PREDICTING SEDIMENT TRANSPORT IN HAMPTON ROADS WITH RISING SEAS: QUANTIFYING SHORELINE CHANGE

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Abstract:

Coastal communities are threatened by accelerating sea level rise (SLR) with increasing flood intensity and beach erosion globally. Understanding the long-term beach morphology requires utilizing physics-based models that solve cross-shore and longshore sediment transport. Few studies have looked at the role of SLR on local hydrodynamic and morphodynamic interactions. In this study, a widely used computational model that can simulate hydrodynamics and sediment transport, namely Delft3D, is used to calculate long-term evolution of coastlines in Southeast Virginia. This region is being impacted by vertical land motion along with glacial isostatic rebound making sea level rise a more pressing issue in Southeastern VA compared than other regions along the US coasts. This sea level change along with projected stronger storms will alter the current sediment transport patterns by producing lager waves and increased erosion. The goal of this project is to develop a science-based approach to understand coastal sediment management and transport. Currently there are preexisting profile surveys, monitoring data, and local tide and wave gauges that are used for validation. These datasets are sparse in both time and space, making newly available high resolution satellite imagery vital for validation for coastal change with its increased spatial and temporal resolution. The resulting developed modeling framework can be generalized to other geographic regions with high rates of erosion to assess their vulnerabilities to SLR.

Introduction:

Coastlines account for only 10% of the total land in the United States yet now almost 40% of the population resides in these areas (NOAA, 2014). These coastal communities are continuously developing up to near or fully built. Data shows that sea level trend is increasing and has variable accelerating rate (NCA, 2018 & Sweet et al. 2017). Sea level rise (SLR) increases flood duration and intensity (e.g. Castrucci and Tahvildari, 2018) and is being exacerbated by the frequency and increasing number of intense storms due to climate change (e.g. Emanuel et al. 2008). SLR is not uniform, and the rates vary regionally. An example of this concept is commonly explained as the bathtub method, such that if you add water, you get an equal rise on all boundaries. The increase of sea level is not linear and does not result with the same level of storm surge and changes regionally (Atkinson et al. 2013).

It is expected that the vulnerability of coastal infrastructure will increase in the future with additional flooding and erosional rates. This increased erosion with SLR is partially due to shoreline recessions based on equilibrium profile theory. Beaches respond to SLR by taking sediments from the shoreline and deposit them in the offshore subaqueous part of the beach to maintain a constant shape with respect to sea level. This process is known as the Brunn rule (1962). The Brunn rule can only last as long as it has a sediment source and with limited longshore transport. Therefore, other models are necessary to predict beach shape. The complex physics and interactions between tides, waves, bathymetry and overland flow add to the need of using a process based numerical model to better study sediment transport and water heights.

There is a need for science-based approach to coastal sediment management that can better estimate the sediment transport in response to changing hydrodynamic with climate change. A widely used computational model that can simulate hydrodynamics and waves is the Delft3D-FLOW + WAVE (e.g. Hopkins et al., 2016). Such a model can provide hydrodynamic forcing that causes sediment transport.

Computational models heavily rely on data for calibration and validation. *In-situ* observations are scarce and limited in geographic coverage (Barnard et al., 2015) whereas the availability of satellite data provides the opportunity to analyze shorelines with decades of imagery enabling studying shoreline changes due to short-term forces such as storms and long-term forces such as sea level rise. Publicly available data from satellites Sentinel-2 and Landsat series have improved in their spatial resolution and revisit periods thus can reasonably be used to study shoreline evolution. Several studies were completed to detect long term changes in the shoreline on global and local scales and could show the impact of sub-annual and decadal scale processes from the data extracted from satellite imagery (Almonacid-Caballer et al., 2016, Luijendrick et al., 2018, Vos et al., 2019). However, computational erosion models are not validated with high-resolution satellite data and this research aims to address this shortcoming.

The goal of this project is to improve a predictive modeling framework for coastal hydrodynamics, sediment transport, and shoreline erosion for events and long-term processes. Using satellite data, we can quantify shoreline changes on sub annual timescales – particularly due to storms and beach nourishment projects and identify changes on decadal scales. Additionally, we will be able to validate the performance of a beach morphological model with the shoreline evolution data from the satellite imagery.

Study Area

Our model encompasses the Chesapeake Bay including the northeastern most part of North Carolina. Specifically, our model is focusing on the southwest region of Virginia called Hampton Roads. This region is important for a variety of reasons including military bases and recreation. Norfolk and Virginia Beach are the 1st and 3rd most populated cities in Virginia. Besides its general population, Hampton Roads attracts people from all over the globe. This area is well known for recreation and tourism revenue with multiple state parks and beaches. This region is also heavily important for national security interests, with having the largest Naval Base in the world and being the only NATO location in North America. This location is also a well-studied area due to its high rate of sea level rise. The sea level rise rates at the Swells Point tide gauge have been found to be 6.6 mm/year compared to the global average of 3.5

mm/year (Church and White 2011, Ezer 2013) This region has the highest rate of SLR on the east coast; pairing with its societal and economic impacts makes it as an ideal study site.

In addition to sea level rise beaches in this region are expected to see higher erosional rates. Ocean View in Norfolk and the Oceanfront in Virginia Beach are 2 of the largest beaches in the study region and experience variable but high erosional rates. These beaches undergo periodic beach nourishments to maintain the shoreline and beach width. These beaches also have preexisting profile surveys and monitoring, as well as local tide and wave gauges to provide additional data for model validation.

Methodology

Our model utilizes delft3D. Delft3D is a 3d modeling suite that investigates hydrodynamics, morphology, and sediment transports in estuarine and coastal environments. The software has been used in many places around the world. Some areas of application include the following: tide and wind driven flows, density driven flows, river flow, freshwater discharge, salt intrusion, tsunamis, and transport of dissolved materials and pollutants and sediment transport and morphology. This model is using both the FLOW and WAVE model. Flow is a multidimensional hydrodynamic and transport simulation program which calculates the non-steady flow and transport resulting from tidal and meteorological forcing. Delft 3D-FLOW can calculate non steady flow and transport that result from tidal and meteorological forcing on rectangular or curvilinear boundary fitted grids. Wave uses the SWAN model to simulate wind driven waves the coastal environment including inlets, barrier islands, channels, estuaries, and more. This is a phased averaged wave model that computes propagation, dissipation and interactions incorporating non-linear wave-wave interactions.

Model setup

Resolving certain physical processes
is imperative when calculating sediment transport. This is a fine balance to manage the finest resolution possible such that you can capture the physical processes necessary, but limit to grid size to reduce complexity and computational time. Therefore, to have a reasonable model a balance of grid resolution and size must be considered.

Delft3D version 4.04.02 produces a structured grid that has a uniform grid resolution across the study area. To maximize computational time and have a reasonable run time for multiple simulations we chose to run multiple models with different domains in a nested or multi-layer model. The lower resolution grid is the larger geographic region and produces the boundary conditions for the finer resolution model that is in the bounds of the 2nd model. This process can be repeated as many times as necessary with an increasing number of layers. For this study we have chosen to have a 2-level model. The second layer of the model will be created with Delft3D- Flexible Mesh. Flexible Mesh is similar to Delft3D- FLOW with its utility but can use both structured and unstructured grids resulting in the ability to have even further refined grid cells as you move closer to the coast.

Grid

The level 1 grid was extended from a previous model to include an area that could capture more storm tracts from large storms such as Atlantic hurricanes and nor'easters. The grid area extends past the Virginia to North Carolina. Forming a large rectangle that includes most of the Chesapeake Bay and extends to approximately 35-40 km offshore. The grid size values for level one are approximately 100 x 200 m^2. Grid sizes for level 2 are more refined and are approximately 10 x 10 m^2. This grid runs along the northern parts of Norfolk, VA and extends east to Virginia Beach and just below the North Carolina boarder.

Figure 1 shows the extent of the 1st and 2 level model.

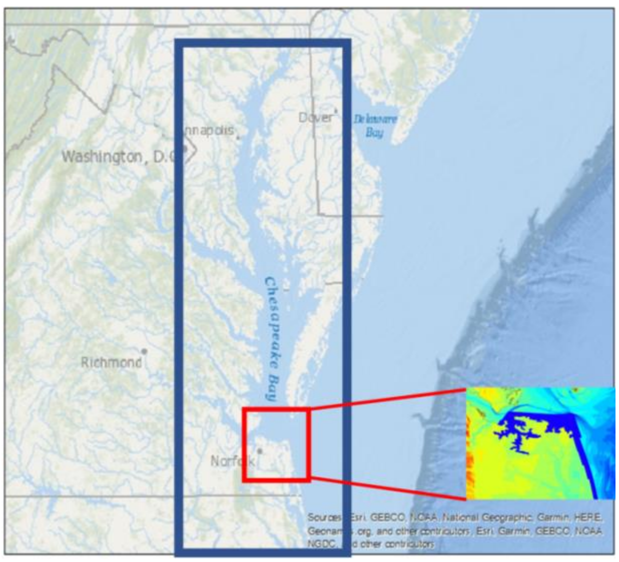

Figure 1: Model domain of level 1 and level 2 grids. Level one in blue is the lower resolution model. Layer 2 is located in the red box selected. The grid itself is the dark blue region along the coast of the digital elevation model.

Boundary Conditions

Topography and Bathymetry

Grid generation and integrated bathymetry or topography has a large impact on the results of the model. Following the nested structure, we can better utilize high resolution data by using increasingly finer depth data with a higher resolution grid. All topography and bathymetry data were freely available from NOAA. The data from the U.S. Coastal Relief Model (CRM) Horizontal Datum is NAVD 88 and the vertical datum being mean lower low water. The differences between the two datums are negligible with the differences being less than the vertical accuracy of the CRM. Therefore, the vertical datum is considered Mean Sea Level. The data for level 1 was from the CRM Vol.2. at a resolution of 3 arc-second which is approximately 90m. Level 2 being much smaller in domain size allowed us to use a more detailed digital elevation model for both the topography and bathymetry with a resolution of 10m. This data came from a variety of sources including the US Geologic Survey, the US Army corps of Engineers, the Federal Emergency Management Agency, the National Ocean Service, the National Geophysical Data Center, and various federal, state, and local governments, academic institutions, and private industry. The datum's for the 2nd layer are Mean High Water and WGS 84. Table 1 summarizes the sources of the topographic and bathymetric data along with their resolution nesting level.

Table 1: NOAA bathymetric and topographic data with resolution.

Data	Source	Resolution	Level
Topography	US Coastal Relief Model	3 arc second ~ 90 m	Level 1
Topography	National Geophysical Data Center	1/3 arc second ~ 10 m	Level 2
Bathymetry	US Coastal Relief Model	3 arc second ~90 m	Level 1
Bathymetry	National Geophysical Data Center	1/3 arc second ~ 10 m	Level 2

Tides

Our model includes 9 different tidal constituents. The tidal data came from Oregon State University TPXO tide models with a resolution of 1/30 degree. TPXO9-atlas is a global model of ocean tides, which uses the best fit of least squares to the Laplace Tidal Equations and altimetry data. The tidal model included 3 components depth grid, elevations and transports. Tidal elevations are given as complex amplitudes so that at a single time t for a single constituent at a location x is given by the formula 1. With tidal elevations referenced to mean sea level.

$$h(t,x) = pu(t,x) \cdot Re\ [\ h(x)\ exp\ \{\ i\ [w\ (t - t0) + V0(t0)+ph(t,x)]\ \}\ ] \quad (1)$$

where *V0(t0)* is the astronomical argument for the constituent at time *t0*, *pu(t,x)* and *ph(t,x)* are nodal corrections. Then amplitude = | *h* | and phase = *atan (-Im(h)/Re(h))*.

Our model is utilizing the primary constituents K1, K2, M2, N2, O1, P1, Q1, S2 and one non-linear harmonic constituent m4 at the open boundaries of the level 1 model. The amplitudes and phases of the 9 constituents were extracted from the TXPO model and interpolated across the boundary of level 1.

Other model parameters include uniform horizontal eddy viscosity at $1 m^2/s$. The ocean water density of $1025\ kg/m^3$. Bottom roughness was resolved with the manning formula uniform velocities of .02 in both the U and V directions.

Model Validation and Discussion

Model validation with Tide Gauges

Our model must be validated to help ensure accuracy and performance. To validate sea level, 3 observation points were selected in the Level 1 model. The locations include Swell's Point, Cape Henry, and the Chesapeake Bay Bridge Tunnel. Each of these three locations has a NOAA tide gauge that can be compared to the output of the Delft3D. These locations were selected because they are close to the boundaries of level 2 and have tide gauges.

The first storm selected for validation was the 2019 Hurricane Dorian. The main worries of Dorian included life-threatening storm surges, inland flooding, and strong winds. Dorian was expected to bring 3 to 8 inches of rain to southeastern Virginia and northeastern North Carolina, with isolated totals up to 15 inches. In actuality, totals rain fall in Hampton Roads and coastal sections of Virginia Beach were between 2-5". With increased ENE winds Dorian caused moderate to major tidal flooding across Southeast Virginia.

The Cape Henry gauge did not collect data therefore we will only show the Chesapeake Bay Bridge Tunnel and Swells Point.

Validation with Remote Sensing

In situ data for beach morphology is poor in the temporal and spatial components. The typical model validation is completed with beach surveys that are expensive to complete. This is why the higher resolution satellite imagery is so vital. Landsat 4-8 and Sentinel 2 have swath crossovers that range from days to a few weeks apart. And as we collect more of this data, we can also examine long term and seasonal changes along the coasts.

Future Work

In order to continue to develop a physics based predictive modeling framework we have to continue to look at the sediment transport and how it is changed by both short-term and long-term processes. It can be challenging to combine the modeling of both types of conditions because they have different dominant processes and time scales. (Bodde W.P., 2017). Having a framework like this could lead to being able to look at episodic events with background nourishing events such as seasonal variability and long-term behavior of nourishment projects. We are currently exploring an approach similar to (Bodde W.P., 2017) that cycles under daily conditions to simulate beach processes over a one year period with an average wave climate. This then couples with a separate configuration that models large, short-term events such as storms.

Next steps include higher resolution wind data to better capture the East North East winds in Hampton Roads that led to the moderate to major flooding during Hurricane Dorian. We hope to improve the accuracy of this storm to better match the tide gauge data available before moving forward with the satellite imagery. We are currently running the simulation for 2011's Hurricane Irene. Hurricane Irene provides another storm with similar effect to Dorian. Irene also caused significant storm surge damage as well as storm surge flooding comparable to Hurricane Isabel in 2003 that wreaked havoc on this region.

After we are able to better simulate shoreline changes, we can compare the performance of our new coupled model with satellite data. Satellite imagery for our region and times have been collected and are on the university server. We have a variety of resolutions in both time and space to choose from. With this we can answer our objective to quantify short-term erosion due to intense weather events, examine the evolution of beach nourishment projects, and assess long-term change due to SLR. This work is in line with NASA mission to support research in "Sea Level Rise, and "Surface Dynamics, Geological Hazards and Disasters".

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