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

Lauren Sommers
Advisor: Navid Tahvildari
Old Dominion University

Abstract:

Sea level rise is expected to contribute to an increase in flooding and shoreline erosion along the global coasts. Few studies have looked at the role of sea level rise on local hydrodynamic and morphodynamic interactions, which is the purpose of this study. To quantify shoreline erosion and sediment transport in response to sea level rise, we used a computational model Delft3D that solves hydrodynamics of waves and currents as well as sediment transport. We applied the model to the southeast region of Virginia known as Hampton Roads, specifically the cities of Norfolk and Virginia Beach. These two cities have interconnected sandy beaches that experience variable erosion rates and undergo periodic beach nourishments. We used the model to study sediment transport and shoreline erosion in response to short-term processes such as hurricanes in addition to the impact of sea level rise. The model will be calibrated and validated with existing surveys and satellite data. This gives us an improved predictive modeling framework for short-term and long-term processes in southeastern coastal Virginia, which can be generalized to other geographic regions.

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). Data shows that the global sea level trend is increasing and has variable acceleration rates throughout the world (NCA, 2018 & Sweet et al. 2017). As sea levels rise (SLR), this increases flood duration and intensity (e.g. Castrucci and Tahvildari, 2018). Flooding is continually being exacerbated by the frequency and increasing number of intense storms due to climate change (e.g. Emanuel et al. 2008). SLR does not follow the bathtub method, such that if you add water you get an equal rise on all boundaries. SLR is not linear, each region along the coast seeing different sea level rise rates. This correlates to regions seeing different storm surge levels, which can have an effect on erosion rates (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 depositing them in the offshore subaqueous portion of the beach to maintain a constant shape with respect to sea level. This process is known as the Brunn rule (1962).

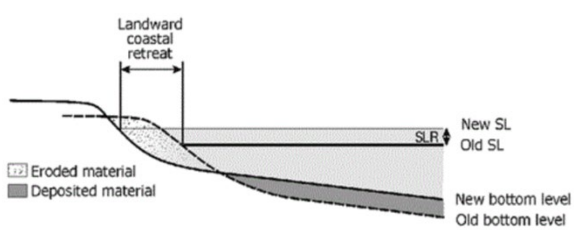

Figure 1: Illustration from the Brunn Rule from Davidson-Arnott 2005.

The Brunn rule can only last if it has a sediment source with limited longshore transport. If there in no longer material to erode the beach can not maintain its shape. Therefore, other models are necessary to predict beach shape. The complex physics and interactions between tides, waves, bathymetry and overland flow support the need to use a process based numerical model to better study sediment transport and water heights.

A science-based approach for coastal sediment management is necessary so we can better estimate sediment transport in response to changing hydrodynamics due to 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 observed data for calibration and validation. *In-situ* observations are scarce and limited in geographic coverage (Barnard et al., 2015), whereas satellite data has decades of imagery. This provides the opportunity to analyze 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 frequency thus can reasonably be used to study shoreline evolution. Several studies have detected long term changes on global and local scale shorelines and can 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, these studies used computational erosion models, which 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 southwest region of Virginia called Hampton Roads. Specifically, our model is focusing on Norfolk and Virginia Beach down to the North Carolina border. Norfolk and Virginia Beach are the 1st and 3rd most populated cities in Virginia and is well known for recreation and tourism revenue with multiple state parks and beaches. This region is important for national security interests, hosting the largest Naval Base in the world. Hampton Roads is a well-studied area due to its high rate of SLR. Measured by the Swells point tide gauge at the naval port north of downtown Norfolk, sea level rates are 4.73 ± -.22 mm/year (NOAA), compared to the global average of 3.15 ± 0.3 mm/year (Albain et al., 2019). This region has one of the highest rates of SLR on the east coast; pairing with its societal and economic impacts makes it as an ideal study site.

In addition to SLR, beaches in this region are expected to see higher erosional rates. Ocean View in Norfolk and the Oceanfront in Virginia Beach are two 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. 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. The model that we use is the flow 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.

Model setup

It is imperative to consider the physical processes one is trying to capture when selecting a grid size. Having a large area with a fine resolution will result in a long computational time. Therefore, to have a reasonable model, a balance of grid resolution and size must be considered. Delft3D produces a structured grid that has the same grid resolution in all locations. This means that the same grid size will expand across the entire study area. In order to make the computational time reasonable one can 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.

Grid

The level 1 grid (Figure 2) was created to allow tidal conditions to flow into the Chesapeake Bay. The grid area covers 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.

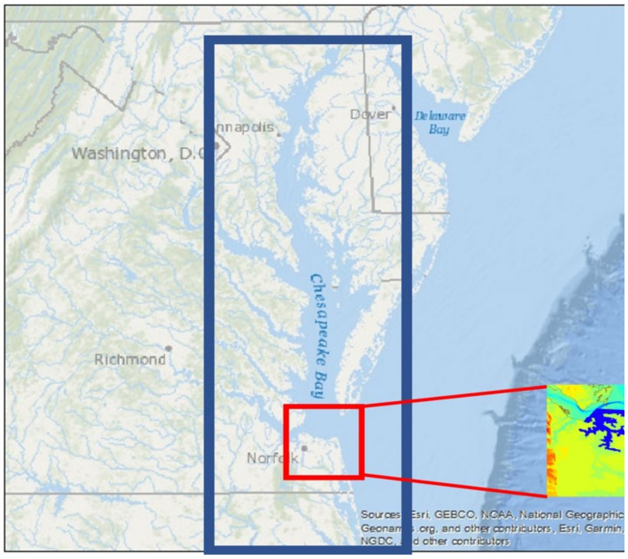

Figure 2: Model domain of level 1 and level 2 grids. Level one in blue is the lower resolution model. Layer 2 is located in the red box selected. The grid itself is the dark blue region along the coast of the digital elevation model.

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 Horizontal Datum was World Geodetic System 84 and the vertical datum being Mean High Water. In addition to using a coarser grid cell size for the level 1 data, lower resolution bathymetry data was also selected. The data for level 1 was from the U.S. Coastal Relief Model (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. 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	Coastal Digital Elevation Model	1/3 arc second ~ 10 m	Level 2
Bathymetry	US Coastal Relief Model	3 arc second ~90 m	Level 1
Bathymetry	Coastal Digital Elevation Model	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 location x is given by the formula 1. With tidal elevations referenced to mean sea level.

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

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 $1 m^2/s$, ocean water density of $1025 kg/m^3$, and bottom roughness resolved with the manning formula uniform velocities of .02 in both the U and V directions.

Model Validation and Discussion

Model validation

The 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.

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. As we collect more of this data, we can also examine long term and seasonal changes along the coasts.

Future Work

To continue developing a physics based predictive modeling framework, we have 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 condition types because they have different dominant processes and time scales. (Bodde W.P., 2017). However, having a coupled framework could lead to analysis of 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 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.

After we are able to better simulate shoreline changes, we can compare the performance of our new coupled model with satellite data. 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”.

Acknowledgements

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