Feature Detection and Change Analysis using Satellite Derived Bathymetry

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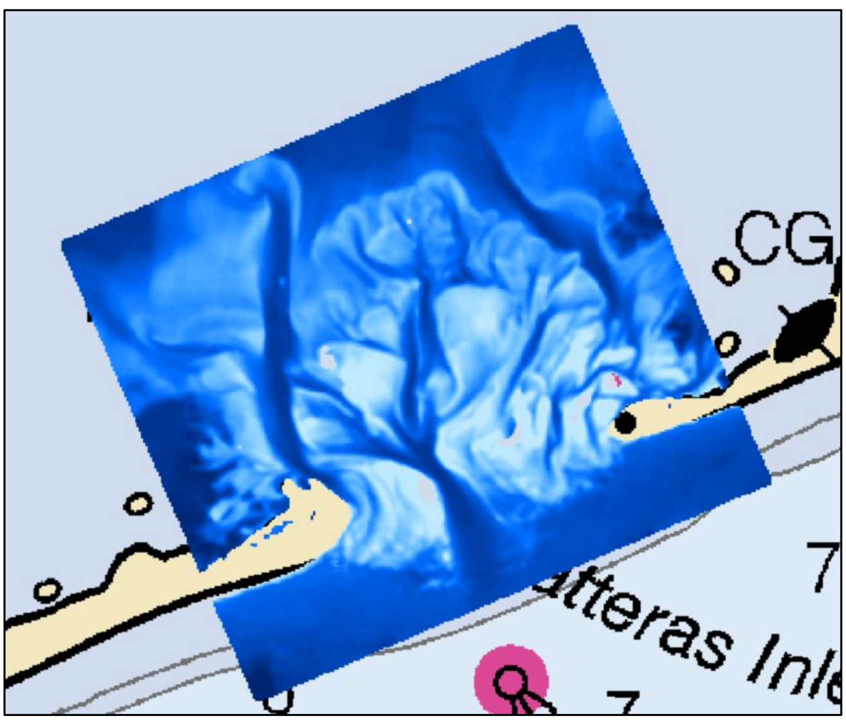

Introduction

The goal of this project is to conduct a qualitative assessment for feature detection and change analysis of coastal features using satellite derived bathymetry (SDB). The test site for this project will be the Hatteras Inlet located on the outer banks of North Carolina. This area is a dynamic channel with various sandbars, shoals, and navigation routes. Due to the high dynamic nature of the channel, it is important to track and monitor the movements of shoals and sandbars for navigation safety of vessels, whether private or commercial.

Along with analyzing the changes in the inlet the purpose of this project is to determine which methods are best suited for performing feature detection going forward. SDB provides a unique resource where the data is being collected periodically with the only limitations being weather events and cloud coverage. For dynamic areas it is impossible to fly lidar or collect sonar data on a frequent schedule. SDB could provide a valuable asset in updating navigation routes between more comprehensive data collections.

The objective of this project is to analyze satellite imagery from the Landsat8 system using the Stumpf algorithm (Stumpf et al., 2003) for satellite derived bathymetry. The imagery being examined in this project encompasses the past decade with datasets being downloaded at approximately 6-month intervals. By analyzing the SDB with the slope tool in ArcGIS Pro the goal is to identify features in the inlet that may be hazards to navigation. By analyzing the resulting features over the ten-year time span it should be possible to determine if certain areas are accreting, eroding, stable, or dynamic in nature. Knowing which areas are the most stable is essential for navigating the area safely.

Site Description

The Hatteras Inlet is a 4km wide inlet located west of Hatteras, NC in the Outer Banks of the United States. The Outer Banks are highly dynamic barrier islands with an oceanside and bay side. Barrier islands are typified by cycles of erosion and deposition as the oceanside erodes and sand is deposited on the back bay side. The study site for Hatteras Inlet will compose the approximate 5km by 5km region formed in the middle of the inlet, see image 1.

Study Site for SDB feature and change detection

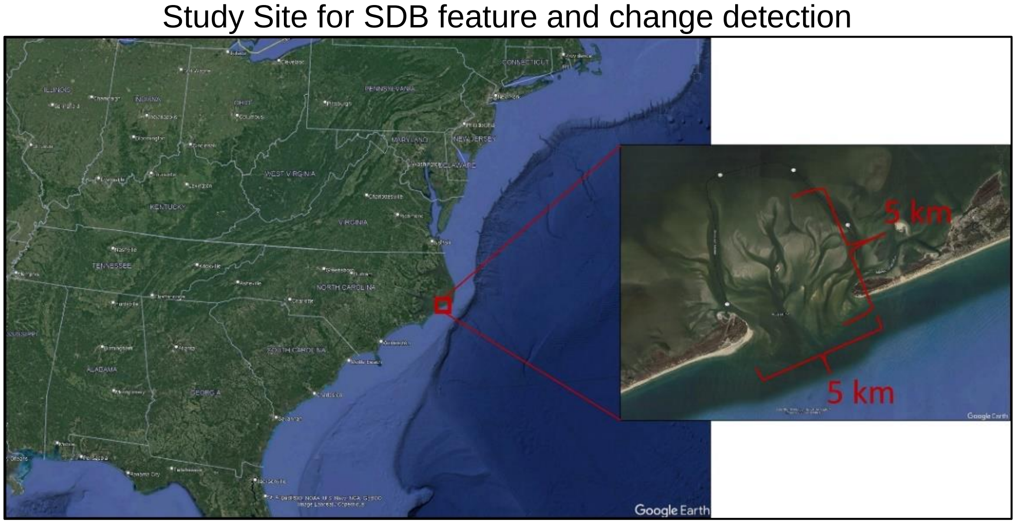

Image 1: Location of the Hatteras Inlet along with the dimensions of the study site for the final project. (Images from Google Earth)

For the study site the main features being examined are the bathymetry of the inlet, any above water surface land areas in the channel, and the shore/land east and west of the inlet. The data being processed is strictly from Landsat8 imagery. Various raster and vector data will be created from each of the 21 Landsat8 epochs for the study site.

Study Site overlayed on Landsat8 Imagery for the Hatteras Inlet

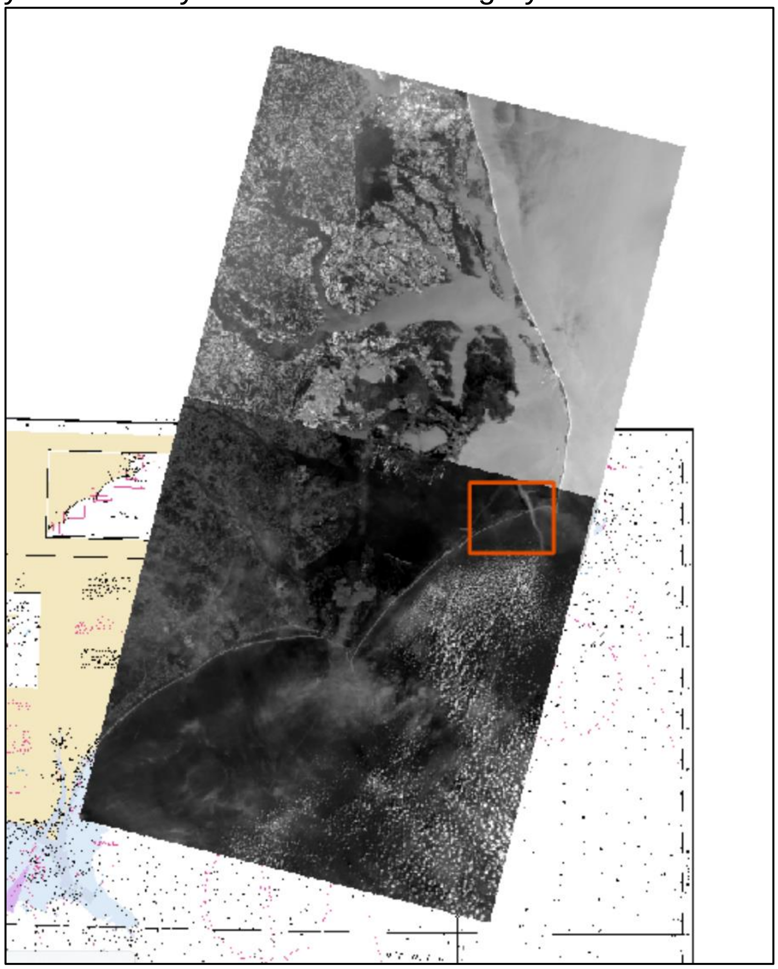

Image 2: Landsat8 imagery band from 2 adjacent data snapshots, both of these positions cover the designated study site of Hatteras Inlet.

Data

The data sources for this project are comprised of Landsat8 multispectral imagery and a lidar digital elevation model (DEM) for comparing SDB to. The Landsat8 imagery being used for this project comprises band 2, band 3, and band 6 of the multispectral data. These bands are downloaded as tifs, therefore raster data, and have a resolution of 30m. The specifications of the bands can be found below in table 1. The Landsat8 data is downloaded from the USGS EarthExplorer website, located at https://earthexplorer.usgs.gov/.

Landsat8 Specifications for the Operational Land Imager Sensor

Operational Land Imager (OLI)

- Nine spectral bands, including a pan band:
  - Band 1 Coastal Aerosol (0.43 - 0.45 µm) 30 m
  - Band 2 Blue (0.450 - 0.51 µm) 30 m
  - Band 3 Green (0.53 - 0.59 µm) 30 m
  - Band 4 Red (0.64 - 0.67 µm) 30 m
  - Band 5 Near-Infrared (0.85 - 0.88 µm) 30 m
  - Band 6 SWIR 1(1.57 - 1.65 µm) 30 m
  - Band 7 SWIR 2 (2.11 - 2.29 µm) 30 m
  - Band 8 Panchromatic (PAN) (0.50 - 0.68 µm) 15 m
  - Band 9 Cirrus (1.36 - 1.38 µm) 30 m

Table 1: Specifications of the wavelength of each band of the OLI sensor and its respective resolution.

The lidar DEMs are downloaded from NOAA's Digital Coast website as 1-meter GeoTiffs (raster data). The Landsat8 imagery is downloaded with a map projection of WGS 1984 UTM Zone 18 and the lidar DEMs have a spatial reference of NAD 1983 (2011) UTM Zone 18. From the Landsat8 imagery a SDB layer will be created for each epoch followed by slope rasters, land rasters, slope vector data (polygon), and land vector data (polygon). A vector polygon is created and used to extract the study site area of the Hatteras Inlet.

GIS Methods

The methods for creating the satellite derived bathymetry are shown in model builder diagram in image 3. The steps for creating SDB involve taking a ratio of logs of the blue and green band of each satellite image. The first step is extracting the study site using a polygon of the study site. Following the extraction, it is important to convert each band to float data, followed by a low pass filter which will also help eliminate null values. The raster calculator is used to perform the following equation:

$$\frac{Ln(blue\ band)}{Ln(green\ band)}$$

Simultaneously to the SDB being created the IR band is being used to create a water only mask. This mask is used to create a land layer, showing all above water ground areas and to mask the land from the SDB layer in order to have only bathymetry for the SDB layer. The raster calculator uses the equation in image 4 to extract the land areas and the raster calculator uses the equation in image 5 to extract only the below water areas for the SDB.

Model Builder Workflow for Creating Satellite Derived Bathymetry, Land, and Slope Rasters

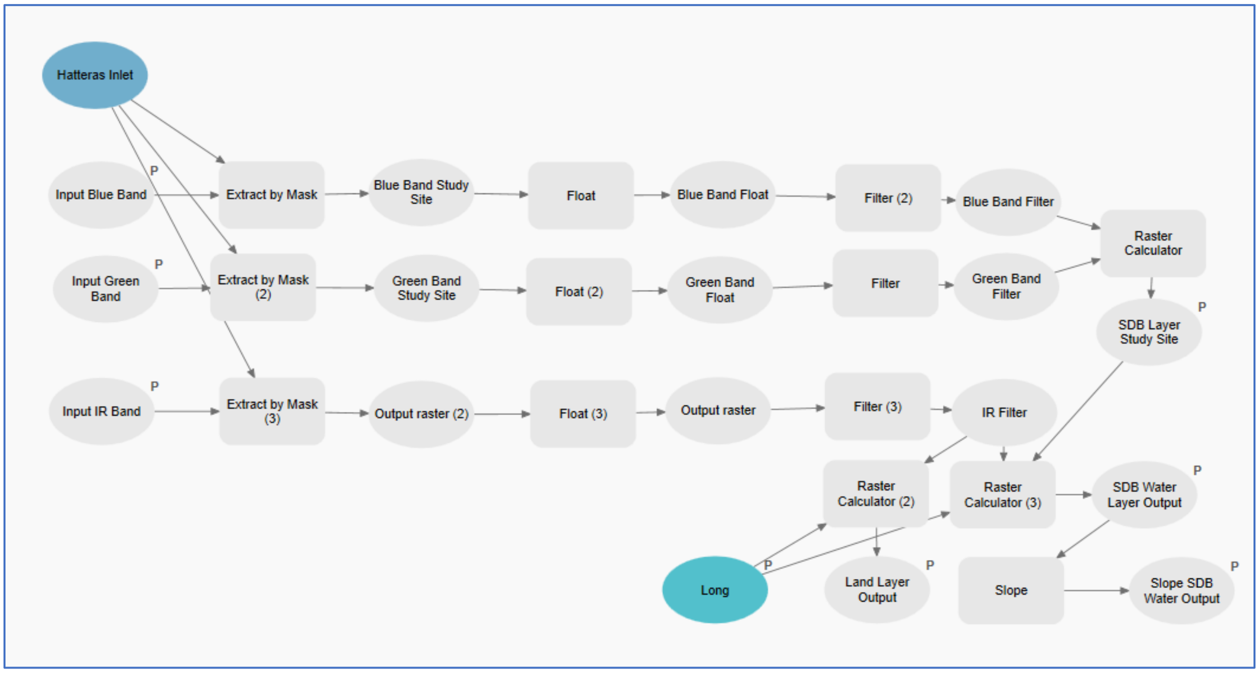

Image 3: The model builder above was created in ArcGIS Pro to perform the SDB workflow where the blue, green, and IR bands are utilized to create a water only SDB layer, a land layer, and slope layer of the SDB.

Raster Calculator Expression for Extracting Land

```
"%IR Filter%" > %Long%
```

Image 4: Expression used for extracting land from the IR band of the Landsat8 imagery.

Raster Calculator Expression for Extracting Below Water SDB

```
SetNull("%IR Filter%" > %Long%, "%SDB Layer Study Site%")
```

Image 5: Expression used for extracting the below water SDB only data.

The IR band is used to create the mask for the land/water interface as IR light is absorbed quickly in water. Image 6 shows the clear distinction from water and land in the IR band imagery. The value at which water and land is separated is the threshold value, which is used as the Long value in the model builder and for equations in image 4 and 5. Image 7 shows a profile view of the threshold value.

Land/Water Threshold in Band 6 of the Landsat8 Imagery

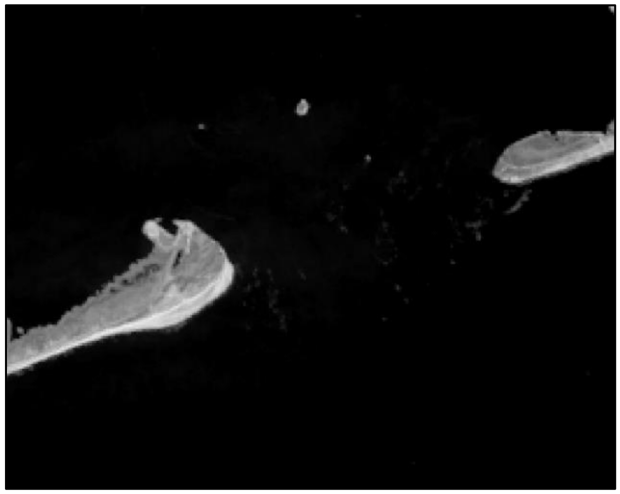

Image 6: IR band (band 6) of Landsat 8 imagery. The water absorbs IR light very rapidly causing a very dark return, making it easy to discern from the land.

Profile View of the Threshold Value for Land/Water Interface

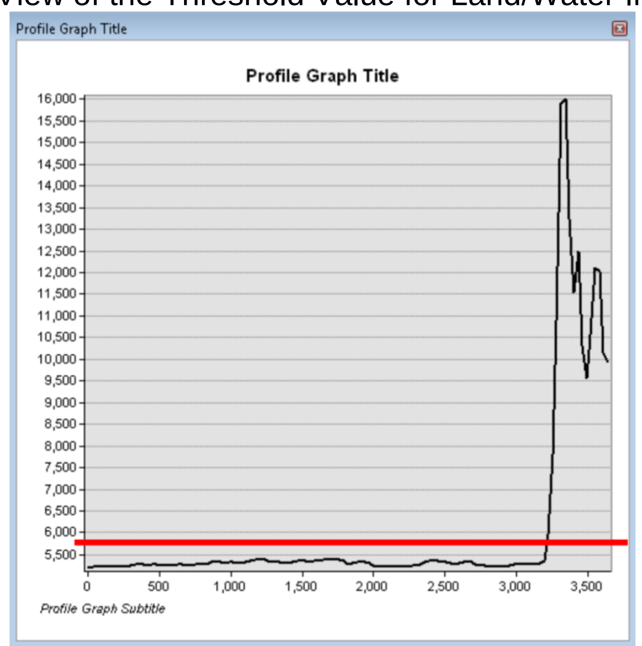

Image 7: Profile view showing the stark contrast of water value returns (lower values) vs the land return values. This property is used to create a land/water mask for extracting various layers. Red line is the value used for the threshold. (GEBCO Cookbook)

After creating the SDB layer, land layer, and slope layer for each Landsat8 epoch a few more processing steps were performed. These steps can be seen in the workflow in image 8. These steps were conducted in order to convert the land and slope layers into vector data that could then be combined into a single layer for visualization purposes. The slope layers each had a unique threshold value that was determined qualitatively for extracting the features of interest.

Workflow for Creating Vector Data from SDB Products

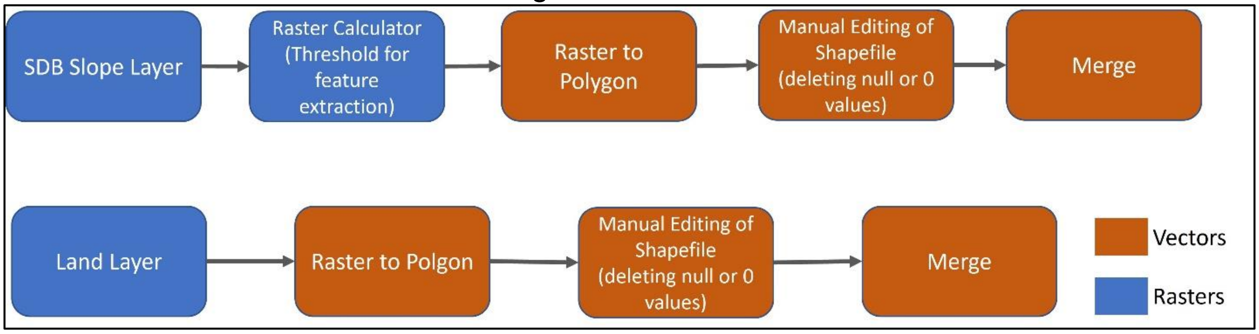

Image 8: Workflow and steps used for converting land and slope layers to vector data.

Outcomes and Results

From the 21 Landsat8 epochs that were utilized 21 SDB layers, 21 land layers, and 18 feature detection layers (slope) were created. The results of for this project were most qualitative but can be summarized in a few major points. The SDB and land layers show mostly consistent erosion and accretion patterns in the outlet for the past 10 years. The eastern and western shores have eroded consistently in the past 10 years and can be seen in image 9, the merged land layers. The eastern shore has eroded approximately 800 meters and the western shore 750 meters. Within the inlet a couple of land features have entirely eroded while a few land features have accreted, with some shifting areas slowly during that time span.

Merged Land Layer of the Hatteras Inlet

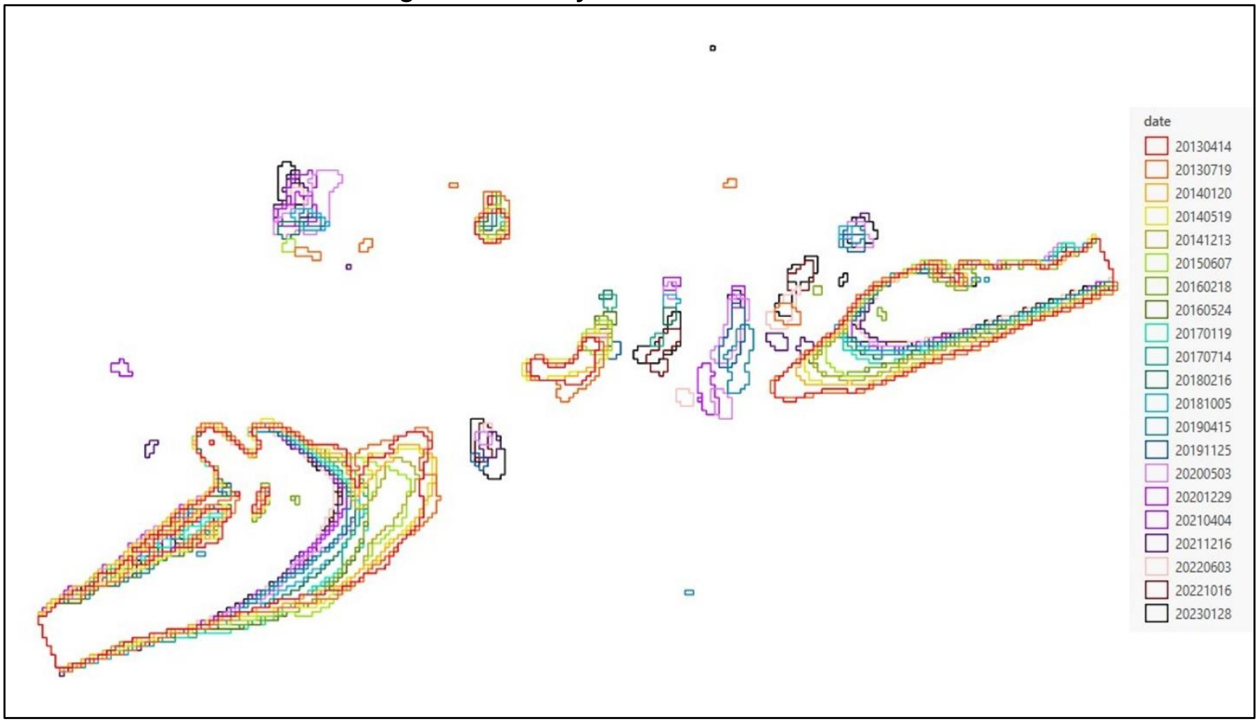

Image 9: Merged land layers from 2013 to 2023. A consistent erosion of the barrier island can be seen along with erosion and accretion of various parts inside the inlet.

The SDB layer along with the slope layer show a good first approximation for use as a feature detection source. The feature detection layer, i.e. slope, follows the bathymetry well within the channels in the inlet and around the other coastal features captured in the SDB. Image 10 below shows a composite of the feature detection layer overlayed on the SDB layer.

SDB Layer with the Feature Detection Layer for 05Oct2018

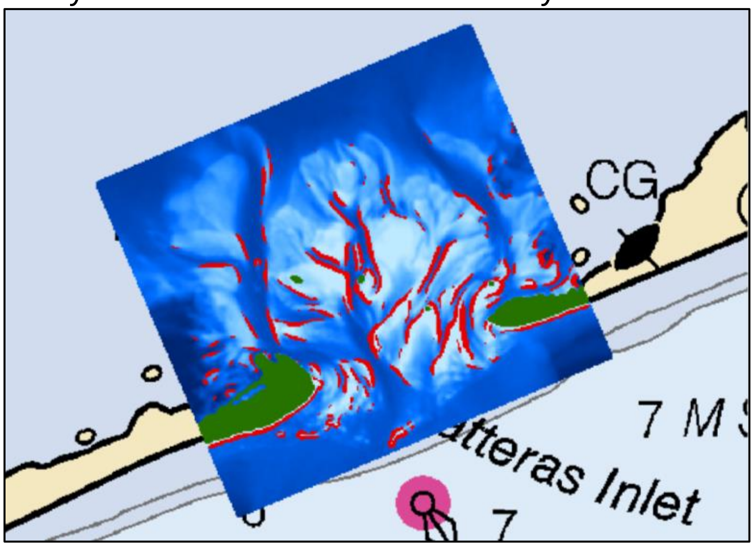

Image 10: SDB layer in graduated blue, feature detection layer in red, and land in green. Shows proof of concept that the feature detection follows the SDB channels well.

When compiling and merging all the feature detection layers together, the results are mixed. It is hard to distinguish patterns with all of the various lines displayed. However it is possible to discern a couple of results. There are several channels that can be seen as stable for the past 10 years however most of the inlet appears to change slowly throughout the 10 years. The results show small changes in movement, therefore not likely to be seasonal. Image 11 below shows a compilation of all feature detection layers.

When comparing 2 or 3 feature detection layers at a time it is easier to discern patterns and other traits. Image 12 shows consecutive year to year feature detection layers. There are subtle changes in the layers however for the most part there are no changes between the 2 layers. This suggests a gradual change in the coastal features instead of drastic changes caused by seasonality or storm events.

Feature Detection Layers from 2013 to 2023

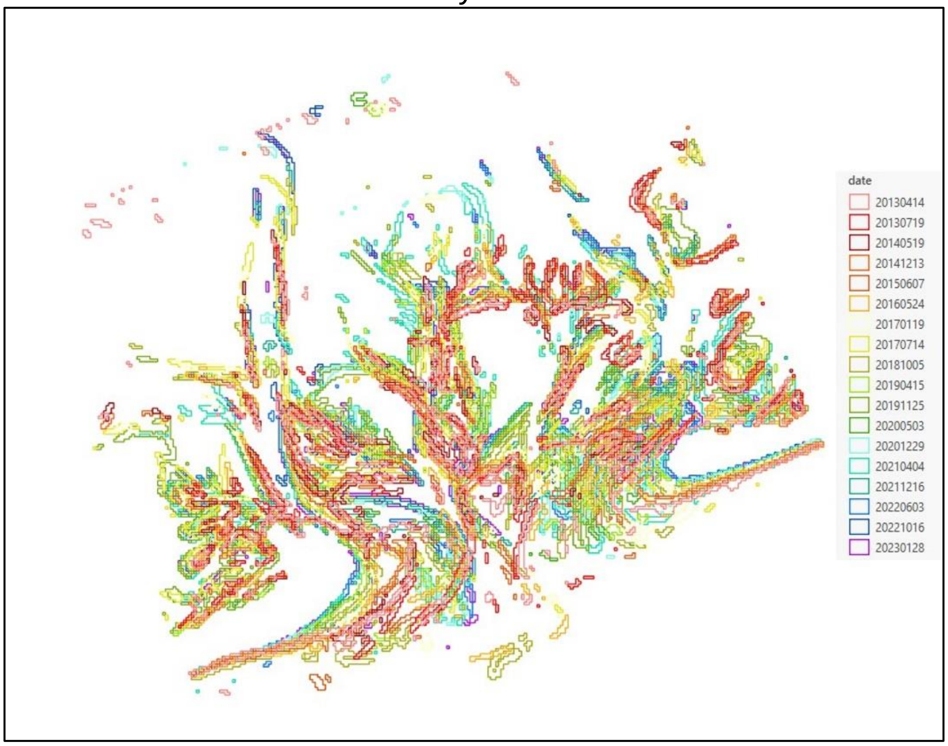

Image 11: Compilation of all feature detection layers for imagery ranging from 2013 to 2023. No discernible trends can be seen in the all-compiled image however a few stable channels can be made out.

Feature Detection between 70Jun2015 and 24May2016

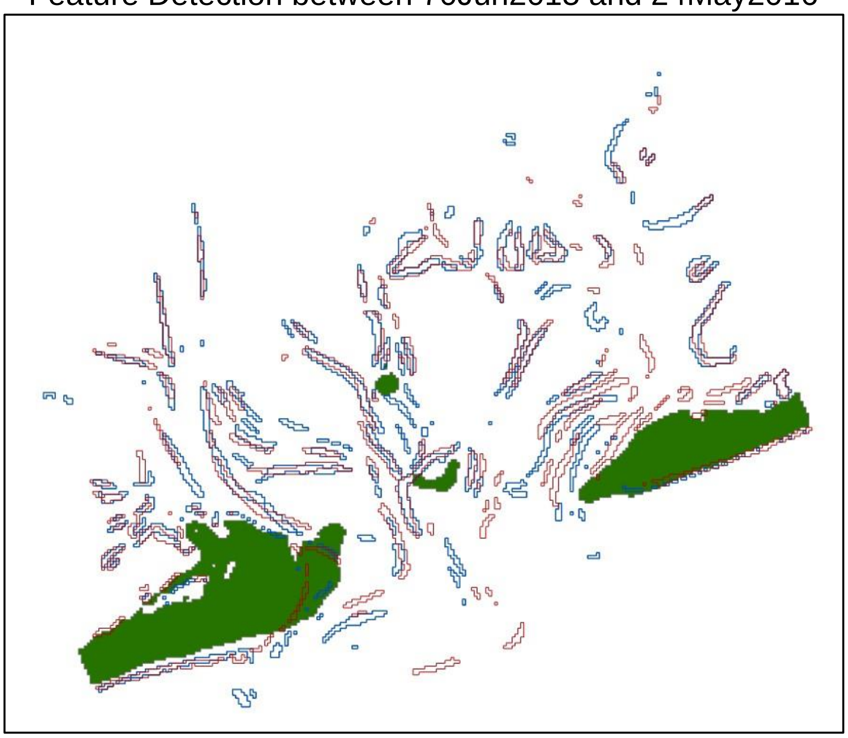

Image 12: Feature detection changes between 2015 and 2016. There are few changes between the layers suggesting overall stability and gradual erosion/accretion of coastal features.

When comparing the composite layers of SDB, land, and slope from each end of the epoch it is clear that the area has undergone changes in the locations of the channels. This leads credence to the idea that SDB is a useful tool for assisting with dynamic areas as the nautical charts and information in this area are now out of date. Image 13 shows the earliest and latest epoch used in this project. Image 14 below shows the current nautical downloaded for the Hatteras Inlet area (large area chart) and how the land areas no longer match what is present.

Changes in SDB, Land, and Features from 14Apr2013 to 28Jan2023

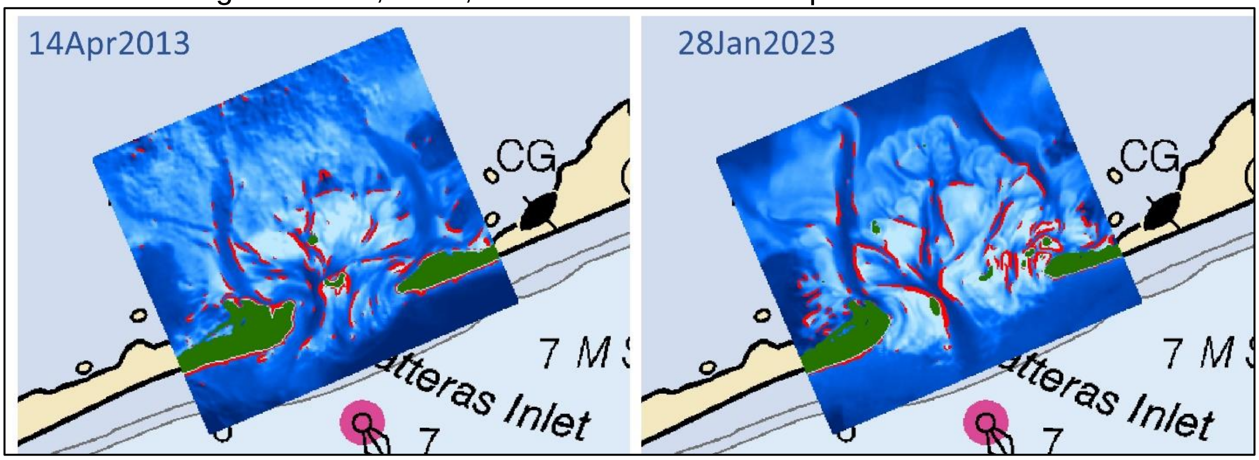

Image 13: Changes from 2013 to 2023 based on the SDB, land, and feature detection layers created in this project. There are a few stable channels to the east and west but the mouth of the inlet shows changes in geomorphology.

Land Area from 28Jan2023 Compared to NOAA Nautical Chart

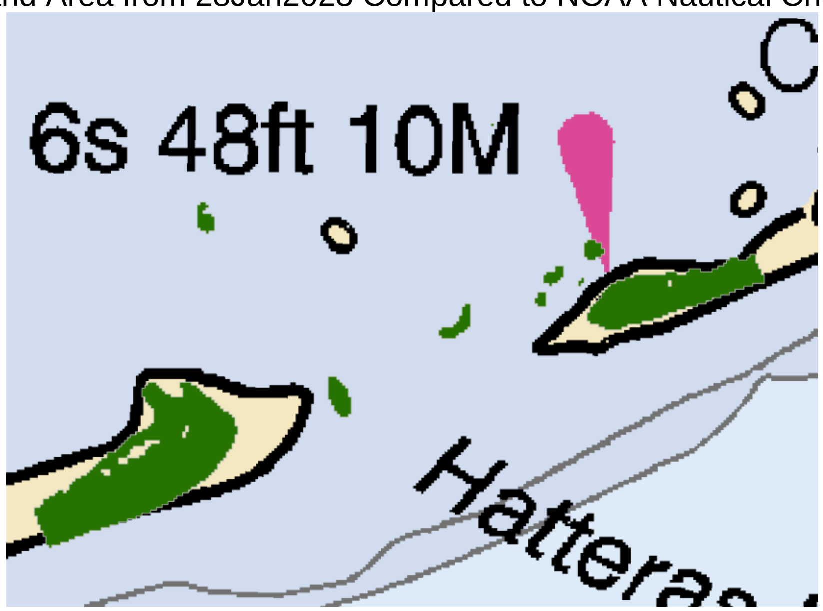

Image 14: Land area from 28Jan2023 overlayed on the nautical chart from NOAA. The chart can be seen to be outdated with added land and coastal features present in the center of the inlet.

When comparing the feature detection data against a lidar DEM collected roughly during the same time there were promising results. The feature detection aligned very nicely with the lidar dataset which helps verify the validity of the SDB feature detection process. Image 15 shows the results of a 2017 lidar DEM compared to a Landsat8 derived product from the same timeframe. An advantage of the feature detection layer is the satellite imagery covers a much larger footprint than the lidar, even if the resolution is more poor.

Lidar DEM Compared to Feature Detection Layer from SDB Using Landsat8

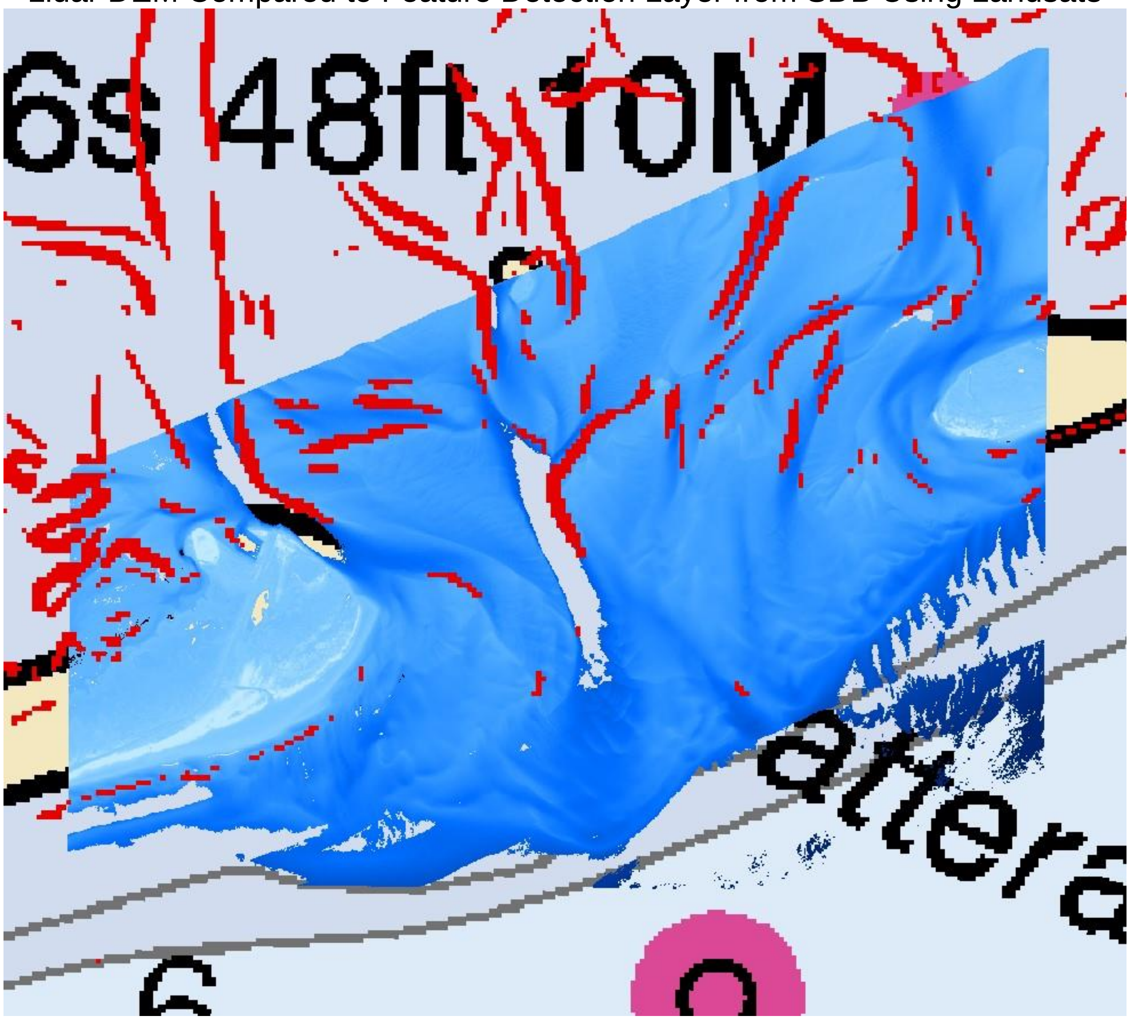

Image 15: Feature detection from 14Jul2017 overlayed on a lidar DEM from 2017. (Data from NOAA Digital Coast)

Challenges and Problems

Some of the challenges encountered during this study were mostly focused on how to refine the data products and the next steps that need to be taken in order to achieve better results. Due to the time constraints for this class project, it was not possible to flush out this project to its fullest potential. However, this does provide a good opportunity for future work on the topic. In order to complete a more advanced study of this area and other dynamic areas it would be essential to fine tine the workflows being used as well as utilizing higher resolution datasets as well, such as Sentinel-2. For the imagery downloaded it was important to avoid scenes with cloud coverage over the study site. This was easily avoided due to the preview images being available on the EarthExplorer website. However, it was not possible to discern ocean conditions prior to the data being downloaded. This led to several scenes with strong wave activities that made it difficult to obtain optimal data and features.

The problems that were encountered during this project mostly stemmed from ArcGIS Pro and model builder. A couple glitches were encountered where parameters in the model were not being saved properly even when the model was saved. This led to ArcGIS Pro having to be re-started between each run through of the model. Other problems centered around the limitations of ArcGIS Pro's model builder without converting the code to python. Going forward it would be useful to expand on the model builder by converting the code to python and expanding what could be run and automated for the process.

Appendix

Caballero, I. and Stumpf, R.P., 2021. On the use of Sentinel-2 satellites and lidar surveys for the change detection of shallow bathymetry: The case study of North Carolina inlets. Coastal Engineering 169 (2021).

International Hydrographic Organization, Intergovernmental Oceanographic Commission, The IHO-IOC GEBCO Cook Book, IHO Publication B-11, Monaco, Sep. 2018, 416 pp - IOC Manuals and Guides 63, France, Sep. 2018, 429 pp.

Stumpf, R.P., Holderied, K., Sinclair, M., 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnol. Oceanogr. 48(1part2), 547–556.