Quantifying the Future Flood Impact and Damages in the Chesapeake Bay Regions Due to Storm Surge, Sea Level Rise and Marsh Migration

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Abstract

The recurrent flood risks on coastal areas in the United States due to storm surge are likely to increase with warmer climate, frequent storms, and increasing coastal population. In addition, the increasing rate of sea level rise (SLR) is expected to cause submergence of wetlands and marshes across the coastal landscape. Before decision makers can develop effective floodplain management and climate adaptation plans, they need reliable scientific information about the extent of flooding and estimate of future damage due to storm surge, sea level rise and marsh migration. In this study, coastal flood vulnerability in the Chesapeake Bay regions is investigated by using a coupled storm surge and waves model (ADCIRC+SWAN) for low and high intensity historical storms. Regional rate of SLR are combined with respective marsh migration projections in the modeling approach to estimate the future change in flooding, in addition to the existing inundation. To estimate flood damage, modeling results are combined with parcel-level residential property values and flood depth-damage functions for the storms under current conditions and predicted change in sea level and land use. The results suggests that considering a 2.3m SLR scenario, strong hurricanes can result in 3300 Km^2 flooded area with 1-3m depth in coastal counties of Maryland. Comparison between current and future scenarios indicates a 110 to 550 % increase in total flooded area depending on the impact of the hurricanes. The estimated residential property damage due to the combined impact of storm surge and sea level can range from $69.9 to $2310 million affecting more than 0.1 million households in the Bay regions. Increasing inundated area and property loss in the coastal counties also indicate the vulnerability to coastal flooding and necessity to quantify the flood risk for better floodplain management plan.

Introduction:

Coastal areas in the United States (US) are a highly desirable places to live, work, retire and recreate (Board, O. S., 2014), yet they are frequently threatened by flood damages and erosion due to hurricane wind and storm surges. More than 39 percent of the US population (NOAA, 2013) live in the coastal counties which contribute to 37 percent of employment and 42 percent of the national GDP (Kildow et al., 2014). The National Climate Assessment (USGCRP, 2014) suggested that about 25 million people in US are living under the threat of coastal flooding. Additionally, global financial losses from hurricanes are expected to double by 2100 (Hallegatte 2012) due to the combined effect of climate change, sea-level rise (SLR), the predicted hurricane intensification due to a warmer climate (Knutson et al. 2010), with more frequent storms and increasing coastal populations (Emanuel 2005). Although there is debate on how much the sea level will increase, both tidal records and satellite altimetry from last century indicate a global rise in sea level (Cazenave, 2013). Also, due to different land accretion and subsidence rate (Cazenave, 2010) the SLR rates varies along the US coast (Yin, 2009). While the increasing trend of sea water level would increase flooding and salinity in coastal areas in the short term, reduction in coastal wetlands are more likely to happen on a long term basis (Nicholls, 2010). Furthermore, the combined impact of higher surge heights and increased wave heights is likely to increase tidal inundation and gradual shoreline recession (Stevens, 2010). Though some tidal wetlands might sustain with small relative changes in sea level (Morris et al. 2002; Krauss et al. 2014), higher increase in SLR will lead towards submergence of marshland and landward movement across the coastal landscape (Doyle et al. 2010).

Therefore, to devise effective floodplain management and climate adaptation plans it is highly important to estimate the future flooding and associated damages due to storm surge and sea level rise. Multiple studies (Nicholls, 2002; Hinkerl, 2014; Hallegatte, 2013) have addressed the coastal flooding impacts in a global or regional scale. As the sea level varies on a local scale and effect of hurricanes can be different based on location, intensity, local topography, it is important to quantify the flood risk and vulnerability in a local scale. In this paper, we investigate the potential change in coastal flooding and associated damage due to storm surge, sea level rise and marsh migration. Our study focuses on coastal counties within the Chesapeake Bare areas that are vulnerable to coastal flooding. Using coupled storm surge and wave models (ADCIRC+SWAN) flood inundations are simulated for historical storms for current conditions and future projections. Simulated flood results are combined with depth-damage functions to prepare an estimate in property damage for future scenarios. Comparison of inundation and respective damage for current and future scenarios are evaluated in a county level to address the vulnerability to coastal flooding.

Study Area, Hurricanes and Sea Level Rise:

The Chesapeake Bay is the largest estuary in the US, with an open boundary in the Atlantic Ocean in Virginia to the closed freshwater end in Maryland. The bay is an estuary for a of 64,299-square-mile (166,534 km2) watershed and has about 11,684 miles (18,808 km) of shoreline (Boon, 2010). The Bay ecosystem consists of three kinds of wetlands – salt marsh, brackish marsh and tidal freshwater marsh. Most of the land-water boundaries are low-lying areas which are experiencing a higher land subsidence than accretion (Boon, 2015). Our work focuses on the coastal counties of Maryland (MD) and Virginia (VA) that are within the vicinity of the Chesapeake Bay (Figure 1a).

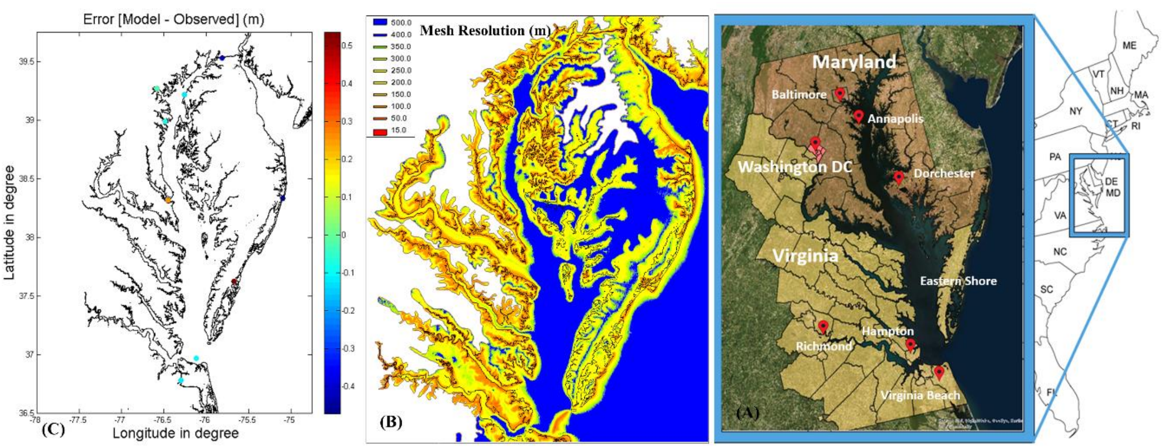

Figure 1: (A) Study Area; (B) Mesh Resolution in the study area; (C) Model Performance

Study by Sallenger (2012) has identified this part of the North Atlantic Coast of US as a "hot spot" for sea level rise. Analyzing the observed data for 1976-2007, Boon (2010) found that the absolute sea level rise rate of about 1.8 mm/yr and 53% relative rise in sea level over the 1976-2007 period. Additionally, inundation from tropical cyclones and extra-tropical storms have amplified the flood vulnerability in the floodplains of the Bay regions. For example, Hurricane Isabel in 2003 caused $5.3 billion in property damage, nearly 80 percent of which was in VA and MD (Blake et al. 2011; NOAA 2004). In 2012, the

Insurance Information Institute ranked Virginia 9th among all states in value of insured properties ($182 billion) vulnerable to hurricanes and coastal flooding.

Models and Methods

To investigate the impact of coastal flooding due to storm surge and sea level rise, the coupled version (Dietrich, 2010; 2011) of hydrodynamic model (ADCIRC) and waves model (SWAN) is implemented for the study area. ADCIRC (Luettich et al. 1992; Westerink et al. 1994) is finite element shallow water hydrodynamic model that solves the generalized wave continuity equation and vertically integrated momentum equations to compute the water surface elevation and current velocity respectively. SWAN is a third generation spectral wave model (Booij et al. 1999) that computes random, short crested wind-generated waves and waves transformation in near shore regions. The coupled ADCIRC+SWAN model runs on same computational unstructured mesh where ADCIRC simulates the water level, current and wind velocities at each computational nodes (Dietrich, 2011) and transfer the computed parameters to SWAN. Using the ADCIRC computed water level, current and wind velocities SWAN recalculates the water depth and wave radiation stresses and their gradients, and then passes it back to ADCIRC as a forcing function (Dietrich, 2011). For this study, Federal Emergency Management Agency (FEMA) Region III mesh is used as the computational domain. The mesh has 1.87 million nodes and a large domain from 60 degree west meridian to coastal inland regions up to 15m contour line (Hanson, 2013). It has a minimum resolution up to 14m in the Chesapeake Bay areas and relatively lower resolution as it extends towards the Atlantic Ocean. Figure 1b shows the variation in mesh resolution in the study area. The bathymetry and topography data for the mesh are combined from multiple national and local sources such as USGS National Elevation Data; NOAA National Ocean Service, National Geophysical Data Center, and USACE database (Forte, 2011). The land cover and land use information are incorporated in the model though frictional drag co-efficient (Manning's N) as bottom shear stress and free surface stress due to winds which is computed using Garret's drag law (Garret, 1977). Land cover data from NOAA's Coastal Change Analysis Program is used to compute the friction parameters in the model. The model is forced with tide in the open boundary which is taken from the Le Provost database (Le Provost et al. 1994). For this study, two historical storms are selected based on wind velocity and pressure intensity to evaluate the range of coastal flooding responses to high and low intensity hurricanes. Hurricane Isabel (2003) with 269 km/hr maximum sustained wind speed and 915 hPa minimum central pressure is considered as one the strongest storms. While with 167 maximum sustained wind speed and 962 hPa minimum central pressure, Hurricane Dennis (1999) is selected as a low intensity storm. The hurricane track location and intensity data are collected from the National Hurricane Center best track database. This study uses the asymmetric Holland wind model (Holland, 1980) built in ADCIRC to compute the wind velocity and pressure at each mesh vertices. In figure 1c, comparison between NOAA tidal gauges and simulated water levels indicates satisfactory model performance with a range of 0.1-0.4m underestimation and overestimation of peak surge heights within the Bay regions.

Sea Level Rise and Marsh Migration

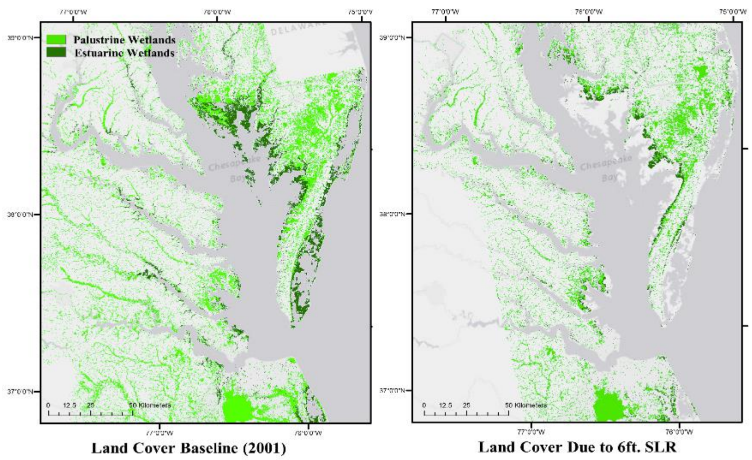

Figure 2: Change in Wetlands and Marshes due to increase in Sea Level Rise

To incorporate sea level rise and respective changes in land cover, local SLR projections are taken from a recent study by Mitchel (2013), and the marsh migration scenarios are collected from NOAA SLR mapping tool. The local SLR projections are adopted from the National Climate Assessment (Parris et al. 2012) by adding the local subsidence rate from observed tidal record. The scenario consists of four projections based on different rate of rise in sea level. To capture the range of the coastal flooding due to SLR, the study incorporates the most extreme or worst scenario, ‘highest’, which resulted from maximum possible ice sheet loss and glacial melting and the lowest or 'historic' scenario taken from the projection of observed long term rate of sea level rise (Mitchel et al, 2013). For changes in wetlands and marshes due to sea level rise, NOAA estimates the landward or seaward movement of marshes for 1 to 6 ft. rise in sea level. The underlying assumption is, with increase in sea level, tidal range and salinity, certain types of marshes, especially the salt marshes, will be unable to maintain their relative elevation and sustain the vegetation within an established tidal range (Marcy, 2011), and eventually submerge in the sea or convert into an intertidal mudflat or open water (Morris et al., 2002). The projection used a modified bathtub approach that includes local tidal range and hydrological connectivity though complex coastal processes such erosion or subsidence are not considered. Figure 2 shows the projected reduction of wetlands and marshes due to 6ft. increase in sea level in the study area. To combine the projected land use change with local SLR the closest marsh migration scenarios are selected for 'historic' and 'highest' SLR. In table 1, projected SLR are provided with baseline and future scenarios that are modeled to estimate the potential coastal flooding.

Table 1: Storms in Baseline and Future Projections

Storm/ Scenarios	**Baseline**	**Storm + Historic SLR + Marsh Migration**		**Storm + Highest SLR + Marsh Migration**	
	No SLR & Existing Land Use	Projected SLR at 2100	Nearest Marsh Migration	Projected SLR at 2100	Nearest Marsh Migration
Isabel (2003)	2001	1.6ft (0.49m)	2 ft.	7.6ft (2.32m)	6 ft.
Dennis (1999)	2001	1.6ft (0.49m)	2 ft.	7.6ft (2.32m)	6 ft.

Results and Discussion

In this section, the absolute and relative change maximum flood elevation, total flooded area are presented and discussed with respective household property damage and population affected due to the combined impact of storm surge, sea level rise and marsh migration. Analyzing the projected land use changes due to SLR, it is found that Maryland is likely to lose 88% of its estuarine and 56% of the existing palustrine wetlands for the highest increase in sea level. However, because of the volume of results and availability of the household property data, the results will focus on the coastal counties of Maryland. Investigating the simulated flooding for current and future scenarios, the results indicate that the impacts of sea level rise on coastal inundation is significantly higher with strong intensity storms than the low intensity ones.

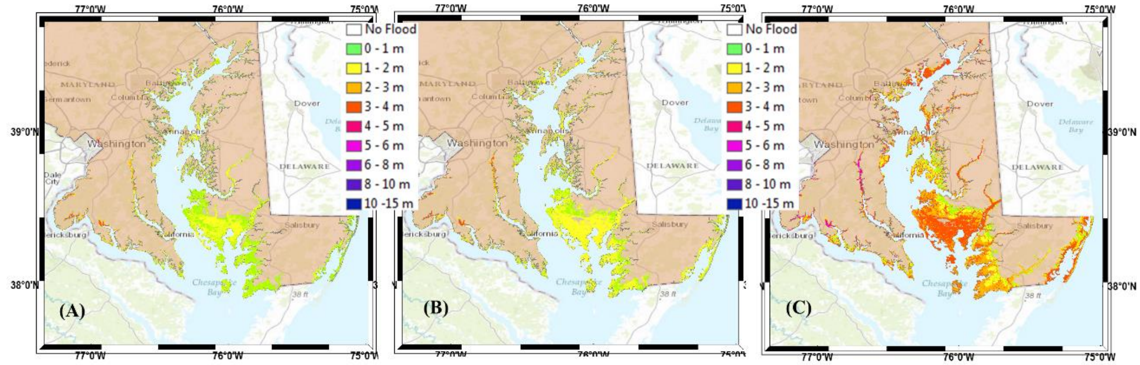

Figure 3: Maximum Flood Elevation Due to Isabel (A) Baseline (B) 2ft. SLR (C) 6ft. SLR

In table 2, the total flooded area and maximum inundation depth are provided for the selected storms and scenarios. Though the total flooded area due to combined impact of hurricane Isabel and a 0.49m (Historic) SLR is considerably higher than hurricane Dennis, the percentage increase in flooded area for Dennis is greater as in present scenario the storm had less inundation. With a 2.3m rise (Highest) in SLR Isabel are expected to inundate about 3300 Km^2 areas in the study area, and the projected inundated area for Dennis is 2266 Km^2. It can also be observed from the table that with a higher rise in sea level the difference in flooded area due to high and low intensity storms are reduced; meaning that an extreme rise in sea water level will likely to have catastrophic impacts on the Bay area regardless of the strength of the storm.

Table 2: Total Flooded Area and Maximum Inundation Depth Analysis

Inundation	**Total Flooded Area (Km^2) (% Increase from Baseline)**		**Maximum Flood Depth (% of Total Flooded Area)**	
Scenarios/ Storms	*Dennis*	*Isabel*	*Dennis*	*Isabel*
Baseline	348	1520	0 - 0.5m (88%)	0 -1.5 m (75 %)
Historic SLR	820 (130%)	1817 (20%)	0 -1 m (82%)	0.5-2m (68 %)
Highest SLR	2266 (550%)	3300 (110%)	0.5 - 2m (95%)	1-3m (78%)

To estimate the expected damages for the scenarios, the depth-damage functions are applied from FEMA's Hazus Flood Model library (Scawthorn, 2006) and combined with residential property values from the Maryland Department of Planning's MDProperty View database*. The projected property damage in Table 3 shows that the highest SLR can increase the residential property damage up to $1572 and $2046 million from the current condition for low and strong intensity storms respectively. Even with a lower rise in sea level can cause about $69.9 and $488 million damage if hit by Dennis and Isabel like storms in future.

Table 3: Estimated Household Property Damage and Population Affected in Coastal Maryland

Impacts	Household Property Damage (Million USD) *(Increase from Baseline)*		Total No. of Flooded Household *(% Increase from Baseline)*		Coastal Population Affected *(% Increase from Baseline)*	
Storms/ Scenarios	*Dennis*	*Isabel*	*Dennis*	*Isabel*	*Dennis*	*Isabel*
Baseline	$7.7	$264	3791	28694	119025	221169
Historic SLR	$69.9 ($62.2)	$488 ($224)	16221 (327%)	42149 (47%)	161101 (35%)	247621 (11%)
Highest SLR	$1,580 ($1572.3)	$2,310 ($2046)	90550 (2280%)	123195 (320%)	306009 (157%)	407725 (84%)

Additionally, the number of flooded household increases rapidly with increase in sea level. In terms of percentage increase the values are higher for the weak storm as in current conditions the damage was relatively low. The clearly indicates that coastal flood vulnerability will largely amplify in the study area [i]for sea level rise and loss in wetlands. Using the gridded population density data from NASA Socioeconomic Data and Applications Center (SEDAC)[**] the number of affected population is also computed for the inundated coastal counties. The closest available data for the storm baseline is found for the year 2000 and using the same population density for the future scenarios, the impacts are compared.

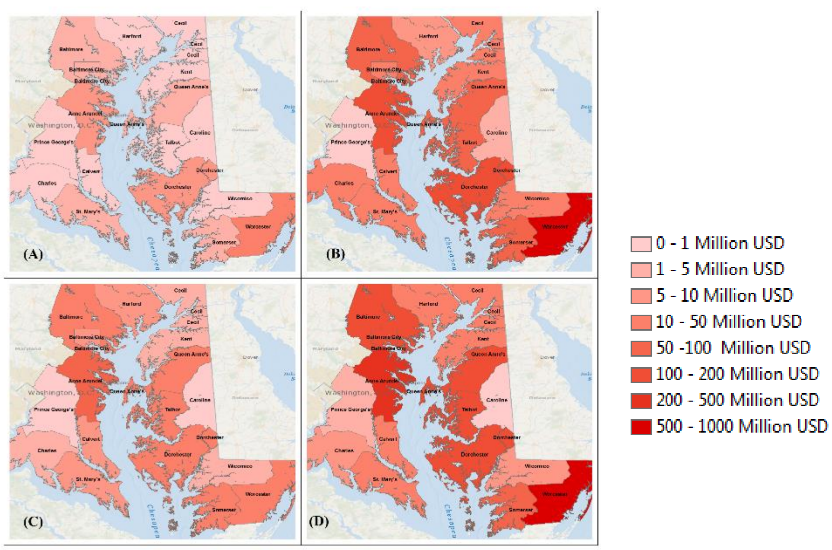

Figure 4: Estimated Increase in Household Property Damage (A) Dennis & 2ft SLR (B) Dennis & 6ft SLR (C) Isabel & 2ft SLR (D) Isabel & 6ft SLR

With increasing trend in population in the coastal areas the real numbers are expected to be higher than the estimation – still the analysis suggest that regardless of the storm there would about 0.2 million increase in affected population due to sea level rise. This study also evaluated the flood vulnerability on a county level. Figure 4 exhibits the increase in property damage in the flooded coastal counties due historic and highest rate of SLR for the selected storms. It can be seen increase in both storm intensity and sea level will augment the household property damage and expand the vulnerability for counties with less damage in current conditions. The increasing red color in figure 4 evidently indicates that counties that are already affected by storm surge will experience worse inundation and damage while the least affected counties are likely to face significant damage due to storm surge and flooding.

Conclusion

In order to evaluate vulnerability to coastal flooding due to storm surge and sea level rise in the Chesapeake Bay areas, this study quantified the inundation extent, intensity, expected damage and population affected. Results suggest that with a 4-5m maximum flood elevation, the total flooded area can increase up to 100-500% depending on the variability of storm damage in the current situation. Accordingly, the residential property damage can rise up to $2,310 million dollar affecting a 0.1 million households and 0.4 million people living near the coast and the Bay. A remarkable finding is while the impact of storm intensity can make substantial differences in flooding and respective damages in current conditions and lower rate of SLR, with an extreme increase in sea surface elevation the flood risk will be immense in the study area regardless of the strength of the Hurricane. It should also be noted that, incorporating the local and regional projection in the coastal inundation modeling can offer substantial and quantified indicative information that can be used in developing future coastal landscape and floodplain management plan. This will also assist local and regional policy makers to take informed decision to combat the impact of climate change and sea level rise, and thus build a resilient coastal community.

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