 1.5m elevation contour. In 2009, Wu et al. applied DEMs with higher (10m) horizontal resolution. The model output resulted in an estimation of 1,700 km² of land in Maryland and Virginia that lies below the 0.7m contour.

The Maryland Department of Natural Resources (MD-DNR) Coastal Zone Management Division has also directed efforts toward analyzing the impact of rising sea level along the State’s shoreline. At the present time, MD-DNR in conjunction with USGS have only developed sea-level rise inundation models for Worcester County and the Blackwater Wildlife Refuge in Dorchester County (Johnson et al., 2006). The primary product of this model has been the creation of a large-scale dataset that visually illustrates sea-level-rise inundation coupled with storm surge over a 100-year time frame.
A more focused approach to address the impacts of sea-level rise has been carried out for the South Atlantic Coast, and lately for the Delaware Bay and the Chesapeake Bay regions. Sponsored by the U.S. Environmental Protection Agency (EPA), researchers from the University of Georgia, Indiana University, University of Houston, Ecomodeling, and Warren Pinnacle Consulting worked in conjunction to develop the Sea-level rise Affects Marshes Model (SLAMM). The model simulates the principal processes involved in wetland conversions and shoreline modifications during long-term sea-level rise. The processes considered within the SLAMM v.5.0 are inundation, erosion, overwash, saturation, and salinity. The model incorporates IPCC projections as well as fixed rates of sea-level rise. The National Elevation Dataset (NED) is applied as a principal source of elevation. NED data usually do not have the vertical resolution required for accurate predictions of marsh elevations. To solve some of these problems, SLAMM computes wetland elevations based on National Wetlands Inventory (NWI) categories. Regarding the erosion process, in the present implementation of SLAMM 5.0, constant erosion is triggered only when the average fetch exceeds 9 km. In addition, based on a combination of professional judgment and literature review, the default erosion rates in the model (fixed values) are assumed and set to 2.0 meters per year for marshes, 1.0 meter per year for swamps, and 0.5 meter per year for tidal flats (Warren Pinnacle Consulting, Inc., 2008).

Recently, SLAMM 5.0 was applied to the Chesapeake Bay and Delaware Bay regions. Model results vary significantly by site, but generally, the most considerable changes to coastal wetlands and other habitats take place in the eastern and southern
regions of the Chesapeake Bay, and most of the Delaware Bay (NWF, 2008). Even though this model is a valuable tool for identifying areas where sea-level rise will potentially impact wetland habitats under specific scenarios, critical features (e.g. riparian land use, and shoreline hardening) that interfere in the natural migration of wetlands as a response to rising sea level were not taken into account.

**Shoreline Erosion**

The erosion process results in landward movement of the shoreline contour. It occurs over a full range of time scales, including short-term events such as waves, tides, and storms, and long-term changes due to sea-level rise (National Research Council, 2006). Short-term processes in conjunction with the long-term process of sea-level rise are responsible for the changes that the Chesapeake Bay shoreline is experiencing today. These processes can affect erosion independently or can have a synergistic effect. While erosion is primarily a direct consequence of wind and wave action, the continued rise in sea level permits these agents to affect the shoreline at progressively higher levels over time, causing constant erosion (Langland and Cronin, 2003).

It is important to emphasize that the challenges created by shoreline erosion reflect the unique combination of natural and man-made conditions affecting a particular shoreline region. Natural conditions that affect shoreline erosion include weather, soil composition, geomorphology, fetch, and surface water and groundwater conditions. Shores of very fine or unconsolidated sediments are mainly at risk, in particular when
they are under the effects of strong winds, and wave energy. Anthropogenic factors affecting shoreline erosion include land use choices, surface and ground water usage, and shoreline reinforcement activities.

Inappropriate planning and management interferes with the natural erosion process and can accelerate erosion under certain circumstances. There are several direct and indirect costs associated with shoreline erosion that must be taken into account, such as the loss of land and its ecological, cultural and economic values, and the impacts produced by increased sediment and nutrient loading to the water resources.

Approximately 85% of Chesapeake Bay’s shoreline is in the hands of private landowners (Chesapeake Bay Program, 2005). The presence of man-made structures such as riprap, bulkheads, and groins, among others, alters the processes of erosion depending on the location, type and design of the structure. In some cases, structures erected to prevent erosion along one stretch of shoreline can exacerbate the erosion problem on adjacent sections. Sandy sediments are usually derived from shoreline erosion and moved along a length of shore by wave action. Hence, a stabilization structure used to prevent erosion can also eliminate the local source of sand that supplied adjacent regions (Dean and Dalrymple, 2002).

Depending on the composition of the land along the shoreline and the environmental conditions, the erosion rates of the shoreline can be quite variable (Riggs, 2001; Riggs and Ames, 2003). Rates of erosion are dependent on the frequency and
intensity of different agents (such as wind and wave height) as well as site characteristics such as bank height, composition, and shoreline geometry. The geographic orientation with respect to fetch affects the exposure to wind wave attack. Sinuosity or irregularity of shorelines (e.g. marshes) tends to break up wave energy better than straight shorelines (Hardaway and Anderson, 1980).

**Shoreline Erosion Models**

Shoreline analyses offer the basis to understand how a specific coast has changed through time and how it might progress in the future. Shoreline variability depends on the temporal and spatial scale that is being considered. In general, the proxies utilized for the analysis of shoreline variability are one of two types: either a feature that is visibly discernable in aerial photography (e.g. high water line) or the intersection of the coastal profile with a tidal datum (e.g. mean high water) (Boak and Turner, 2005).

Erosion rates employed to analyze shoreline recession can be extrapolated to future shoreline position. The extrapolation provides an estimate of future shoreline behavior based on past performance. These erosion rates correspond to linear summaries of the processes that have impacted the coast through time. However, the reliability of using linear methods for predicting future shoreline positions diminishes for shorelines that behave in a nonlinear, cyclic, or chaotic fashion (Fenster et al., 1993).
Different data sources are available to determine shoreline position. The most common data sources utilized are historical land-based photographs, coastal maps and charts, aerial photographs, shoreline surveys, airborne light detection and ranging (LIDAR), and multispectral/hyperspectral images. Depending on the availability of the data, and the objective of the research, different sources are, in general, used in a single study. For instance, in the historical land-based photographs, there is generally no information regarding the sea conditions (tide and waves) at the time the specific photograph was taken. As a result, the majority of historical photographs are of limited value for quantitative mapping and analysis of past shorelines (Dolan et al., 1983). For that reason, it is necessary to consider this data source in conjunction with other data sets in order to perform more accurate analyses.

One of the most significant factors in any shoreline change analysis using shoreline models is consistency of model results when applied across different coastal regions. The natural forces responsible for shoreline movements are a function of space and time given that these forces change in intensity according to geographic location and seasonal variations. The major challenge in shoreline prediction modeling has been to create models with sophisticated spatial-temporal numerical analysis that can be calibrated in the real world to reflect a realistic coastal erosion system (Fletcher et al., 2003).

In shoreline studies, several methodologies and programs have been employed to estimate rates of erosion. For instance, Byrne and Anderson (1976) conducted the first comprehensive evaluation of erosion for the entire Virginia Chesapeake Bay system.
Topographic map series of the 1840’s and the 1950’s were employed as data sources in this study. Assessments were made considering high water shoreline positions at both periods, with measurements consisting of areal changes for individual segments (reaches) of shoreline. The reaches correspond to segments where the shoreline experienced erosion or accretion along the entire length. To calculate the rate of change in a reach, an electronic X-Y digitizer was used to measure several parameters in each segment such as area change (area enclosed between the newer and older shoreline position), and length of the shoreline (the new shoreline). These parameters were the basis for computing the mean erosion or accretion distance (parameter calculated by dividing the area by the length of the shoreline), and the average rate of erosion or accretion (parameter calculated by dividing the mean distance by the time in years between the applicable surveys).

Spoeri et al. (1985) performed a statistical model of historic shore erosion rates on the Chesapeake Bay in Maryland. In this case, the authors calculated the erosion rates using historical erosion rates and shoreline maps (topographic quadrangle sheets) compiled by Maryland Geological Survey in 1975 (charts dating back as far as 1841). Erosion rates were computed by dividing the linear recession of the shoreline by the number of years in between the surveys.

Hobbs et al. (1999) analyzed the rates and patterns of shoreline change in relative shore-term beach profile data, and long-term historical shoreline data from the southeast ocean coast of Virginia. Survey data (29 beach profiles) were gathered from the City of Virigina Beach. The Interactive Survey Reduction Program (ISRP) (U.S. Army Corps of
Engineers, 1994) was employed to manipulate and analyze the data. This program is a powerful tool for studying beach profile changes given that it allows editing, analyzing, and plotting beach profile data. Historical shoreline position maps were utilized to evaluate long-term trends in the shoreline position. Rates of shoreline change were calculated using the End Point method and average shoreline change calculated from shoreline maps and beach profile data.

At the present time, erosion models can have greater reliability, accuracy, and capabilities due to Geographic Information System (GIS) technology. The application of GIS technology in erosion models helps overcome many difficulties of past models. For example, in the past, the deficiency of spatial-temporal tools for analyzing the trend of shoreline changes and the errors in the process of identifying shoreline positions and digitization were the potential causes for restricting the ability of models to provide justifiable evaluations about shoreline change rates (Srivastava et al., 2005).

In 2003, the Towson University's Center for Geographic Information Sciences in collaboration with the Maryland Geological Survey calculated shoreline erosion rates for the entire State of Maryland. They assigned generalized rate-of-change categories to recent shoreline vectors using transect-based erosion rates, which were generated by a U.S. Geological Survey (USGS) computer program called Digital Shoreline Analysis System (DSAS) (Danforth and Thieler, 1992). DSAS software computes rate-of-change statistics from multiple historic shoreline positions residing in a GIS. DSAS version 3.2 is a software extension to ArcGIS v.9+. The components of the extension and user-guide
comprise: 1) instruction on the proper way to define a reference baseline for measurements; 2) automated and manual generation of measurement transects with user-specified parameters; and 3) output of calculated rates of shoreline change and other statistical information. DSAS applies the following statistical techniques in its output: 1) endpoint rate; 2) average rates; 3) simple linear regression; and 4) jackknife iterative regression techniques. All output data are written to the attribute table related to each transect. This software is intended to facilitate the shoreline change calculation process, providing both rate-of-change information and the statistical data necessary to establish the reliability of the results. Moreover, the DSAS is suitable for any “generic positional change over time” application. It can compute rate of change for problems that integrate a clearly identified feature position at discrete times, such as river edge boundaries, and land cover changes, among others (Danforth and Thieler, 1992).

Hardaway et al. (2006) utilized recent and historic aerial photography to observe, analyze, and estimate past shoreline positions and trends in different regions of Virginia. The aerial photos were orthorectified and the shorelines were digitized using GIS technology (ArcGIS). In order to analyze the shoreline rate of change, a custom ArcView extension (called “shoreline”) was applied. This extension generates equally-spaced transects along a baseline and computes distances from the baseline to each shoreline period. The distances of the digitized shoreline from the baseline are used to determine the rates of change.
Topography

Topography is defined as the configuration of a surface including its relief and the position of its natural and man-made features (Merriam-Webster Dictionary). Topography is a direct reflection of the balance between two competing mechanisms: tectonic (mainly constructional) and erosive (mainly destructive) processes.

Topographic features influence erosion potential in different ways. For instance, watershed size and shape affect runoff rates and volumes. Moreover, the length and the steepness of the slope are critical factors in erosion potential, since they determine, in large part, the velocity of runoff. The shape and orientation of a slope play significant roles on erosion potential as well.

Maryland's shoreline on the Chesapeake Bay is highly dendritic and consists of banks and bluffs ranging in height from about a meter above high tide to over thirty meters in Calvert County (U.S. Army Corp of Engineers, 1971). The state has twenty three rivers and other bays, as well as many lakes and creeks. In the particular case of Dorchester County, the general topography is flat with elevations increasing from south to north (the highest elevation is seventeen meters above sea level). The increasing elevation in northern Dorchester generates a gently rolling terrain. Southern Dorchester is very flat and is usually at (or slightly above) sea level, which makes this area subject to significant flooding.
Currently, the most used types of digital elevation data available for topographic studies are Light Detection and Ranging (LIDAR) data and USGS digital elevation models (DEMs). The USGS 7.5-minute DEM data set covers the entire nation. Nevertheless, with its root mean squared error (RMSE) of 7m, which easily exceeds most estimates of projected sea-level rise over the next 100 years, DEMs may not be useful for evaluating impacts of sea-level rise on coastal areas (CARA, 2006).

The Maryland Department of Natural Resources in cooperation with various Maryland State Geographic Information Committee affiliates is collecting and distributing several LIDAR-derived elevation data products. This method uses laser light to determine the elevation of ground surface relative to a known elevation datum. A scanning laser is mounted on an aircraft and, while the aircraft flies along a track line, the laser emits a continuous series of light pulses. The time necessary for the pulse to return to the aircraft is recorded. The position of the aircraft and its altitude is also recorded during the flight using Global Positioning System (MD-DNR, 2005). Elevation data obtained by this method are very detailed and accurate. A vertical precision of 10 cm can be achieved in bare areas without relief and approximately 15 cm when the terrain type generates noise, as in the case with vegetation and slope (Johnson et al., 2006).
Wetlands

Wetlands are defined by the United States Army Corps of Engineers (USACE) and the United States Environmental Protection Agency (EPA) as "those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetations typically adapted for life in saturated soils. Wetlands generally include swamps, marshes, bogs, and similar areas." Wetlands found in the United States fall into four categories: marshes, swamps, bogs, and fens. Marshes are wetlands dominated by soft-stemmed vegetation, whereas swamps typically have woody plants. Bogs are freshwater wetlands, often formed in old glacial lakes, differentiated by spongy peat deposits, shrubs and evergreen trees. Fens are freshwater peat-forming wetlands covered generally by grasses, reeds, sedges, and wildflowers (EPA, 2004).

Even though a broad range of wetlands exists in Maryland, two basic types are generally recognized: nontidal wetlands and tidal wetlands. Tidal wetlands represent a transition zone between tidal flats and uplands. They are abundant on the lower Eastern Shore of the Coastal Plain and cover broad areas. More than half of the coastal wetlands in Maryland are located in the Pocomoke, Nanticoke, and Choptank River basins. These coastal wetlands are extremely important to the Chesapeake Bay ecosystem and the economy of Maryland (Tiner and Burke, 1995).
The Maryland Wetland Act of 1970 (Maryland Annotated Code, Environment Article, Title 16, Md. Env. Code Ann. §§ 16-101 – 16-503) classifies tidal wetlands into either of two categories: State wetlands, and private wetlands. State wetlands are defined as “any land under the navigable waters of the State below the mean high tide, affected by the regular rise and fall of the tide. Wetlands of this category which have been transferred by the State by valid grant, lease, patent or grant confirmed by Article 5 of the Maryland Declaration of Rights shall be considered “private wetland” to the extent of the interest transferred.” Private wetlands are defined as “any land not considered “State wetland” bordering on or lying beneath tidal waters, which is subject to regular or periodic tidal action and supports aquatic growth”.

State maps have been employed to identify and delineate regulatory boundaries of wetlands under the jurisdiction of the Maryland Tidal Wetlands Act. The inland boundary of the tidal wetlands is defined by the interface between the wetland and the upland areas, or between the tidal wetland and wetlands that do not border on tidal waters. This limit was established by interpretation of aerial photography and field inspections. Wetland maps for Maryland were created using high-altitude aerial photography (digital orthophoto quarter quadrangle (DOQQ) maps (scale of 1 inch = 600 feet)) (McCormick and Somes, 1982).

Wetlands perform several ecological functions and have special characteristics that make them important and valuable natural resources. Wetlands serve to filter and remove several pollutants. They can intercept runoff and transform and store sediment,
nutrients, and certain heavy metals without being degraded. Moreover, wetlands buffer and absorb wind and storm induced wave energy providing protection to the upland bank. Hardaway and Byrne (1999) suggested that as fetch increases, a wider marsh fringe is necessary to attenuate energy generated by larger waves.

Wetland losses due to erosion have been identified in many estuaries around the world (Delaune et al., 1983; Brivio and Ziliolo, 1996). Other natural and anthropogenic causes also contribute to the degradation and loss of wetland habitats (e.g. subsidence, increased air temperature, excess of nutrients, hurricanes and storms, droughts, drainage, dredging, and filling, among others). All of these factors impact and jeopardize species composition and wetland functions. For that reason, the identification of these factors is important in developing management strategies for eroded wetlands (Castillo et al., 2002).

In the past decades, attention has focused on the threat that salt marshes worldwide are experiencing from accelerating sea-level rise (Morris et al. 2002; Reed 2002; Church and White, 2006). Inundation, erosion, horizontal migration, and vertical accretion are critical processes that define the stability and sustainability of the marshes. The evaluation of these processes, which control the elevation and evolution of the marsh surface, is critical to understand and forecast the impact that sea-level rise might have on these habitats.
An important characteristic of salt marshes is the periodic flooding they are exposed to. Salt marshes extend seaward to approximately the elevation that is flooded at mean tide, and landward to the elevation that approximates spring tide (the highest astronomical tide every 15 days). The type of vegetation that is present in the wetland depends on the frequency that these habitats are flooded. Coastal wetlands flooded once or twice daily sustain "low marsh" vegetation; whereas areas flooded less regularly sustain “high marsh” species. In areas flooded less than twice a month, transitional wetlands can be found above the high marsh. Therefore, increases in the duration and frequency of inundations can significantly modify the structure of these ecosystems. For instance, if the seaward limit is inundated more frequently, much of the marsh vegetation will drown and the marsh soil will erode. Low marsh species may invade these areas, and the high marsh zone will transition inland if the landscape allows it (Titus, 1988).

Wetlands naturally respond to rising sea level by migrating upward (vertical accretion) and inland. Landward migration of these habitats can compensate for some of the loss in areal extent, unless the local upland slope or human infrastructure prevents this natural process. In addition, if these habitats are unable to accrete vertically at the same rate as rising sea level through the deposition of inorganic and organic material, they will be converted to intertidal and open water areas (Donnelly and Bertness, 2001).

There are several predictive models for wetland response to sea-level rise that specifically consider their capacity to vertically accrete (e.g. Cahoon, 2002 and Morris et al., 2002). Nevertheless, there is no consensus in the literature regarding vertical
accretion rates for wetlands under rising sea level conditions. Some studies have suggested wetlands can increase accretion rates to keep pace with modest increases in current sea level rise (e.g. Cahoon et al., 2006). Others have suggested that wetlands are already at or beyond their maximum rate of vertical accretion. For instance, Perry and Hershner, (1999), Hershner (2002) and Davies (2004) have documented changes in the vegetation communities of Sweet Hall Marsh as a result of the inability of the wetland to vertically accrete and keep pace with accelerated rates of sea level rise. French (2006) proposed a zero-dimensional mass-balance model based on an extensive data set from published literature (U.S. East and Gulf coast data), including rates of sea level rise, tidal range, and sediment supply. The results show that marshes dominated by inorganic sediment supply are in general near to an equilibrium status with present rates of sea level rise. Kirwan and Murray (2007) proposed a simplified 3-D model that suggests increasing rates of marsh vegetation productivity will be able to drive elevation gain sufficient to keep up with rising sea level. Titus et al. (2006) conducted a study for the Mid-Atlantic region to evaluate different site-specific scenarios for wetlands accretion as sea level rises. This study concluded that many coastal wetlands of the Mid Atlantic, under current sea-level rise, appear to be maintaining themselves. However, as rates of sea level rise accelerate, their survival depends upon optimal hydrology and sediment supply conditions; and beyond a threshold, wetlands will not be able to keep pace with rising sea level and will succumb to increasing tidal inundation.

Vertical accretion is a complex response to multiple factors, which vary spatially and temporally. Even though various site-specific field studies can provide information
for local areas, the evaluation of the vertical accretion process as a response to sea-level rise over large regions cannot currently be predicted by available models (Titus et al., 2006).
MAIN PURPOSE AND SPECIFIC OBJECTIVES

The main goal of this study is to assess the influence that relative sea-level rise and shoreline erosion have on long-term wetland stability and sustainability. To that end, the present spatially explicit model considers the following forces: inundation (due to sea-level rise), shoreline erosion, wetland capacity for horizontal migration, and wetland vertical accretion (Figure 2).

Specific Objectives

- Forecast shoreline position over the next 50 years employing topographic data and sea-level rise projections within the framework of a three-dimensional spatial analysis

- Forecast shoreline position by assessing shoreline erosion/accretion over the next 50 years utilizing planimetric historic erosion rate data within the framework of a two-dimensional spatial analysis

- Integrate the outputs derived from the inundation and erosion forecasts to evaluate the independent and combined effect of these physical processes

- Evaluate the long-term risk to nearshore wetlands and the potential habitat zone that wetlands can occupy in 50 years
MATERIALS AND METHODS

Study Area

The geospatial model developed for this study was applied in Dorchester County, Maryland, located in the central part of Maryland's Eastern Shore (Figure 3). Dorchester is bordered on the northwest by Talbot County, on the northeast by Caroline County, on the east by the State of Delaware, on the southeast by Wicomico County, and on the west by the Chesapeake Bay. This county was chosen for the study because of its extensive wetlands (40% of the entire state's wetlands are in Dorchester County) (McCormick and Somes, 1982). In addition, Dorchester has diverse shoreline geometry and orientation, which enables the study to experiment with different settings.

Shoreline Forecasting (50 years)

*Forecasting Based on Inundation due to Sea-level rise*

The future position of the shoreline was initially addressed using a three-dimensional analysis, which predicts shoreline change by assessing inundation as a function of topography and sea-level rise. These physical parameters represent diverse pressures that constrain the shoreline from different directions.

Any study incorporating change in water elevation must establish a baseline for the study. This study used mean sea level (MSL) and employed the VDatum software
program developed by NOAA to determine the elevation value of MSL in the NAVD88 (vertical datum). Mean sea level, as well as other tidal datums necessary for the study (Table 1), were averaged for the study area using random sampling points (n = 30). ESRI’s ArcGIS®3D Spatial Analyst 9.3 was used to interpolate future MSL positions using current elevation data.

In order to accurately evaluate the future impacts of sea-level rise, a merged land/water elevation surface must be generated. To that end, topography and bathymetry data were integrated to generate a digital elevation model (DEM).

*Bathymetry*

Bathymetric digital sounding data were obtained from the NOAA National Ocean Service Hydrographic Database, which is maintained by the National Geophysical Data Center. A total of 45 surveys were employed in this study. These data are in the form of soundings gathered from the early 1900s to the present.

Bathymetric data are referenced to local tidal datums such as mean low water; however, topographic data are referenced to a standard vertical datum with a fixed benchmark. In order to merge these different datasets to create a seamless surface, they must be referenced to the same datum. For this study, the VDatum program was employed to convert bathymetric data values (in mean low water and mean lower low water) into the fixed datum coordinate system used in the topographic data (NAVD88).
**Topography**

Topographic data for the study area was obtained from Maryland Department of Natural Resources (MD-DNR). This data set was collected using Light Detection and Ranging (LIDAR). Raw LIDAR data were collected by Airborne 1, Inc. in April 2005. In order to allow correlation of the point values with tidal gauge stations, the data were collected flying tidal shoreline areas during the low tide cycle (slack – low tide – slack) as predicted for local tide stations. Raw data were referenced to the Universal Transverse Mercator (UTM) coordinate system. The processing of the raw data was carried out by the Computational Consulting Services. Artifacts and features that did not reflect ground elevation (e.g. rooftops) were eliminated to generate “Bare Earth Mass Point” files. Data were cast in the Maryland State Coordinate System, NAD 83, with elevation in meters referenced to the NAVD88. A gridded digital elevation model was developed from the Bare Earth Mass Points files.

From the different LIDAR elevation data products available through MD-DNR, a DEM raster was selected for this project. This data set is provided as GRIDs in e00 format. Several scripts and the ArcMap Raster Calculator were used in this study to generate the final grid (cell size: 10m), which was more compatible for the analysis in ArcGIS.
Topography/Bathymetry Merge Processing (3-D seamless elevation surface)

To generate the seamless 3-D surface, bathymetric and topographic point data were combined and interpolated into a raster using the “Topo to Raster tool” included in the ESRI’s ArcGIS® 3-D 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.

Given that the merging process requires significant computer memory and storage, the study area was divided into 7 manageable segments (Figure 4) for which surfaces were independently generated. In addition, it was necessary to include in the surface only data at the land/water interface of the study area (600m landward and seaward) to efficiently run the Topo to Raster tool. After the independent surfaces were generated, they were combined using the “Mosaic to a New Raster” tool.

Modeled Sea-level rise Scenarios

Based on the 3-D bathymetric/topographic surface and different sea-level rise projections reported in the literature, three different sea-level rise scenarios were modeled to evaluate impacts due to conservative and accelerated estimates. Future shoreline positions were forecast 50-years from the present. These forecasts assume that sea-level rise is the only force controlling shoreline trends. No other forces apply. Each projection represents an approximation of the potential area that could be inundated in 50-years and
assumes a total loss of resources within the area of shoreline retreat. Potential inundated areas were identified and calculated using ESRI’s ArcGIS® Spatial Analyst v.9.3.

The first sea-level rise scenario employed the averaged annual rate of sea-level rise derived from long-term historic rates of sea level at NOAA’s Cambridge Tidal Gauge Station in Dorchester County. These rates and the mean sea level trend were calculated by the National Oceanographic and Atmospheric Administration, Center for Operational Oceanographic Products and Services (CO-OPS). Calculations were based on water level records collected by NOAA tide gauges. The averaged sea-level rise rate computed at this station is 3.48 millimeters/year with a 95% confidence interval of +/- 0.39 mm/yr based on monthly mean sea level data from 1943 to 2006. Using the rate of 3.48 mm/yr, MSL was adjusted for a 50-year rise. This scenario comprises the most conservative approach. It assumes that rates of sea-level rise will not change over time, and the potential impact of sea-level rise will occur at the same rate as was observed over the last century.

The second and third scenarios were based on projections provided by the recent STAC Report (Pyke et al., 2008) on climate change impacts in the Chesapeake Bay. The report suggests that sea level will increase between 700 and 1600 mm by 2100. These estimations are based on tide records over the past decade and projections of impacts due to warming oceans and melting ice masses. Using that range, accelerated rates of 7 mm/yr and 16 mm/year were applied to the second and third sea-level rise scenarios.
respectively. These rates were applied to the elevation values for MSL, and revised surface projections for inundated areas were computed.

**Forecasting Based on Shoreline Erosion**

Three scenarios (a conservative and two accelerated scenarios) were applied again to the erosion forecast. The first considers shoreline retreat as a function of estimated erosion rates only. These rates assume, but do not specifically incorporate sea-level rise as an independent forcing function. The second and third scenarios do consider sea-level rise as an independent or additive value in the model.

Historic erosion rates applied in all three scenarios were calculated by the Maryland Geological Survey (Hennessee et al., 2003). Erosion rates were estimated along the tidal shoreline in Maryland using digital shorelines dating from 1841 – 1995. Given that this time period starts before the time period utilized for the calculation of the historic rates of sea-level rise (1943 - 2006), an assessment of the spatial distribution of rates inside and outside of the overlap period was undertaken (see Appendix A). Based on this evaluation, it was concluded that comparison and integration of the historic rates of erosion and sea-level rise for the study area were acceptable.

For the estimation of the historic erosion rates, Maryland Geological Survey (MGS) employed different digital shorelines, which came from various sources: 1) Historical Erosion Rate and Shorelines maps compiled by MGS in 1975, 2) recent
Coastal Survey maps produced by the National Ocean Service (NOS), a branch of the National Oceanic and Atmospheric Administration (NOAA), and 3) a digital wetlands delineation based on photo interpretation of 1988 – 1995 digital orthophoto quarter quadrangles (DOQQs). The recent digital shorelines (1988-1995) were employed to construct the “base shoreline”, in which rates of shoreline changes were assessed at 20 meters intervals alongshore. In order to compute the rate of change along the shoreline, the Digital Shoreline Analysis System (DSAS) (Danforth and Thieler, 1992) was employed using transects cast across the reference shorelines. The following erosion rate classification was generated by MGS to characterize shoreline change based on these results: “high” (more than 2.4 m/yr), “moderate” (1.2 - 2.4 m/yr), “low” (0.6 - 1.2 m/yr), “slight (0 - 0.6 m/yr), “protected” (presence of structures) and “no change“(0 m/yr) and “accretion” (Hennessee et al., 2003).

For this study, the median value of each class was used when calculating the 50-year projection. Due to large geographic gaps in the MGS data set, the original survey data was updated for the present analysis in order to complete those segments of the shoreline where there were no data available and to reflect the current status of shoreline protection. The Maryland Shoreline Inventory developed by the Center for Coastal Resources Management – VIMS (Berman et al., 2006) provided the updated condition of shoreline protection and stability. The Inventory is based on field surveys, which were conducted during 2002 - 2006. Based on this data set, the structures delineated in the Maryland Shoreline Inventory took priority over any segment of the shoreline classified as “protected” by MGS. The rationale for this action is based on the fact that the
structures in the Shoreline Inventory were more recent and surveyed on the ground, while the MGS datasets were developed interpreting moderately high-resolution vertical imagery where delineation of structures from this medium presents a low degree of accuracy. In addition, erosion condition interpreted from the Maryland Shoreline Inventory was used as a surrogate for erosion rate along segments not computed in the original MGS data set. The qualitative attributes associated with bank condition (e.g. stable, unstable, and undercut) were interpreted in the following manner: the stable attribute found predominantly in short fetch environments was classified as “no change”; undercut and unstable attributes were classified as “slight” (erosion rate: 0 – 0.6 m/yr). In areas where there are no Inventory data for bank erosion, the shoreline segments were classified as “no data”.

The erosion rates associated in the updated MGS shoreline provided the basis for extrapolating future shoreline rates of change. The MGS shoreline is different than the baseline shoreline (relative to MSL) projected with the inundation model. In order to make the outputs comparable for the integrated forecasts, both models (inundation and erosion) need to be referenced to the same baseline shoreline. For that reason, the erosion rates (i.e. median values of each class) associated with the MGS shoreline were transferred to the baseline shoreline at MSL using different geoprocessing tools in the ESRI’s ArcGIS® 9.3: dissolve (data management tool); buffer and identity (analysis tools). Next, the final output was manually corrected for any spatial discrepancies. This final output was projected for 50 years within the framework of a two dimensional spatial model using ESRI’s ArcGIS® Spatial Analyst 9.3.
In the first scenario, using only the computed erosion/accretion rates from the above, the resulting conservative 50-year shoreline projection represents an approximation of land loss in 50 years and assumes loss of resources and infrastructure within the area of shoreline retreat. Based on the different erosion rates, the current shoreline was shifted landward (or seaward in the case of accretion) by the median annual rate (m/year) multiplied by 50. The analysis assumes no change in management of the shoreline in the next 50 years (i.e. actions that can interfere with the natural erosion rates). Moreover, calculations did not include factors such as upland slope, deposition or re-distribution of sediment along the shore, or catastrophic events.

In the second and third scenario, accelerated rates of shoreline erosion/accretion were predicted based on the combined effects of historical retreat and sea-level rise. There are different approaches to model the response of a shoreline to future sea-level rise based on historic rates of erosion and the corresponding rate of sea-level rise. Bray and Hooke (1997) developed a simplistic predictive model for soft cliff retreat, but it is also commonly applicable to the retreat of any uniform lithology/sediment body, such as dune front or salt marsh. The model forecasts future rates of erosion ($R_2$) based on historical retreat ($R_1$), which was experienced under a given rate of sea-level rise ($S_1$), and predictions of future sea-level rise ($S_2$) according to the following equation:

$$R_2 = \left( \frac{R_1}{S_1} \right) \times S_2$$
The historic erosion rates (R1) along the shoreline was recomputed (R2) using the
historic sea-level rise rate of 3.48 mm/yr (S1) and the accelerated sea level rates of 7
mm/yr and 16 mm/yr (S2). The analysis assumes that the historic sea level rates are
comparable with the historic shoreline erosion rates obtained for the study area (see
Appendix A).

Employing the same methodology applied in developing the conservative 50-year
erosion/accretion projection, the accelerated 50-year erosion/accretion projections
incorporated the accelerated rates of sea-level rise using the above equation.

Integrated Shoreline Forecast

Two different approaches were employed to spatially analyze the outputs of the
forecasts based on inundation and erosion. A maximum change approach and a
characterization of the inundation forecast were performed for each scenario. ESRI’s
ArcGIS® v.9.3 was used to produce mappable shoreline forecast comparisons. Schematic
representations of the two approaches are displayed in Figure 5.

Maximum Change Approach

The maximum change approach consists of combining the outputs from the two-
dimensional erosion model with the three-dimensional inundation model. In each
scenario, the areas that potentially will be lost (one projected by the inundation model
and the other by the erosion model) were combined using the Union Tool in the ESRI’s ArcGIS® 9.3, which computes a geometric intersection of the inputs features. As a result, the two input data sets were overlaid and saved as a new integrated data layer.

This maximum change approach displays the worst-case scenario. It considers the maximum inland extent based on the integrated shoreline. The future position of the integrated shoreline was defined by the current shoreline (relative to MSL) repositioned by the estimated erosion/accretion rates or the current topography, in case inundation moves inland faster than estimated erosion (such in the case of low-lying topography).

This approach allows comparing the different shoreline forecasts individually and as an integrated projection. Land loss estimates are derived from the integrated shoreline forecast and from the independent projections due to inundation and erosion. The spatial comparisons of the different projections and scenarios are summarized in Table 2.

**Characterization of the Inundation Forecast**

The purpose of this approach is to convey the underlying uncertainties associated with the forecasting models. The integration of erosion and inundation models is challenged by variable spatial and temporal scales and accuracies of the two analyses. The simple maximum change approach effectively hides the underlying uncertainty in the final depiction of its output. The goal in this second integrated approach is to develop a strategy for incorporating some acknowledgement of uncertainty in the final output.
The erosion and inundation models each rely on different data sources, with consequent differences in resolution and accuracy. For example, the erosion model incorporates potential errors associated with historical coastal maps and charts. The errors arise in part from variations through time in scale, datums, surveying and publication standards, projection errors, among others. In the case of the inundation model, the high-resolution elevation data (LIDAR data) that was employed provides much greater accuracy in determining areas potentially inundated due to sea-level rise. As a consequence, the inundation model is likely to generate a more precise estimation of the future shoreline position.

For that reason, this approach puts a premium on the inundation model. It defines the future position of the shoreline based on the current shoreline (relative to MSL) repositioned by the current topography. In order to provide a more realistic and reliable simulation, the shoreline based on the inundation forecast was characterized with respect to the location of the shoreline derived from the erosion model.

The spatial difference between the shorelines generated by the inundation and erosion model was used to characterize the output from the inundation model. This spatial difference was defined by the spatial location of both shorelines and the present erosion rates. Based on these criteria, the shoreline derived from the inundation model forecast was characterized with different degree of uncertainty: high, moderate, and low uncertainty.
Those areas where the shoreline based on erosion was located inland with respect to the shoreline based on inundation were categorized as high or moderate uncertainty. It is probable that the inundation model underestimates the geomorphic processes acting in those areas, and for that reason, elevated degrees of uncertainty were assigned to those segments in the projected shoreline. On the other hand, when the shoreline based on inundation was located inland with respect to the shoreline based on erosion, the shoreline was categorized as low uncertainty.

To determine the extent of the high and moderate uncertainty class, it was considered the erosion rates that the current shoreline presents. The projection of the shoreline that coincides with the slight and low erosion categories were coded as moderate uncertainty, whereas moderate and high erosion categories were classified as high uncertainty. On the other side, the projections of the shoreline that coincides with the erosion rates in the categories no change, protected or accretion were characterized as low uncertainty.

Both integrated forecast approaches attempt to combine erosion and inundation process in order to evaluate the potential transgression of MSL into the future. In doing so, the study assesses the impacts these processes have over future shallow water habitat, in particular, tidal wetlands. Since MSL marks the seaward boundary of tidal wetland habitat, any long-term shift in the position of this datum will impact the long-term sustainability of tidal marsh communities. The following analysis examines this concept in more detail.
Wetland Stability and Sustainability

Considering the outputs of the Maximum Change approach in each scenario, the long-term risk to nearshore wetlands and the potential habitat zone that wetlands can occupy in 50 years were assessed taking into account the projected shorelines (relative to MSL) and the upper limit for vegetated tidal wetlands. The future distribution of tidal wetlands under the projected scenarios of sea-level rise was estimated for the study area in three primary ways. The first analysis was conducted to estimate potential tidal wetland habitat area (vegetated wetlands) in relation to sea-level rise and land development. The second analysis assessed the net change of wetlands under the three different scenarios, which was computed based on wetland loss and their capacity to vertically accrete and/or horizontally migrate. In those areas where wetlands cannot keep pace with the sea-level rise, the potential of landward migration of the wetland was assessed. The final evaluation considers the vulnerability of existing tidal marshes to anticipated sea-level rise over the next 50 years based on landscape conditions including bank height, shoreline hardening, and riparian land development.

Potential Tidal Wetland Habitat (vegetated wetlands)

Tidal wetland habitat was defined as the area between the shoreline (relative to MSL) and the landward elevation at twice the tidal range above mean low water (MLW). Existing and projected potential tidal wetland habitat areas (based on sea-level rise scenarios) were estimated using ESRI’s ArcGIS® 3D Analyst. Land use data (2002 Land
Use/Land Cover for Maryland – from Maryland Department of Planning) were analyzed in relation to recently defined shifts in tidal wetland habitat, given that land development has the potential to prevent habitat horizontal migration. Using the GIS Identity function, which calculates a geometric intersection of the input features (potential wetland habitat) and identity features (land use); area of development coincident with projected tidal wetland habitat was computed. The area of land development (2002 Land Use categories: high-density residential; medium-density residential; low-density residential; commercial; industrial; and institutional) that occurred within the projected change in the tidal wetland habitat zone was then subtracted from projected tidal wetland habitat.

The current tidal wetland habitat zone was originally analyzed to extend from MSL to an elevation above MLW equal to 1.5 times the mean tide range (based on jurisdictional wetland boundaries in Virginia (Code of Virginia § 28.2-1300). Upon examination of tidal wetland distribution with respect to this elevation, it was observed that wetlands extended above that zone in some cases. For that reason, the delineation of the current and potential wetland habitat zone was extended from MSL to double the tidal range to accommodate a higher percentage of existing wetlands.

After developing the contour lines for the projected upper limit of vegetated wetlands for each scenario, it was observed, in many cases, that these contours were present inland of the 600 meter landward cutoff established for this study. For that reason, the wetland analysis was restricted only to the segment number 1 (section of the
Choptank River shoreline). This area of Dorchester presents higher topography, and as a result, all projected contours fall inside the 3-D surface generated for this study.

**Potential Net Change of Wetland Coverage (vegetated wetlands)**

The criteria to determine the potential areas of wetland loss were based on the presence of wetlands within the area lost (area between baseline MSL and projected shorelines derived from the maximum change approach) and the capacity of the wetland to accrete vertically and/or migrate horizontally landward. Potential areas of wetland loss were identified and computed. In order to calculate the net change of wetland coverage in each scenario, the potential area of wetland loss was corrected with the corresponding potential wetland habitat that will be available for wetland migration under the different rates of sea-level rise.

An important process that was considered when evaluating the potential wetland loss is vertical accretion. As discussed before, given that there is no consensus in the literature regarding a vertical accretion rate for wetlands under rising sea level conditions, this study assumed that wetlands cannot accrete vertically at rates greater than 3.48 mm/yr (conservative estimate for sea-level rise used in this study). This means that only under the first scenario do wetlands have the opportunity to vertically accrete. At any accelerated rate of sea-level rise, they are unlikely to keep pace with rising water levels and will be subject to in-place drowning and conversion to open water unless horizontal
landward migration can occur. Based on this assumption, future position of wetlands is controlled by erosion rates only in the first scenario (sea-level rate of 3.48 mm/yr).

*Tidal Marsh Vulnerability (vegetated wetlands)*

This study uses wetland distribution and areal extent from the Maryland Department of Natural Resources (MD DNR). These digital data files are records of wetland location and classification as defined by the U.S. Fish & Wildlife Service's National Wetlands Inventory (NWI) program. These wetlands were mapped using Maryland's Digital Orthophoto Quarter Quads Data (3.75 minute by 3.75 minute blocks). The wetlands were interpreted from the photography flown during the period 1988 – 1995.

The vulnerability of existing tidal marshes to anticipated sea-level rise was assessed in relation to the landscape. This study assumed that high bank height, onshore structures, and developed riparian land will impede the natural migration of wetlands. In other words, vegetated wetlands within a landscape setting that contains upland managed lands, erosion control structures placed landward of the wetland, and/or high bank height are more vulnerable to sea-level rise due to their inability for landward transgression.

Data on shoreline and riparian characteristics were extracted from the Maryland Comprehensive Shoreline Inventory (Berman et al., 2006). The Inventory evaluates land use, shoreline protection (presence of shoreline structures for shore protection and
recreational purposes), as well as information about shoreline stability. This data set provides updated information about the riparian zone, which is defined as a 9-meter zone from the water edge. This distance is based on the buffer width presumed necessary to reduce nutrient input from upland runoff into receiving waters. The Inventory categorizes bank height at the shore in four ranges: 0 to 1.5 meters, 1.5m to 3m, 3m to 9m, and >9m.

The slope of the bank would be the ideal variable to assess opportunities for wetland horizontal migration. The calculation of bank slope needs to be made using the cells of the DEM corresponding to the land-water interface. Unfortunately, accurate calculation of the slope is not feasible in this project because the resolution of the available bathymetry data is too coarse to support an appropriate and useful computation. For that reason, this study used bank height data from the Maryland Comprehensive Shoreline Inventory for the analysis. Based on the shoreline bank height categories, this study assumed that the 0 - 1.5 meter bank height category represented conditions under which inland migration may occur.

Lands adjacent or coincident with each tidal marsh were assessed for the presence of obstacles to landward migration: 1) shoreline structures (riprap, bulkhead, or dilapidated bulkhead), 2) riparian development (commercial, industrial, residential, or paved), and/or 3) high bank height (> 1.5 meters). Hence, the potential wetland habitat is restricted to areas of low bank height (0 - 1.5 meters) that are not currently developed and/or do not have a shoreline defense structure directly inland.
Based on these criteria, the current tidal marshes were classified as high, moderate, or low risk. High risk marshes are those completely adjacent to hardened shoreline, riparian land development (e.g. commercial, industrial, residential, paved) and/or banks > 1.5 meters in height. Moderate risk marshes are those adjacent to mixed land use conditions (e.g. partial association with shoreline hardening or riparian development). Marshes that are entirely adjacent to natural lands, a shoreline without structures (bulkhead, dilapidated bulkhead, or riprap), and banks < 1.5 meters were classified as low risk marshes.
RESULTS AND DISCUSSION

Shoreline Forecasting (50 years)

*Forecasting Based on Inundation due to Sea-level rise*

Based on the 3-D surface generated for Dorchester County (study area: 600 m buffer), the current shoreline position was projected and future shoreline positions were forecast (Figure 6). Subsequently, inundation areas were defined and computed for each sea-level rise scenario (Figure 7). In order to make the outputs from the erosion and inundation model comparable, the 2-D inundated area was the parameter used in the calculations.

Inundated areas increase dramatically as the rate of sea-level rise increases (Figure 8). Under the conservative scenario, 6% of the study area will be inundated. When examining accelerated rates of sea-level rise, inundated areas increase considerably. In the second scenario (rate of sea-level rise: 7 mm/yr), the percentage of inundated area increases to 19%. In the third scenario (rate of sea-level rise: 16 mm/yr) the inundated area is increased to 63%. For all scenarios, major inundated areas correspond mainly to the low-lying topography in the southern portion of the county (especially land by the Fishing Bay).
Data Limitations

Forecasting models involve several assumptions and approximations. A common procedure to assess the model’s predictive accuracy is to perform a propagation of error analysis to quantify the errors in the projections. In the present study, this procedure was not feasible given that the original datasets that were employed do not have any error values associated with them.

There are different sources of potential error in the generation of the 3-D elevation surface. A major one is the variable accuracy of bathymetric data, which span a long historic period. The accuracy in those areas without recent bathymetry is more questionable given that erosion and sedimentation processes modify those soundings.

Resampling of topographic data derived from LIDAR was necessary because the original data set contains millions of points and processing times were prohibitive for this project. In addition, this process requires significant computer memory and storage. The resampled dataset was a lower resolution product (10-meter) but enabled the ArcGIS geoprocessing tools to run efficiently.

The merging of the bathymetric and topographic data presented different challenges as well. There are also diverse causes for improper functioning of the Topo to Raster tool. The primary problem faced was insufficient system resources. The algorithms employed in Topo to Raster hold as much information as possible in memory
during processing. This permits point and contour data to be accessed simultaneously. It is essential to have sufficient amounts of system swap space on disk as well (ESRI 2009). This issue was addressed by splitting the study area into 7 manageable segments discussed above, and generating surfaces for each segment. This approach can introduce slight errors in the final mosaic of the segments due to edge effects.

**Forecasting Based on Erosion**

Potential area lost due to the erosion process, and potential area that can be gained through the accretion process was computed in each scenario (Figure 9). In the three cases, the net area loss was calculated (area lost by erosion minus area gained by accretion), and subsequently utilized in the comparison with the inundation model outputs.

Within the 600 m buffer, the total area lost under the conservative scenario was 3%. The area lost in the accelerated scenarios with rates of sea-level rise of 7 mm/yr and 16 mm/yr were 7% and 16 %, respectively (Figure 10). As expected, areas undergoing the most erosion were found at the mouth of the Choptank River and along the Chesapeake Bay (areas with high fetch).
Data Limitations

When forecasting erosion, the final outputs are limited because the calculations did not include factors such as upland slope, deposition and/or re-distribution of sediment along the shore, or impacts of catastrophic events. In addition, potential changes in wind field due to climate change were not considered. Changes in wind field directly affect the wave energy that impacts on the shoreline, but attempting to calculate those changes was beyond the scope of this study. Moreover, demographic changes and the potential for an increase in the use of erosion control structures are not considered in the analysis. Currently, 14.1% of shoreline inventoried in Dorchester tidal waters is hardened (73.8 km hardened/522.7 km shoreline surveyed) (Berman et. al., 2006). However, an increase in shoreline armoring can be expected along developed shoreline for protection against sea-level rise and increased storm intensity. Therefore, the erosion forecast may underestimate or overestimate the adverse impact on different areas of Dorchester shoreline.

Integrated Shoreline Forecast

When comparing the independent outputs of the inundation and the erosion model, the inundation model generated a greater area of land loss than the erosion model. Moreover, as higher rates of sea-level rise were modeled, the area lost due to inundation increased considerably faster than the loss projected in the erosion model (Figure 11).
After integrating the outputs derived from the inundation and the erosion model using the maximum change approach, the greatest possible change in land area for each scenario was obtained (Figure 12). The percentage of area lost under the conservative scenario was 8%, whereas a loss of 24% and 67% were the values in the second and third scenario, respectively. When comparing the results among the two independent models and the integrated model, it was revealed that the inundation model approximates the output of the Maximum Change for all 3 scenarios (Figure 13).

Characterization of the Inundation Model output to reflect the shoreline reach positional uncertainty that might be attributed to erosion allowed determining the percentages of shoreline that fall in each uncertainty class (Figure 14). The percentage refers to the total length of the shoreline in each scenario. Due to the water intrusion in the land, the length of shoreline increases as we move to more accelerated rates of sea-level rise. Table 3 depicts the percentage of shoreline in each uncertainty class for each projected scenario. Despite the length of the shoreline in each scenario, it can be observed that segments along the shorelines with low uncertainty are considerably greater than the segments that fall in the other two categories. In addition, the difference between the low category and the other two categories increases toward accelerated rates of sea-level rise, suggesting that the inundation process plays a more important role when forecasting the accelerated scenarios (Figure 15).
Wetland Stability and Sustainability

*Potential Tidal Wetland Habitat (vegetated wetlands)*

Projected tidal wetland habitat for segment 1 (sections of the shoreline by the Choptank River) experienced an overall decline with rising sea level (Figure 16 and Table 4). The potential loss ranges from 8% under the conservative scenario to 55% when considering the highest accelerated scenario of sea-level rise (16 mm/yr). This estimation assumes no additional increase in development pressure in the future. The projected future decline of tidal wetland habitat for this particular area of the County can be attributed to the increasing relief and increasing proportion of developed land as the shoreline moves inland.

*Potential Net Change of Wetland Coverage*

First, the potential loss of wetland coverage was evaluated along segment 1 using the output of the Maximum Change approach in each scenario. Six percent of the wetland coverage will be potentially lost under the conservative scenario. This loss is attributed solely due to the erosion process. Wetland loss due to inundation was not considered in this scenario based on the assumption that under the rate of sea-level rise of 3.48 mm/yr, wetlands can vertically accrete and keep pace with sea-level rise. When considering the accelerated scenarios, the wetland coverage decreases by 24% and by 77% during the second and third scenario, respectively (Figure 17).
Second, to determine the net change of wetland coverage, these losses were evaluated and corrected with the potential tidal wetland habitat that will be available in each scenario (Table 5). In all the cases, the net change was positive, suggesting that opportunities for wetland landward transgression may exist in this area. Therefore, the calculated loss of wetlands associated with inundation is offset by the opportunity for new wetland creation in areas that were once vegetated uplands.

*Tidal Marsh Vulnerability*

The amount of marshes in segment 1 classified as “low risk” (70%) is considerable greater than the marshes falling in the “moderate risk” or “high risk” category (Figure 18). Given that this vulnerability analysis is based on site-specific conditions, it can be expected that these numbers vary significantly when considering the tidal marsh vulnerability for the entire County.
CONCLUSIONS AND FUTURE WORK

Shoreline Forecasting (50 years)

Inundation models have been developed to estimate the potential effect of sea-level rise on different coastal habitats (e.g. Larsen et al., 2004; Johnson et al., 2006). Nevertheless, these models either do not consider the combined effects of the erosion and inundation process, or they do not take into account the pressure exerted by anthropogenic stressors. To overcome these deficits, the model proposed in this thesis shows new methodologies for combining the results from a two-dimensional erosion model and a static three-dimensional inundation model. This approach allows to more accurately predicting the future shoreline position and the most suitable habitat for wetlands.

Based on the results of the independent and the integrated forecasts, it can be concluded that the inundation model produces a reasonable approximation of the future position of the shoreline in Dorchester County. This would be useful for planning needs for an individual locality or region planning district. However, the output of the erosion model should also be considered in conjunction with the inundation model for site-specific assessments. This is especially true for areas with a long fetch where the potential area lost can be underestimated.
Wetland Stability and Sustainability

Dorchester County is significantly vulnerable to the impacts of rising sea levels, due to its diverse shoreline geometry, orientation, and low lying topography. Even though wetlands and other important habitats currently experience some natural and anthropogenic stress, these resources will become increasingly threatened over time. This will be the result not only from rising sea level, but also from the increase in development pressure and the predisposition to harden shoreline in an effort to protect private properties.

A broad spectrum of environmental problems and their associated economic impacts are created by the loss of tidal wetlands. For instance, this loss will generate degradation in water quality within the region, as well as provoke loss of key organisms (Mitsch and Gosselink 2000), which will lead to changes in the food web. Planners and decision-makers need to rely on existing models to identify those areas where wetlands are under the greatest threat. The integration of the inundation and erosion model presented in this thesis provides important insight into how to determine more accurately habitats that can be lost under different scenarios of sea-level rise. This capacity to map alternate realities (i.e. different sea-level-rise scenarios) allows planners, decision-makers, as well as coastal researchers to forecast the effects of rising sea level on the coastal zone. This information will enhance their capacity to develop better strategies and to identify and mitigate any potential adverse impacts on wetlands habitats. In addition,
this can assist to identify future locations of wetland habitats and where wetland protection and restoration activities can be focused.

Three assessments were presented in this study to provide different perspectives to evaluate wetland stability and sustainability. The outputs resulting from the wetland analysis reflect the unique site-specific characteristics of segment 1 (sections of the Choptank River), and for that reason, results may vary significantly in other sections of the county. For instance, it can be anticipated that in the low-lying Southern part of Dorchester, topography and rate of sea-level rise are the most important variables in forecasting future shoreline position and the fate of the wetlands. In contrast, erosion rates may play a predominant role in future shoreline position and wetland stability in high relief areas by the mainsteam of the Chesapeake Bay. These results will be highly affected by changes in land development which motivates shoreline defense efforts..

The outputs derived from the potential wetland habitat assessment can be overestimated given that calculations were made based on current land use. Nevertheless, this approach in conjunction with the tidal marsh vulnerability assessment allows identifying areas where future development pressures could be controlled in favor of protecting wetlands into the future; giving them the opportunity to migrate landward and be sustained. It has been well documented that under disturbed environmental conditions, wetland habitats require accommodation space that allow them to migrate (Najjar et al., 2000; Nicholls and Lowe, 2004). For that reason, management strategies need to include the conservation of surrounding environments to guarantee that adequate space is
available for vegetation transgression (Hickey and Bruce, 2010). Preserving landscapes that permit the transgression of wetland habitat should be a major conservation priority.

Summary

- Topographic data and sea-level rise projections were employed to forecast shoreline position over the next 50 years within the framework of a three-dimensional spatial analysis.

- Planimetric historic erosion/accretion rate data and estimates of accelerated erosion/accretion rates for the study area were utilized to forecast shoreline position over the next 50 years within the framework of a two-dimensional spatial analysis.

- The outputs derived from the inundation and erosion forecasts were integrated using two different approaches: Maximum Change and Characterization of the Inundation Model. These integrations allowed evaluating the independent and combined effect of these physical processes.

- The evaluation of wetland responses due to the predicted shoreline changes was restricted solely to segment 1 of the study area (sections of the shoreline by the Choptank River). The long-term risk to nearshore wetlands and the potential habitat zone that wetlands can occupy in 50 years were evaluated using three
different analyses: 1) Estimation of the Potential Tidal Wetland Habitat (vegetated wetlands); 2) Estimation of the Potential Net Change of Wetland Coverage; and 3) Tidal Marsh Vulnerability.

The methodology employed in study serves as a first step in combining different forecast approaches to generate a more realistic estimation of the future shoreline position. In addition, it is useful to identify and quantify potential wetland loss due to rising sea level. If a more comprehensive projection is desirable in future studies, the addition of other variables such as wind field, upland slope, deposition or re-distribution of sediment along the shore, vertical accretion rates, and salt intrusion could be incorporated in the forecasting. Moreover, if the anthropogenic and natural changes can be continually updated in the model, more accurate mapping of long-term conditions and trends can be developed.
**Table 1.** Tidal datums for Dorchester County.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>MSL</th>
<th>MLW</th>
<th>MHW</th>
<th>2TR</th>
<th>2TR + MLW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Conditions *</td>
<td>-0.0387</td>
<td>-0.2783</td>
<td>0.2031</td>
<td>0.9628</td>
<td>0.6845</td>
</tr>
<tr>
<td>Conservative (3.48 mm/yr)</td>
<td>0.1053</td>
<td>-0.1043</td>
<td>0.3771</td>
<td>0.9628</td>
<td>0.8585</td>
</tr>
<tr>
<td>Accelerated (7 mm/yr)</td>
<td>0.3113</td>
<td>0.0717</td>
<td>0.5531</td>
<td>0.9628</td>
<td>1.0345</td>
</tr>
<tr>
<td>Accelerated (16 mm/yr)</td>
<td>0.7613</td>
<td>0.5217</td>
<td>1.0031</td>
<td>0.9628</td>
<td>1.4845</td>
</tr>
</tbody>
</table>

Tidal Range for Dorchester = 0.4814

*Calculations for the current conditions were based on VDatum software (NOAA).*

MSL = mean sea level  
MLW = mean low water  
MHW = mean high water  
TR = tidal range
Table 2 – Projected scenarios that were spatially compared.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Shoreline Projection due to INUNDATION</th>
<th>Shoreline Projection due to EROSION</th>
<th>INTEGRATED SHORELINE FORECAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Conservative)</td>
<td>Conservative inundation projection ((Sea-level rise rate = 3.48 \text{ mm/yr}))</td>
<td>Conservative erosion/accretion projection</td>
<td>Conservative inundation projection &amp; Conservative erosion/accretion projection</td>
</tr>
<tr>
<td>2 (Accelerated)</td>
<td>Accelerated inundation projection ((Sea-level rise rate = 7 \text{ mm/yr}))</td>
<td>Accelerated erosion/accretion projection ((Corrected with sea-level rise rate = 7 \text{ mm/yr}))</td>
<td>Accelerated inundation projection &amp; Accelerated erosion/accretion projection ((Sea-level rise rate = 7 \text{ mm/yr}))</td>
</tr>
<tr>
<td>3 (Accelerated)</td>
<td>Accelerated inundation projection ((Sea-level rise rate = 16 \text{ mm/yr}))</td>
<td>Accelerated erosion/accretion projection ((Corrected with sea-level rise rate = 16 \text{ mm/yr}))</td>
<td>Accelerated inundation projection &amp; Accelerated erosion/accretion projection ((Sea-level rise rate = 16 \text{ mm/yr}))</td>
</tr>
</tbody>
</table>
**Table 3** – Characterization of the Inundation Model - Percentage of shoreline in each uncertainty class.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Uncertainty</th>
<th>Moderate Uncertainty</th>
<th>High Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative (3.48 mm/yr)</td>
<td>72</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>Accelerated (7 mm/yr)</td>
<td>81</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Accelerated (16 mm/yr)</td>
<td>87</td>
<td>9</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 4 – Potential change in tidal wetland habitat in segment 1.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>2 x Tidal Range (km²)</th>
<th>Development (km²)</th>
<th>Potential Wetland Habitat * (km²)</th>
<th>Change in Wetland Habitat (km²)</th>
<th>Change in Wetland Habitat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Conditions</td>
<td>7.1</td>
<td>0.4</td>
<td>6.7</td>
<td>...........</td>
<td>...........</td>
</tr>
<tr>
<td>Conservative (3.48 mm/yr)</td>
<td>6.7</td>
<td>0.5</td>
<td>6.2</td>
<td>-0.5</td>
<td>-8</td>
</tr>
<tr>
<td>Accelerated (7 mm/yr)</td>
<td>5.8</td>
<td>0.6</td>
<td>5.2</td>
<td>-1.5</td>
<td>-22</td>
</tr>
<tr>
<td>Accelerated (16 mm/yr)</td>
<td>3.8</td>
<td>0.8</td>
<td>3.0</td>
<td>-3.7</td>
<td>-55</td>
</tr>
</tbody>
</table>

* Potential habitat was computed in each scenario by estimating the area between the MSL and the elevation twice the tidal range above MLW that does not concur with developed lands.
Table 5 – Net change of wetland coverage under each projected scenario.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>Wetland Loss Based on Maximum Change Approach (km²)</th>
<th>Wetland Loss Based on Maximum Change Approach (%)</th>
<th>Potential Wetland Habitat in the next 50 years (km²)</th>
<th>Net Change (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative (3.48 mm/yr) *</td>
<td>0.2</td>
<td>6</td>
<td>6.2</td>
<td>6.0</td>
</tr>
<tr>
<td>Accelerated (7 mm/yr)</td>
<td>0.8</td>
<td>24</td>
<td>5.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Accelerated (16 mm/yr)</td>
<td>2.6</td>
<td>77</td>
<td>3.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* It was considered in the calculations that only under the conservative scenario wetlands will have the opportunity to vertically accrete.
**Figure 1.** Shoreline Change Forecast and Wetland Response Model
*(Model applied in each of the three scenarios)*

![Model Flow Diagram](image-url)
Figure 2. Schematic diagram of the major processes affecting wetland stability and sustainability
Figure 3. Study area - Dorchester County, Maryland.
Figure 4. Segments employed to develop the 3-D model surfaces
**Figure 5** – Schematic representations of the integrated shoreline approaches.

**Maximum Change Approach**

Maximum Change = Inundation + Erosion

**Characterization of the Inundation Model**

Low Uncertainty = Erosion < Inundation
Moderate Uncertainty = Erosion > Inundation
High Uncertainty = Erosion >> Inundation
Figure 6 – Shoreline positions based on the inundation model (sample area: section of segment 1). The inundation model map displays the 3-D surface of the land/water interface and the constructed current and projected mean sea level contours.
Figure 7—Inundated areas in each projected scenario for the sample area in segment 1.
Figure 8 – Percentage of inundated areas in each projected scenario.
Figure 9 – Areas that potentially will be eroded/accreted in each projected scenario for the sample area in segment 1.
Figure 10 – Percentage of eroded area (net loss) in each projected scenario.
Figure 11 – Comparison between the area lost due to the erosion and inundation model.
Figure 12 – Outputs of the individual models and the product of integrating them using the Maximum Change Approach (sample area in segment 2 – mouth of the Choptank River)
Figure 13 – Comparison of the percentage of area lost based on the individual models and the Maximum Change Approach.
Figure 14 – Outputs of the individual models and the product of integrating them using the Characterization of the Inundation Model Approach (sample area in segment 2 – mouth of the Choptank River).
Figure 15 – Characterization of the Inundation Model: Percentage of shoreline in each uncertainty class.

- **Conservative Scenario - 3.48 mm/yr**
  - Low Uncertainty: 72%
  - Moderate Uncertainty: 23%
  - High Uncertainty: 5%

- **Accelerated Scenario - 7 mm/yr**
  - Low Uncertainty: 81%
  - Moderate Uncertainty: 14%
  - High Uncertainty: 4%

- **Accelerated Scenario - 16 mm/yr**
  - Low Uncertainty: 87%
  - Moderate Uncertainty: 9%
  - High Uncertainty: 4%
Figure 16 – Percentage of potential change in tidal wetland habitat (vegetated wetlands) in segment 1. Potential habitat was computed in each scenario by estimating the area between MSL and the elevation twice the tidal range that does not concur with developed lands.
Figure 17 – Percentage of potential tidal wetland loss in segment 1. Potential wetland habitat that will be available in the next 50 years is not considered in these projections.
Figure 18 – Tidal Marsh Vulnerability from projected sea-level rise in relation to landscape settings (i.e. developed lands, hardened shoreline and high bank height) corresponding to segment 1. Total tidal wetlands evaluated = 3.4 km².
APPENDIX A

Assessment of the spatial distribution of historic erosion rates calculated for the study area and their relationship with the historic rates of sea-level rise (at NOAA’s Cambridge Tidal Gauge Station, Dorchester County)

**Historic Rates of Sea-level rise**

<table>
<thead>
<tr>
<th>Station</th>
<th>Data From</th>
<th>Data To</th>
<th>Rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore</td>
<td>1902</td>
<td>2006</td>
<td>3.08</td>
</tr>
<tr>
<td>Annapolis</td>
<td>1928</td>
<td>2006</td>
<td>3.44</td>
</tr>
<tr>
<td>Solomons</td>
<td>1937</td>
<td>2006</td>
<td>3.41</td>
</tr>
<tr>
<td>Cambridge</td>
<td>1943</td>
<td>2006</td>
<td>3.48</td>
</tr>
<tr>
<td>CB City</td>
<td>1972</td>
<td>2006</td>
<td>3.78</td>
</tr>
</tbody>
</table>

For this thesis, the rate of sea-level rise calculated at NOAA’s Cambridge Tidal Gauge Station in Dorchester County was employed. The long-term historic rates of sea level and the mean sea level trend were calculated by the National Oceanographic and Atmospheric Administration, Center for Operational Oceanographic Products and Services (CO-OPS). The averaged sea-level rise rate computed at this station is 3.48 millimeters/year with a 95% confidence interval of +/- 0.39 mm/yr based on monthly mean sea level data from 1943 to 2006.

**Historic Erosion/Accretion Rates**

In the text that follows, a brief overview of how shoreline erosion rates were determined by Hennessee et al. (2003) for the coastal regions of Maryland is presented.

The digital shorelines used for the analysis correspond to the time period: 1841-1995. The extent of the oldest shorelines incorporated on the maps is largely restricted to the main stems of the Chesapeake Bay and its tributaries. Little historical information is available for minor tributaries.

The available shorelines were used as input into a computer program, the Digital Shoreline Analysis System (DSAS). Basically, DSAS constructs a baseline inland of and parallel to a series of shorelines, casts closely spaced transects perpendicular to the baseline across the shorelines, and finally determines rates of change along each transect.
DSAS calculates rates of change for a specific transect by dividing the distance between each shoreline, relative to the baseline, by the time elapsed between shoreline positions.

The number of historical shorelines available for the entire Maryland coast is not constant. In some sections, shorelines for as many as five different years are available; whereas in other places, only one has been digitized. Hence, the number of eras varies from transect to transect. To generalize the DSAS results and assign rate of change attributes to a recent digital shoreline, computer operators assigned rate of change for the most recent era to the recent digital shoreline.

**Rate-of-change attributes assigned to the most recent digital shoreline**

<table>
<thead>
<tr>
<th>Rate code (LEVELID)</th>
<th>Rate descriptor (EROSIONLEVEL)</th>
<th>Range of rates (EROSION(FT))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No change</td>
<td>-0.01 to 0.01 ft/yr</td>
</tr>
<tr>
<td>1</td>
<td>Accretion</td>
<td>&gt; 0.01 ft/yr</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
<td>-0.01 to -2.00 ft/yr</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>-2.00 to -4.00 ft/yr</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>-4.00 to -8.00 ft/yr</td>
</tr>
<tr>
<td>5</td>
<td>High</td>
<td>&lt; -8.00 ft/yr</td>
</tr>
<tr>
<td>6</td>
<td>Protected</td>
<td>Protected area</td>
</tr>
<tr>
<td>7</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Based on the above table, computer operators color-coding the transects according to the range of rates. For instance, all transects characterized by a “low” rate of erosion (between -2.00 and -4.00 ft/yr) were depicted in orange, all transects characterized by a “moderate” rate were depicted in red, etc. Conducting a visual scanning of the display, operators cut the shoreline wherever the transect color changed, highlighted the newly cut segment, and assigned the appropriate LEVELID value from the above table. In addition, operators applied the change of attributes only after encountering a series of four or more transects of a different color. The purpose of this step was to delineate fairly long reaches of shoreline sharing similar rates of change (transects were spaced at 20-meter intervals). MGS decided that “fairly long” meant 80 meters or more. Therefore, if a series of red transects was interrupted by three green ones, the entire stretch was classified as though it were red. However, if the series of red transects was interrupted by four or more green ones, the shoreline was cut on either side of the green transects and it was assigned a different rate attribute.
Assessment of the Spatial Distribution of Historic Erosion Rates for Dorchester County

Transects Generated Using DSAS

- Transects - Data before 1943
- Transects - Data after 1943
- Dorchester County
- Land
- Water

0 5 10 20 Kilometers
It can be observed from the above figures that the majority of the transects have data corresponding to the time period after 1943. Only isolated transects correspond to the time period before 1943. Based on the methodology explained before, the coding of the different sections of the shoreline was based on a minimum of 4 consecutive transects with the same rate of change. As the example shows, the transect with data before 1943 did not count in the final classification of that segment of shoreline. This is also the case for the other transects in Dorchester County that fall in the same time period. As a result, it was concluded that the comparison and integration of the historic rates of erosion and sea-level rise for the study area was acceptable in so far as the underlying data was largely contemporaneous.
LITERATURE CITED


Maryland Department of Natural Resources. 1993. DNR Wetlands. http://www.msgic.state.md.us/techtool

Maryland Department of Planning. 2003. 2002 Land Use / Land Cover for Maryland. http://www.mdp.state.md.us


VITA

Mirtha Karinna Nunez Puy

Born in Montevideo, Uruguay on December 19, 1974. Earned a Bachelor of Science in Biochemistry with a concentration in Oceanography from the School of Science, University of the Republic of Uruguay in January 2001. Entered the Master of Science program at the School of Marine Science, Virginia Institute of Marine Science, College of William & Mary in 2007.