Wetlands as a nature-based coastal defense: a numerical modeling and field data integration approach to quantify storm surge attenuation for the Mid-Atlantic region

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I. Introduction

Hurricane Sandy in 2012 demonstrated the vulnerability of the East Coast to extreme events, especially considering projected land development, population growth, and the impacts of sea level rise. These compounding factors have motivated the exploration of resilient coastal defenses that incorporate both hard engineering (i.e., levees, seawalls, breakwaters) and natural strategies such as the restoration, creation and enhancement of coastal wetlands and marshes. The United States Army Corps of Engineers (USACE) has recently begun an effort to build background knowledge of ecosystem-based defenses necessary to implement these strategies in a meaningful manner [1].

The quantification of storm surge attenuation by wetlands has been an area of active research in supporting coastal resilience and risk reduction. A number of previous studies have emphasized the complexity of the hydrodynamic response of wetlands [2]–[4]. Among the many factors impacting the propagation of surge in these natural systems are storm characteristics, surrounding landscape (topo-bathymetry), local surface roughness and vegetation characteristics, as well as the complex interactions of these factors within the marsh environment. This study aims at contributing to the quantification of these impacts and their interactions.

II. Literature Review

Numerical modeling studies have improved our understanding of the interconnectedness of these factors, and have supported the expectation that wetlands have the potential to attenuate storm surge. Modeling approaches evaluating hydrodynamic response in wetland environments have largely focused on representation and analysis of marsh characteristics in an idealized manner. Loder et al. conducted sensitivity of water levels simulated by a numerical model using idealized grids representing marsh areas of varying characteristics including surface roughness [5]. Sheng et al. also employed an idealized domain in a three dimensional model to study the reduction of surge by vegetation canopies [6].

While many field studies have been undertaken to quantitatively assess the storm surge attenuation potential of wetlands, few have been carried out to support the calibration of numerical models such that wetlands can be correctly parametrized on a regional scale. More recently, Hu et al. investigated the sensitivity of vegetation characteristics such as stem density and stem height, and the sensitivity of storm characteristics on storm surge reduction, using a three-dimensional model accounting for vegetation as cylindrical structures. Their results for the Breton Sound Estuary in southeastern Louisiana indicate that vegetation as well as storm characteristics (wind intensity and forward speed) impact surge reduction [7], though their study does not account for seasonal variations in vegetation type, or variations in spatial distribution and continuity of marsh transects.

Rates of attenuation based on field investigation have largely focused on marsh areas along the Gulf of Mexico and Florida. There remains a need for storm surge field data collected during hurricane events [8, 9]. Recent studies have undertaken field measurement approaches to measuring storm surge reduction capabilities of marsh vegetation. Several results of such past field studies are summarized in Table 1.

TABLE I. Summary of Attenuation Rates in Past Field Studies

Study	Area of Interest	Attenuation Rates Observed
Lovelace, J. K., 1994 [10]	Southern Louisiana coastal marshes	1m per 20km of marsh and open water; 1m per 23 km over fairly continuous marsh
McGee et al, 2006 [11]	Marshes in Southern Louisiana, Southeastern Texas	Varying from 1m per 4km to 25 km of marsh
Krauss et al, 2009 [12]	Florida mangroves	9.4 cm per 1 km inland
USACE, 1963 [13]	Southern Louisiana	1m per 14.5 km, with high scatter in data
Jadhav & Chen, 2012 [9]	Louisiana salt marsh	4% to 1.5% per meter
Moller et al, 2014 [14]	300m wave flume with 40 m section of transplanted salt marsh vegetation	0% to 19.5% reduction in wave heights

Of note in these field study results, and as reinforced by the Anderson et al. review of both field and numerical studies of wave dissipation over vegetation, there exists a high degree of scatter in these records as a result of the various hydrodynamic factors involved (plant species, continuity, storm/wave conditions, etc.) [8]. Complex marsh characteristics present a particular challenge for numerical model investigations which

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largely rely on formulations of a drag coefficient C_D. Correct parameterization of marsh and vegetation characteristics is thus critical for incorporation of surge attenuation by wetlands into numerical models.

There is thus a need for a systematic method to link modeling and field work to improve parametrization of wetlands in operational models for design of combined natural and hard structure solutions. This study aims to bridge this gap by employing a concurrent numerical modeling and field investigation approach, applied to coastal wetlands in shallow lagoons, discontinuous marshes, and barrier-island/back-bay systems typical of the United States Mid Atlantic coastline. Here we focus on the marsh systems of the lower Chesapeake Bay and the Virginia portion of the Delmarva Peninsula, on the Atlantic Coast of the United Sates.

In the present paper, we first outline the objectives and broad methodologies of each of these on-going efforts. We then describe the site selection process, criteria and rationale. Five potential study sites in the region were initially identified based on site access. These were considered in detail, as described here, and four sites have been chosen from the initial list. Of these, three are currently operational, in that pressure transducers have been deployed over transects, and the sites are accounted for at high resolution in the numerical model.

III. PROJECT OBJECTIVES

The objective of the numerical modeling portion of this study is to broaden the current state of knowledge of the contributing factors to surge and wave attenuation from coastal wetlands. Marshes in this study area are spatially parameterized in the coupled hydrodynamic-wave model ADCIRC-SWAN [15]–[17]. The numerical mesh was adapted from the FEMA Region III unstructured grid [18], with resolution increased to ~10m in the areas of interest. Mesh characteristics are adjusted based on field investigations and surveys. Coastal vegetation present in marsh systems influences model results via wind stress and consequent effect on momentum transfer to the water column, and via friction resistance at the sea bottom. These are accounted for by a wind reduction coefficient due to surface-driven frictional drag, and by a non-linear bottom friction formulation. Areas with dense canopy result in complete blocking of wind stress effects. We conduct realistic, physically-based, region specific parametrization of marshes in ADCIRC-SWAN, and investigate the sensitivity of water levels, water velocities, and wind fields to parameters in the model by varying (1) spatial characterization of Manning's n values to represent bottom friction at high resolution, (2) spatial characterization of the directional surface roughness length coefficient (z_0) impacting momentum transfer, and (3) spatial identification of dense tree canopies. Meteorological forcing includes both historical storms, with data extracted from the National Hurricane Center database, and synthetic storms of varying characteristics. Preliminary results of semi-idealized conditions in the areas of interest indicate that there exists a wide range in the sensitivity of water surface elevations to variations in values of Manning's n (0% to ~55%), reinforcing the need for a more refined evaluation consistent with regionally present vegetation characteristics.

Concurrent with modeling efforts is a 2-year field monitoring campaign at coastal wetland sites selected within the study region, the objective of which is to allow for iterative integration and improvement of the numerical model. Within each site, pressure transducers have been permanently deployed and strategically placed to capture the propagation of storm surge through wetland areas via time series (6 min) water depth data. Fig. 1 shows a field mission to capture data recorded by pressure transducers at one of these marsh sites. These efforts are complimentary to the United States Geological Survey (USGS) Storm Tide monitoring campaign, and allow for an increased resolution of data collection stations. Field measurements are translated to a rate of attenuation across marsh transects, and support the calibration of model results for an accurate parameterization of coastal wetland vegetation. In collaboration with partners from the USGS, investigations of vegetation characteristics (height, diameter, and stem density) will be conducted through summer and fall 2015 to allow for improved understanding of the factors contributing to flow-resistance. A direct deliverable of this effort is a proposed attenuation rate for fetch-limited waterbodies such as the Chesapeake Bay, qualified by the various processes involved in storm surge development and by vegetation characteristics.

Fig. 1. Field mission to retrieve pressure transducer data at the Magothy Bay Natural Area Preserve (Virginia) marsh transect, one of this study's three currently operational field sites.

IV. SITE SELECTION CONSIDERATIONS

The study region includes the Virginia portions of the semi-enclosed Chesapeake Bay and Delmarva Peninsula, from which four sites were to be selected for field investigations and parameterization in ADCIRC-SWAN. Fig. 2 depicts the study region, with relevant National Oceanic and Atmospheric Administration (NOAA) monitoring stations, as well as the locations of the three currently operational field sites for the present study. Though a > 25m deep channel dominates the bathymetry of the Chesapeake Bay, it is relatively shallow throughout, with a mean depth of 6.5 meters. Site selection for 5 available field sites was determined via a series of criteria deemed important to the objectives of this study. Table 2 summarizes the results of this process, and this section describes the criteria considered.

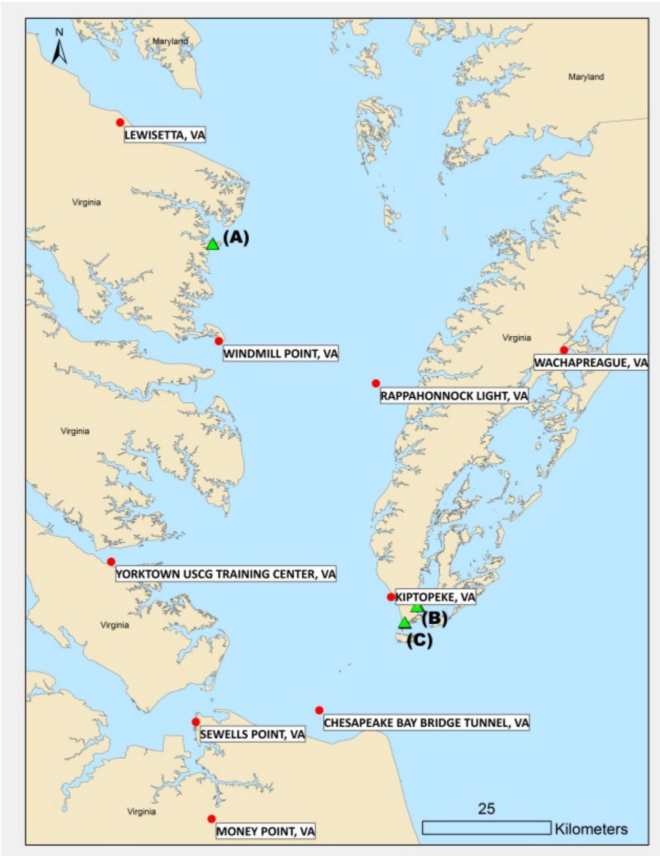

Fig. 2. Study region: The mid and lower portions of the Chesapeake Bay, and the Virginia portion of the Delmarva Peninsula, on the US Atlantic Coastline. NOAA stations used in validation of computational meshes are shown in red, and three operational field site locations are also shown: Dameron Marsh Natural Area Preserve (A), Magothy Bay Natural Area Preserve (B), and Eastern Shore of Virginia National Wildlife Refuge (C).

A. Meteorology & Tides

In such a semi-enclosed bay, hurricane characteristics (forward speed, maximum wind speeds, radius of maximum winds, minimum central pressure) are of particular importance for surge propagation up the bay, and significant accuracy can be gained by increasing spatial resolution of the wind field for numerical modeling of surges [19]. Storm surge maximum water surface elevations (MWSE) were generated for four historical storms which had significant impacts on Chesapeake Bay coastal communities. Hurricanes Floyd (1999), Isabel (2003), Irene (2011), and Sandy (2012) were simulated in ADCIRC-SWAN, using a parametric asymmetric wind model with inputs from the NHC best track database, over a modified FEMA Region III numerical mesh. MWSE maps were examined at each potential site for extent, depth, and apparent direction of flooding. At the Rappahannock Light station near the middle of the Bay, wind speeds and direction were aggregated over a 10-year period (2004 to 2014), to examine the prevalent winds acting on the Bay (Fig. 3). Northerly winds (NNW to NNE) exhibit the highest observed wind speeds, reaching nearly 20 m/s. Northerly winds reaching speeds exceeding 10m/s represent 11% of the record, while Southern winds of similar intensity only comprise 3.4% of the record. The range of tidal amplitudes experienced in the Bay was also considered. A ten-year tidal record was aggregated at 5 NOAA stations along the profile of the Bay, from the mouth at the Chesapeake Bay Bridge station, north to Washington, D.C. along the Potomac River. These results are plotted at each station in Fig. 4.

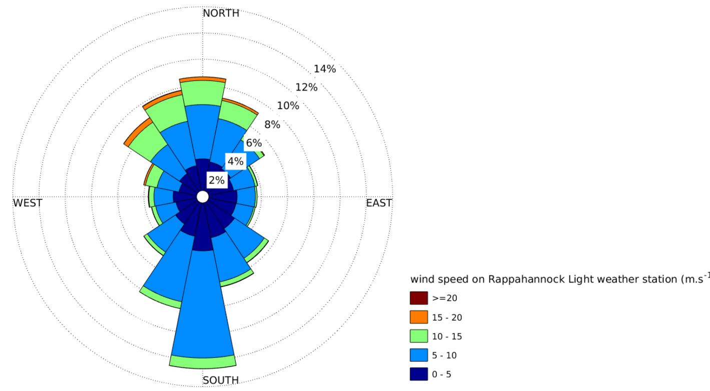

Fig. 3. Wind rose depicting wind speeds, directions, and percent of total from 2004-20014, at Rappahannock Light NOAA Station.

B. Vegetation

The Chesapeake Bay wetlands present various vegetation characteristics. This study considers vegetation in terms of its physical composition and its resistance to storm surge propagation. The choice of multiple sites along the Bay, and along the Delmarva Peninsula, allows for consideration of the interaction of storm surge with various vegetation types present, and thus various characteristics such as stem density and height.

C. Topography & Marsh Geometry

With respect the elevation and internal geometry of each potential marsh, low flat areas reduce the effect of the marsh slope on attenuation, and are thus preferable for isolating the effect of vegetation resistance to surge. The length of each transect is of importance in capturing a measurable attenuation. Transects of various lengths, over similar vegetation types, will allow for the development of a reasonable range of attenuation rates for the predominant vegetation types seen in the study region, and for a range of hydrodynamic conditions (storm characteristics). These rates are then tested in the numerical model to determine the most appropriate vegetation parametrizations for inclusion of wetlands in coastal management considerations.

V. Operational Sites

The project currently has three sites in operation, chosen with consideration of the criteria described above. These are summarized in Table 2. The three sites offer a range of spatial scales (length of possible transects), a range of exposures to storm surge owing to their locations along the Bay or on the Atlantic coastline, and a range of topographic characteristics.

TABLE II. CHARACTERISTICS OF FIELD SITES IN OPERATION

Study site	***Location***	***Max. Fetch Distances***	***Vegetation***	***Max. Transect Lengths***
Dameron Marsh Natural Area Preserve	On Vriginia's Coastal Plain, at widest point of the bay	N: 5 km, NE: 70 km, S: 120 km	Salt marsh	~ 200 m
Magothy Bay Natural Area Preserve	3 km Northeast of Eastern Shore marsh site. Barrier-island back bay system of Delmarva Peninsula	NNW: 100 to 200 km + refraction; S: open sea + barrier island	Salt marsh:	~750 m
Eastern Shore of Virginia National Wildlife Refuge	At Chesapeake Bay mouth, at southernmost edge of Delmarva Peninsula; north of Fisherman's Island, VA	NNW: 100 to 200 km + refraction, S: open sea + barrier island	Salt Marsh	~ 250 m

A. Dameron Marsh Natural Area Preserve

The Dameron Marsh Natural Area Preseve consists of a 2 km, 1.28 km^2 peninsula oriented east to west, off the Northern Peninsula of Virginia. preserve contains one of the most significant wetlands on the Chesapeake Bay for marsh-bird communities, and its pristine beach habitat is highly important for the federally threatened northeastern beach tiger beetle. The site was selected to represent the western coast of the Chesapeake Bay ecosystem and capture wetland response to storm activity within the bay. Although the storm surge conditions are quite different from the eastern shore sites, the Dameron Marsh has a unique geographic location that makes this reserve highly exposed to storm surges generated inside the bay. In such a semi-enclosed bay setting, hurricane characteristics (e.g. forward speed, maximum wind speeds, radius of maximum winds) are particularly significant in surge generation. Three pressure transducers are currently in place on this site to be used to derive water surface elevations for baseline tidal and flooding conditions in model calibration.

B. Magothy Bay Natural Area Preserve

This 1.6 km^2 preserve encompasses woodlands, forested wetlands and extensive salt marshes. These communities provide habitat for a variety of coastal species including waterfowl, shorebirds and wading birds that forage in the salt marsh for mussel, snails, fish and crustaceans. Diamondback terrapins and clapper rails are common on the mud flats. This site offers a unique combination of constructed levees and coastal wetlands that offer redundancy in salt marsh measurements along the outer perimeter while introducing the effects of a levee to differentiate data along this extensive marsh. In examining model-generated flood maps for

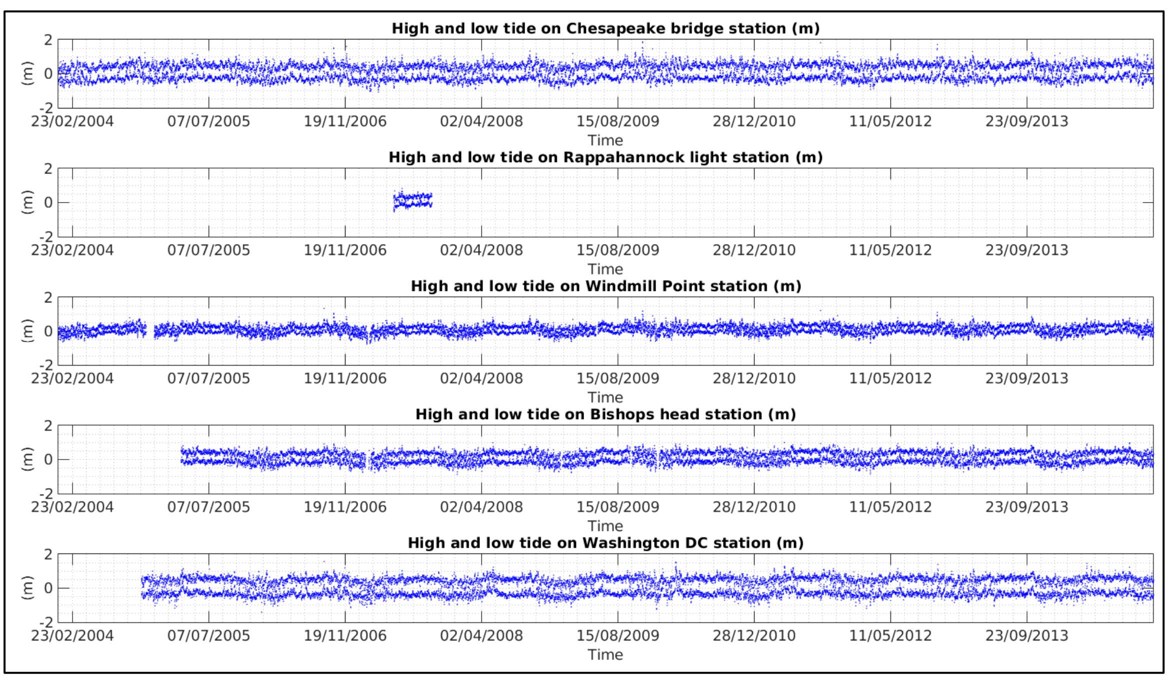

Fig 4. Tidal record from 2004 – 2014 for five NOAA stations along the Chesapeake Bay, with the Chesapeake Bay Bridge Station at the Bay mouth, north to Washington, D.C. station.

Hurricanes Floyd (1999) and Irene (2011), this site showed flood depths of 0.5 – 1 meter. This area also lends itself to a longer transect able to accommodate a dense array of sensors. There are currently five pressure transducers deployed in this marsh.

C. Eastern Shore of Virginia National Wildlife Refuge

Located at the tip of the Delmarva Peninsula, this area is one of the most important avian migration funnels in North America. The ESVR site was selected for instrumentation due to the following favorable characteristics: a) this salt marsh is relatively unprotected by barrier islands at the land-sea interface, and b) the low elevation, low gradient geographic profile decreases potential error in analysis of energy loss due to elevation change. On this site, northerly winds have a fetch distance between 100 km (NNW) and more than 200 km (N), but waves generated in the bay by strong winds will be refracted around the cape of the Delmarva. Southerly winds have an unlimited fetch here, though barrier islands act to attenuate waves. Lovelace, J.K. observed an unexpectedly strong influence of hydrodynamics in the back of similar barrier island systems, owing to low elevation and discontinuity of the marsh. Tidal amplitudes here are moderate (0.5 – 1m), but the site is highly exposed to surge flooding – 2.5m and 4m of flooding were seen during Hurricane Isabel and Floyd model simulations, respectively.

VI. Discussion

This paper has presented the objectives and broad methodology of a 2-year effort to combine field work and numerical modeling to quantify storm surge attenuation of wetlands in the Chesapeake Bay region. The criteria considered in selection of marsh sites included exposure to storm surge based on simulations of historical storms, presence of salt marsh vegetation, topography and internal marsh geometry. Three sites have been identified and have been instrumented with pressure transducers deployed over transects of 200 to 750 m. Future work will present methods used in calibrating ADCIRC-SWAN using the water level data collected and processed from these sites, as well current profiler data. Of particular consideration in numerical modeling efforts for this study is that of computation cost. A high-resolution computational mesh (~10m) is necessary to capture the complex hydrodynamics in marsh systems. Furthermore the computational domain must stretch far enough from the coastline to adequately capture the propagation of waves and storm surge. The mesh employed here is a 1.2 million node mesh extending to the 15m inland contour, and to the 60 degree Prime Meridian in the Atlantic Ocean. To reduce computational costs significantly, while allowing for adjustments to the mesh, and to the vegetation parameterization at the chosen marsh sites, a subdomain modeling method developed by Baugh et al. will be utilized [20].

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