USING TIDAL STAGE TO MODEL OF HURRICANE STORM SURGE INUNDATION RISK TO DEVELOPMENT ALONG THE GEORGIA COAST, USA

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Abstract. Recent hurricanes have generated interest in improved storm surge risk maps along the Georgia coast. Storm surge is defined as flooding due to increased sea level resulting from low atmospheric pressure in the storm center. Risk from storm surge is a function of hurricane's extent, intensity, tidal stage at landfall, and magnitude of anthropogenic development at low elevations. Tidal stage during hurricane landfall is one of the most critical fac-tors in determining the extent of storm surge risk. Our objective was to map risk to anthropogenic development along the Georgia coast from a 1-3m storm surge at a range of tidal stages. A two-meter storm surge was selected based on observed storm surges Mean higher high water (MHHW) and Mean lower low water (MLLW) were based on local NOAA tidal gauges to establish tidal amplitude. Anthropogenic development was mapped using 30 m land use / land cover available through the 2011 National Landcover Dataset. Risk maps were generated by modeling potentially inundated elevations and then overlaying developed LULC data. Categories were based on development level from LULC data; open areas, Low, medium, and high intensity development. Tidal stage produced a significant change in inundation. Development type did not vary significantly across scenarios in proportion inundated.

INTRODUCTION

Nearly 23% of the world's population lives on the coast and is estimated to rise to 50% by 2030 (Gayathri et. al 2017). By 2080, more hurricane and typhoon events are expected to occur due to climate change and the warming of ocean waters creating more severe low-pressure systems (Gayathri et. al 2017). During such large low-pressure systems, storm surges account for 90% of the loss of life (Shultz 2005). Making it critical to study the effects of storm inundation during severe weather events such as hurricanes. It is becoming even more important to assess potential coastal damage during major storm events in order to predict the impacts that will occur in the future with higher sea levels.

Major storms such as tropical storms and hurricanes gain strength over warm waters due to evaporation rising and condensing to attribute to more extreme storm system. While a tropical storm/hurricane is traveling to a coastal region, it gains strength but begins losing energy once onshore due to the loss of water evaporation. Before landfall, however, the low-pressure system and strong winds bring in a substantial amount of ocean water towards the coast, causing detrimental flooding along the coastal region (Gayathri et. al 2017).

Coastal areas with barrier islands are considered the most vulnerable areas due to the inland having a lower elevation (Loftis et. al 2013). The Georgia coast, specifically, has long-sloping continental shelf as well as a low-lying soft shore system. It has the widest tidal range of the Georgia bight. These factors greatly increase the susceptibility of Georgia's coast to high risk storm surge damage (Ho 1974).

Coastal buffer systems are still largely intact and expansive in Georgia. Salt marshes are excellent natural buffers to wave and storm action through attenuation and act as coastal waters overflow (Möller et al 2014). Barrier island receive the bulk of hurricane force due to their position on the coast. Development on these islands are largely limited to three islands St. Simons, Tybee, & Jekyll), while the other most of the land on the barrier islands are publicly own and/or held in a conservation status. Development on these islands are likely to be at greater risk to storm impacts.

The Georgia coast experiences a high tide that brings in ocean water up to ten miles inland. During hurricane and sever storm events from the Atlantic Ocean, this can become drastically exacerbated and ocean water can be pushed in farther than ten miles. Anthropogenic influences and activities can put many people and development along the Georgia coast at risk from storm surges. Much of the developed areas are within the low-lying areas and on the barrier islands. Also, an increasing coastal population is leading to more degradation of natural protections, such as salt marshes. Another anthropogenic factor that increases risk from storm surges are poor building codes that do not take into account potential storm surge levels (Harman et al. 2013).

OBJECTIVES

The objectives of this study were to: (1) assess the relationship of tidal stage and storm surge for storm tide events; (2) determine the relative risk to developed areas of coastal Georgia; and (3) evaluate risks to various types of development.

STUDY AREA

The area of study is the six seaward counties of the eleven counties of Georgia that are managed under the Coastal Zone Management Program. This includes Chatham, Bryan, Liberty, McIntosh, Glynn, and Camden counties.

METHODS

We designed our model to include the parameters relevant to the Georgia Coast including; tidal amplitude, likely storm surge potentials, land area, elevation, and land cover / land use. Coupling these factors into layers in ArcGIS allowed us to assess the potential impacts of storm tides to the area of interest.

We used Tidal data from Fort Pulaski NOAA gauge (#8670870) to establish tidal amplitude of the Georgia coast. This tidal gauge is representative of the Georgia coast and most of the developed area of the modeled area occurs in and around Chatham county, where the Fort Pulaski gauge is located. MHHW and MLLW data points were converted to NAVD88

We based our model inputs on previous storms that have impacted the Georgia coast, including those that did not make land-fall in or directly adjacent to Georgia (Table 1). Over the last decade average storm surge was less than 1m. However, some recent storms and major historical storms had greater ranges. We decided to evaluate storm surges ranging from one to three meters.

Water heights were based on a reclassification of the thirty-meter resolution National Elevation Dataset. We used the National Land Cover Dataset retrieved from USDA Geospatial data gateway. This LCLU layer 2011 data layer was used and is the most recent available at this time. Pixel counts from attributes table were used to determine areas.

MODEL ASSUMPTIONS & LIMITATIONS

The interaction between tidal amplitude and storm surges are not well documented. It is possible that wind or pressure factors that contribute to storm surge affect tidal amplitude or vice versa. Our model assumes that there is no interaction. Therefore, storm surge and tidal height are summed to model a storm tide event.

A second major assumption is that our model does not assess the probability of a storm surge event or the extent of said event. Therefore, we produced a model that assumes the highest inundation level possible for any given area across the whole of the study site. In practice, a storm surge event would be limited to a smaller geographic area with lessoning intensity as distance from the landfall site increases.

Additionally, our model assumes unlimited water and is not based on a basin concept. The result is that some low elevation inland locations maybe modeled as inundated storm tide despite distance to coastal source water.

Table 1. Storms that have produced surge events on the Georgia coast in the last decade and selected historically major storms

Name	Type	Year	Storm tide height (m abv NAVD88)	Storm Surge (m)	Direct landfall
"Georgia Hurricane"	H	1898	~5.0	unknown	Y
David	H	1979	3.65	unknown	Y
Dora	H	1984	3.96	unknown	N
Tammy	TS	2005	unknown	0.97	N
Debby	TS	2012	1.37	0.84	N
Andrea	TS	2013	1.36	0.47	N
Ana	TS	2015	0.37	0.50	N
Hermene	TS	2016	1.45	0.50	N
Matthew	H	2016	2.60	2.35	N
Bonnie	TS	2016	1.20	0.43	N
Colin	TS	2016	1.72	0.45	N
Irma	H	2017	2.49	1.71	N

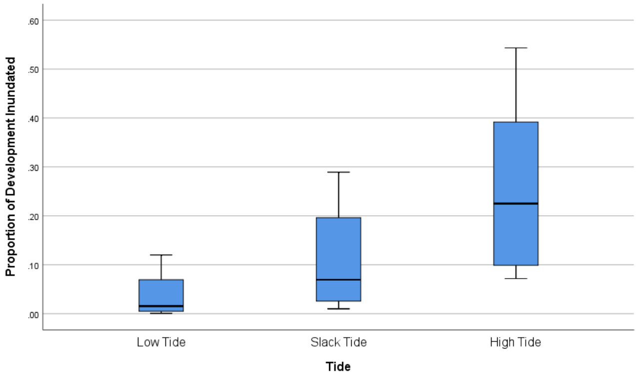

Figure 1. Boxplot of inundation proportion of all development categories. Shows distribution of tidal stage scenarios. Each tide scenario includes a 1-, 2-, & 3-m storm surge scenario. (n=9)

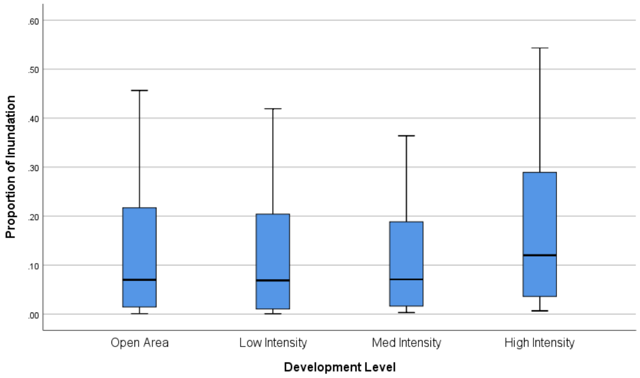

Figure 2. Boxplot of inundation proportion of development categories across all tidal and storm surge scenarios. (n=36)

The main limitation on our model is that our model does not account for other storm impacts which could amplify or mitigate storm surge risk. Other factors include: wind, waves, debris, precipitation, and riverine flows. Two, our model predicted inundation of developed areas, but did not quantify depth of inundation. There is no modeled difference between a pixel that has 0.01 m of inundation or 1.5 m of inundation.

RESULTS

A one-way ANOVA was used to assess relationship of tidal stage and surge height between model outputs. Tidal stage had a significant effect on proportion of development inundated $p<0.001$ (Figure 1). A post-hoc Bonferroni test showed that a high-tide scenario differed from low and slack-tide scenarios ($p<0.001$ & $p=0.007$ respectively) while there was no difference between low-tide and slack-tide scenarios $p=0.337$.

A post-hoc Bonferroni test showed that a 3m surge differed from a 1 and 2-m surge ($p<0.001$ & $p=0.016$ respectively) while there was not a significant difference in a 1 and 2-m surge $p=0.309$. A two-way ANOVA was used to determine the interaction between Surge and Tidal Stage.

We used raw area (km^2) inundated that evaluated the difference between development level and to anecdotally review development types. However, this did not account for differences in total area in each development type. We normalized the data into proportion of land type inundated (Figure 2). A one-way ANOVA was used to compare the proportional amount of inundation between the development levels. There was not a significant difference in proportion inundated between development types ($p=0.788$).

Example of model outputs for a 2-m storm surge are shown in Figures 3 and 4.

DISCUSSION

Tidal stage in Georgia represented a significant influence on modeled storm tide heights and inundation levels in developed areas. This semidiurnal cycle has the potential to change a storms potential impact significantly within the matter of a few hours. This along with the uncertainty involved with storm-track prediction complicates risk management decision along the coast. This change in risk is best demonstrated by hurricanes Matthew and Irma.

Hurricane Matthew impacted the Georgia coast as a Category 2 storm (NOAA 2017 & 2018) while Irma made land fall in the Gulf of Mexico and Coastal Georgia only received tropical storm level winds. Hurricane Matthew's storm surge was approximately 40% greater than Irma's, while the resulting storm tide was only approximately 4% higher. The difference is that Hurricane Irma's impact occurred during an incoming tide while most of hurricane Matthew's impact occurred during an outgoing tide.

Our model showed that roughly 10% of the land area in Coastal Georgia is developed. Much of this development occurs in coastal and low-lying areas. Our study did not assess the annual probability of storm surge or return interval. Our model focused on factors during the surge event.

We found that elevation and distance to a marine waterbody were the key factors. Upland in the first meter above the MHHW was most frequently inundated. This clearly seen in the High-tide 2m surge scenario. Where 33% of the development inundated was located within 500 meters of a coastal water body (shoreline, tidal creek, coastal river, etc.) and nearly 40% of the developed area flooded is below the 2 m elevation NAVD88. Location along the coast is an important factor when assessing risk.

Amounts of development types vary greatly in what was present along the coast. Table 2 shows approximate area of each development type. Inundation generally increased linearly with greater storm tide height. We did not find a storm tide which disproportionally affect one or more types of development when compared to the others. Given that development intensity may be could also be thought of as a function of building height. Actual impact to different development types might better be described by inundation above ground rather than the ground cover focus of our model.

Table 2. Relative proportions and total areas of Open, Low, Medium, and High intensity development and total land area in the study area.

Land Cover	Area (km^2)	
Total Developed	741	10%
Development, Open	417	56%
Low Intensity	196	26%
Medium Intensity	87	12%
High Intensity	42	6%
Total	7500	

Our model has the potential of further development for coastal management decisions. Increased resolution and adding intermediate surge scenarios will provide a more accurate model for management purposes. Next steps would be to validate the model as compared to observed surge events and with NOAA's SLOSH model.

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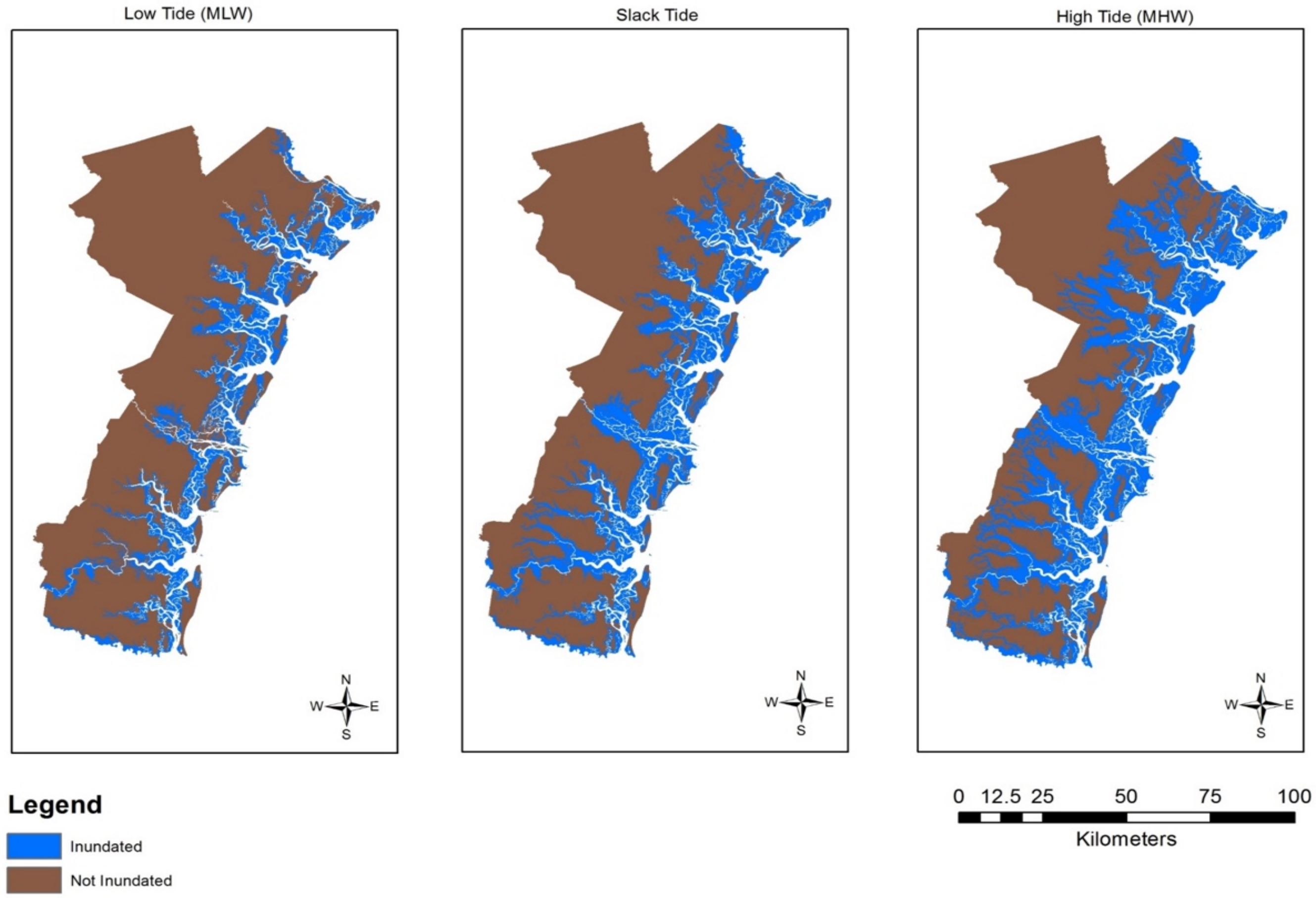

Figure 3. Output from model for 2-m storm surge. Each frame represents a different tidal scenario with the same surge height. Blue represents inundated, Brown represents upland that is not inundated.

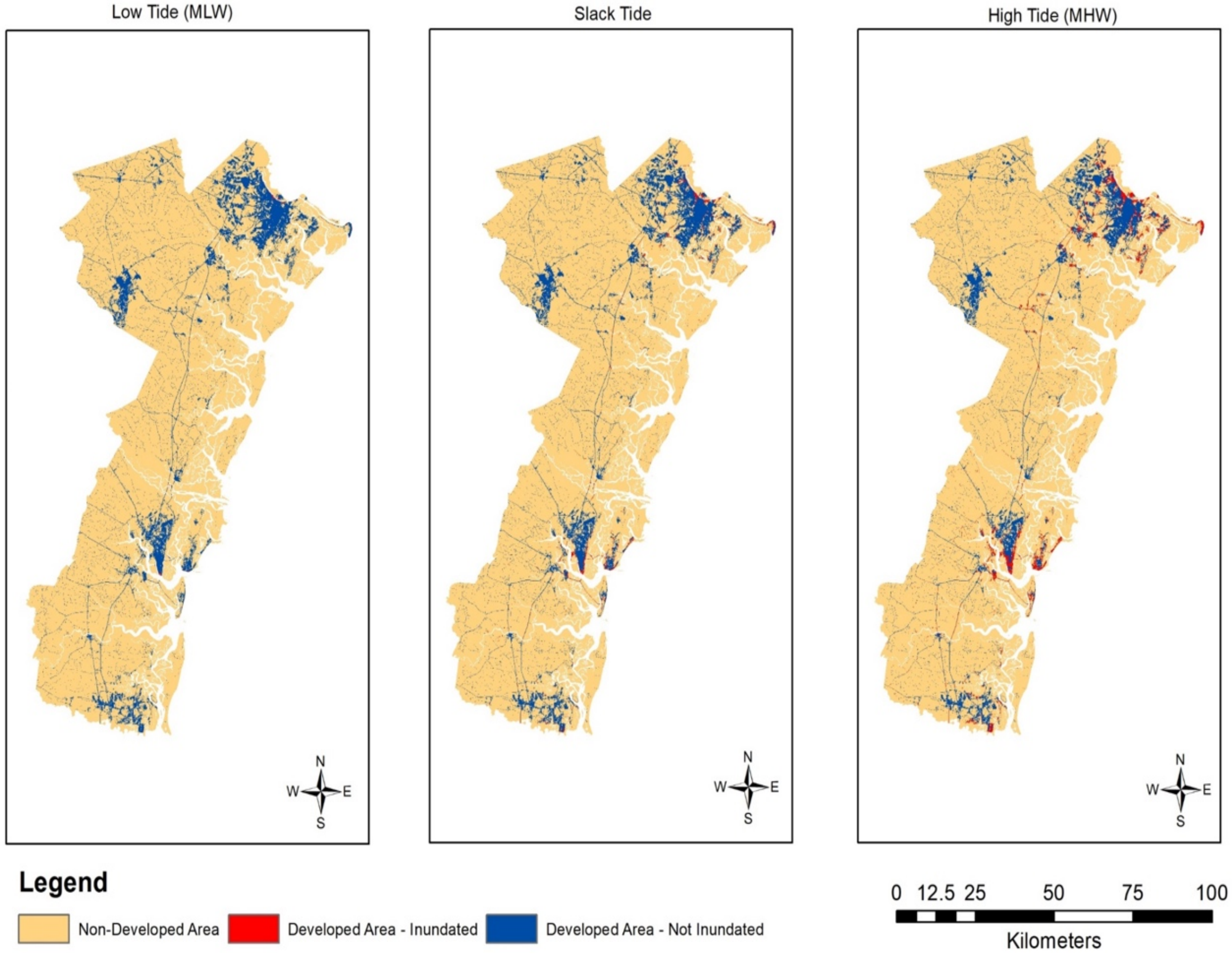

Figure 4. Model output for 2-m storm surge scenario across three tidal stages. Tan represents land area that is not considered developed. Development intensity levels were grouped together for easier viewing. Red represents inundated development and blue represents development that was not inundated.