Development of Synthetic Historical Topography from Shorelines and Lidar to Assess Shoreline Change Risk

Defining the topography/morphology of beaches prior to lidar is difficult, however, to assess the real changes occurring on a beach over the long-term it is important. As a result, we are typically forced to default to shoreline change as a 1D definition in a 3D world. The generation of, or existence of, historic shorelines are much easier to generate and/or find. Such is the situation on Sullivan's Island, SC. Sullivan's Island (SI) is, however, lucky to be home to a long history of lidar collection. Data extend from 1996 to 2017; almost making it a long-term analysis tool itself.

The goal of this work was to really make the lidar data a long-term data set going back to 1958 so that historic topographic trends can be used to describe the risk of shoreline change. Risk is highly dependent on elevation, i.e., if a bluff is 10 ft high and has been for 60 years the chances that it will be below the tideline in the near future is small. If, however, that bluff is transient (growing and washing away at some shorter time interval) then the risk of it being below the tideline is higher. So, in this work I am, in keeping with this example, trying to define how transient the bluff is.

Steps

- Define a Median Beach Topography (MBT) from Lidar
- Generate Historic and Median Shorelines and Profiles
- Create Grid Points of Median Topography and Fit to Historic Shoreline
- Generate Synthetic Historic Topography
- Measure Trends at 5 m Grid Spacings
- Interpolate Trends
- Analysis: Generate Future Topography, Assess Risks

Define a Median Beach Topography from Lidar

The Median Beach Topography (MBT) was generated by using 6 lidar data sets. All of the datasets were sourced from NOAA's Digital Coast. Some of the datasets had bathy data, but most did not. Generic bathymetry from the USGS CoNED was used where needed to populate bathymetry (Figure 1). This is a known source of error in some of the datasets.

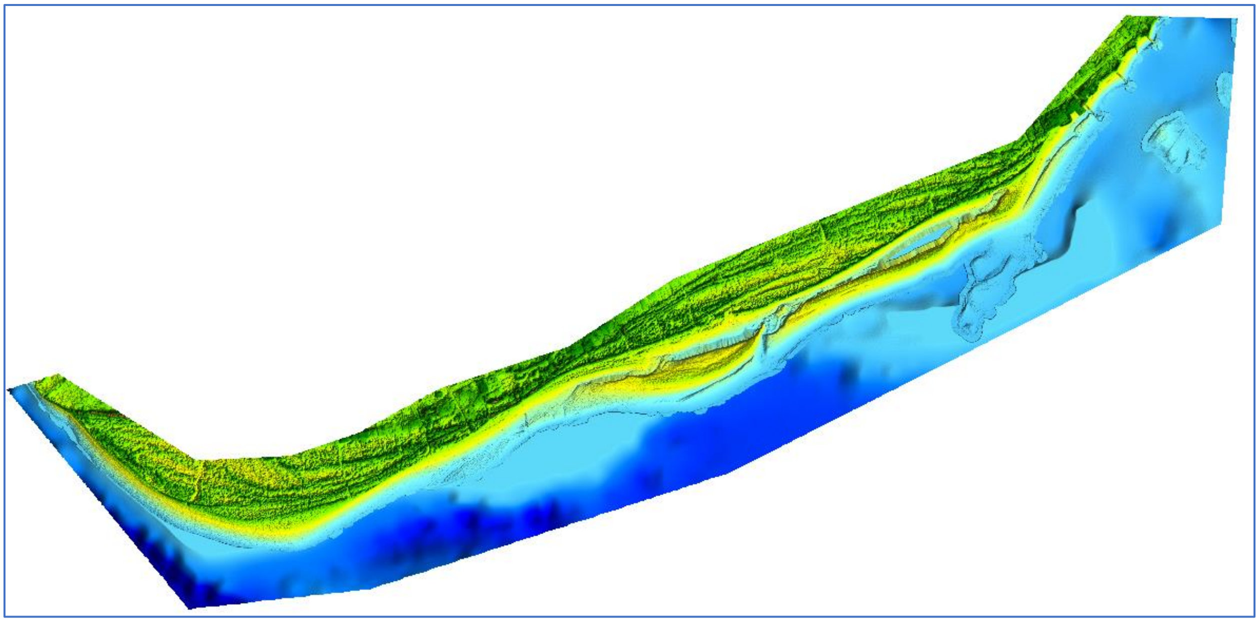

Figure 1. 2007 Topography with bathy from USGS Topo-Bathy surface where data was missing.

Once all data lidar datasets (1997 to 2017) were combined with bathymetry, where needed, a median surface was created (Figure 2). This MBT surface was used along with shorelines to hindcast the 'average' beach morphology.

Earlier work[1] used this median surface along with the standard deviations to define the risks of shoreline change. The risks could, in turn, be used to define the volume of sediment above the normal 'additions' on a renourished beach that were required to maintain a certain level of risk.

[1] See https://www.geosciconsultants.com/blog/2019/2/25/measuring-shoreline-change-using-statistics-a-different-way-to-look-toward-the-future-from-the-past

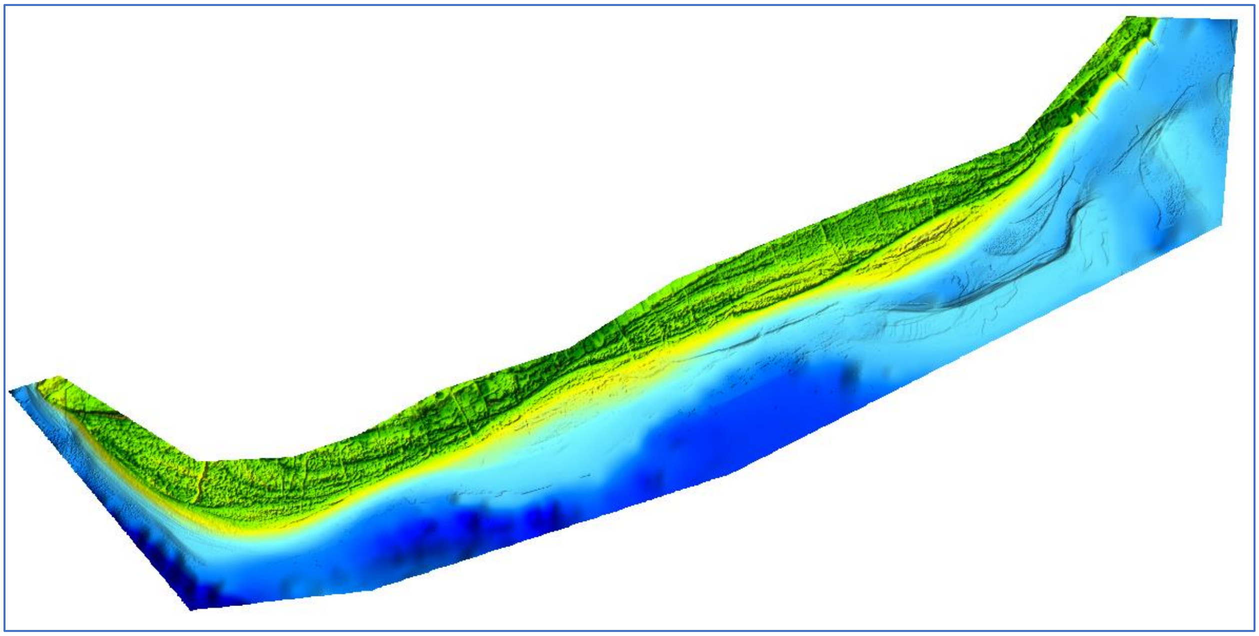

Figure 2. Median Beach Topography

Historic Shorelines and Profiles

Shorelines were generated from aerial imagery and from lidar surfaces. Historic shorelines were digitized from wet-dry lines and used as a surrogate for the mean high water elevation at the time of the imagery. The median topography was contoured at 0.8 m NAVD88 (roughly MHHW) to generate a shoreline representing the "median mean-high-water elevation".

Figure 3. Historic shorelines (black) and the MBT 0.8 m (NAVD88) contour.

To help align the MBT surface to the earlier shorelines a second piece of information was added: generic profiles to help orient the alongshore alignment of the MBT surface. These profiles are used to geolocate the MBT surface via georeferencing points placed at each line endpoint and line intersections. The historic cross-shore profiles are adjusted the same linear distance on- or off-shore as the historic shoreline is in relation to the MBT shoreline (Figure 4).

Figure 4. Cross shore profiles and their adjustment based on shoreline location. The historic shoreline and profiles are blue, the MBT and profiles are red.

Create Grid Points of Median Topography and Fit to Historic Shoreline

The MBT grid (5m) was converted to a lidar point data set. Points falling on the profiles and shoreline (red lines in Figure 4) were re-classified (i.e., from unclassified to ground) simply to provide visual locations for geo-rectification points.

Using 50+ points located at the profile ends and at their intersection with the shoreline the MBT lidar point set was geo-rectified to the historic shoreline and profiles (Figure 4). The data were re-rectified with a 2nd Degree Polynomial transformation. This is not a perfect translation, but it is meant mainly to capture the active profile at the time of shoreline digitization.

Figure 5. MBT surface converted to lidar points. Points falling on the profiles and shorelines were classified differently than the surrounding points.

Figure 6. '1968 synthetic lidar points' with the 1968 shoreline (black line) and the MBT shoreline (red)

Generate Synthetic Historic Topography

Once the historic synthetic lidar was created, each lidar data set was gridded (Figure 7). There are some areas where the match is not exact but given the fact that the historic shoreline was a snapshot in time, the overall agreement appears to be consistent for the long-term use of the data.

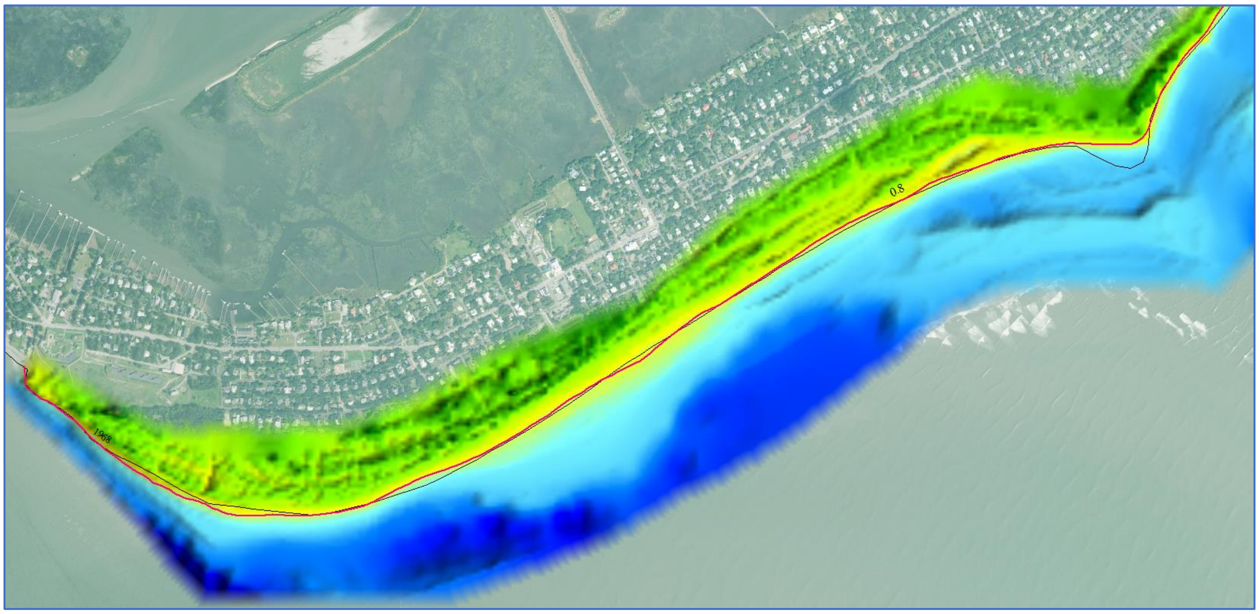

Figure 7. 1968 Synthetic DEM with original shoreline (black line) and the synthetic MHW line (red).

Measure Trends at 5 m Grid Spacings

A 5m grid is used to capture the trends form the 1958 to 2017 topography. Each point contained the elevation of synthetic and real DEMs minus the MBT surface, along with the MBT elevation (Figure 8). The use of the MBT surface kept all the values related to change (datum agnostic) instead of a set datum.

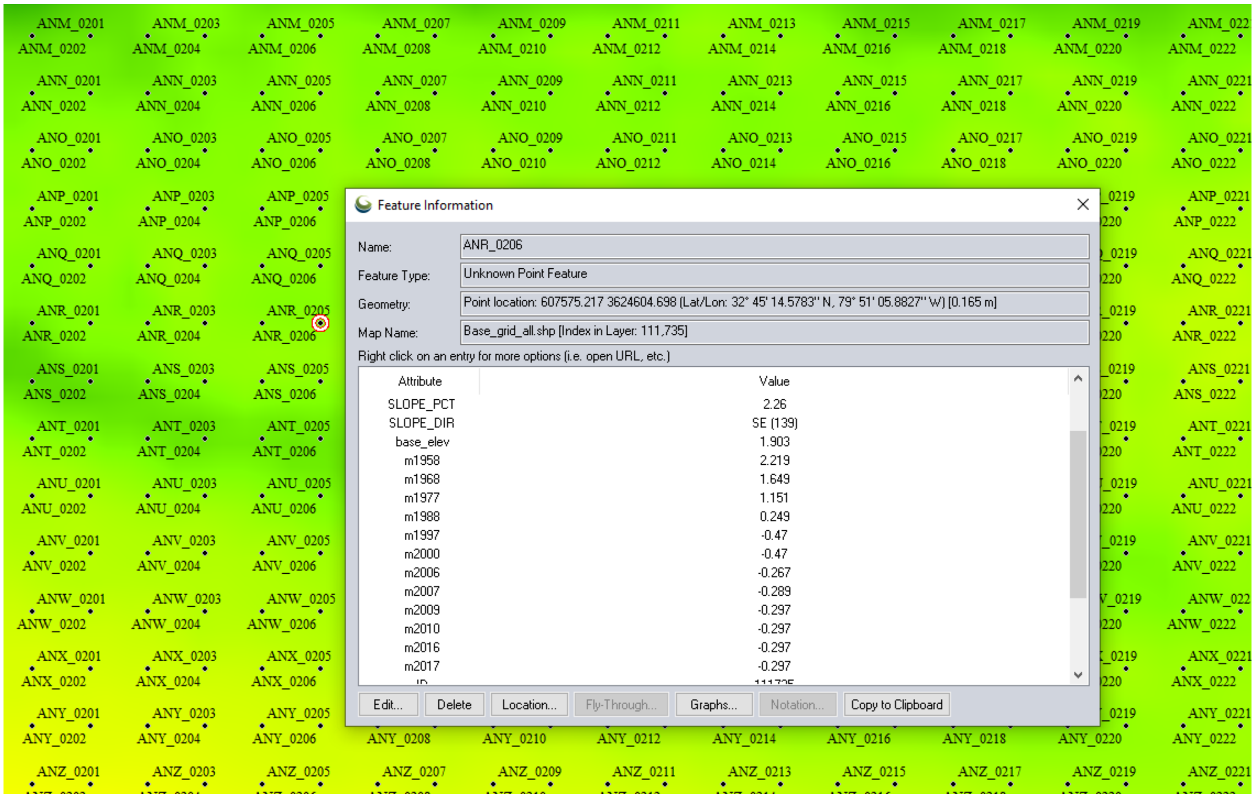

Figure 8. 5m Base Grid with values from the DEMs

Interpolate Trends

Trends were not calculated in the GIS program, instead a spreadsheet was used to generate various linear and polynomial regression equations for each node. After different versions and combinations of polynomial regression equations failed to provide a stable forecast a combination of linear trends was chosen. The linear trends (Figure 9) for the data were calculated for all points (synthetic and real DEMs) and just for the most recent data (real lidar). The two equations were combined to provide an average trend with each having an equal weight. In this case the real lidar was used in both equations but the synthetic lidar only in the long-term (All) equation.

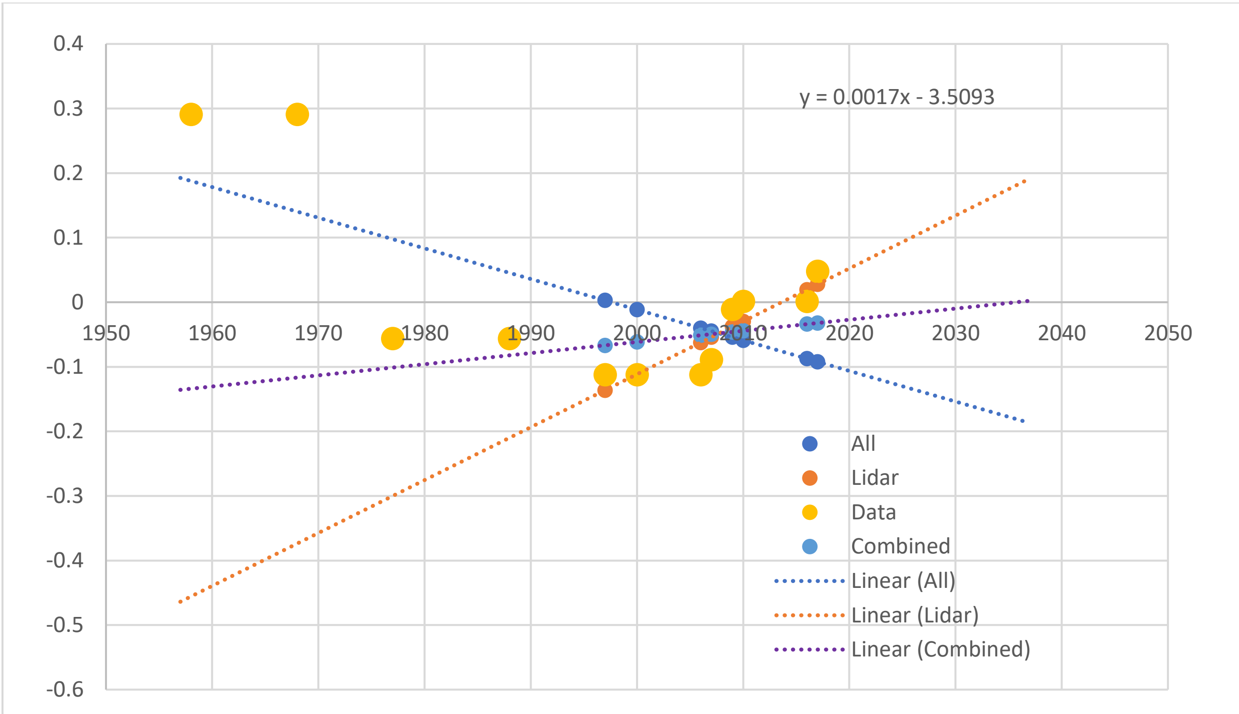

Figure 9. Linear equations used to describe topographic change at each point. Note that positive values (slopes) indicate values less than the MBT surface or trend in time.

Beaches and shorelines are influenced by SLR so to forecast the computed elevation in an MSL datum of each point the local SLR trend (from fitting polynomial equation from local water level data since 1980[2]) was added to the 'Combined' equation. The final equation is unique for each point (5m). In the case below (Figure 10) the trend is toward a loss of elevation (with regards to MSL) in the future.

[2] See https://www.geosciconsultants.com/slr_sullivans for information on defining SLR curve.

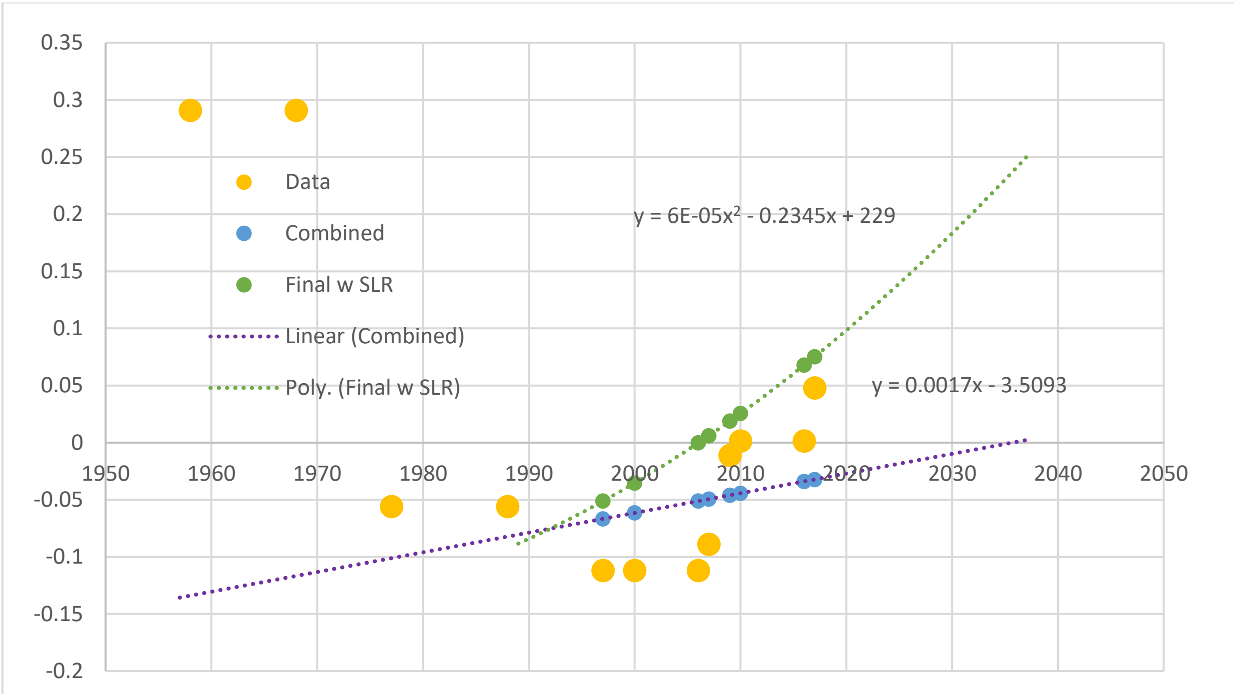

Figure 10. Final equation and trend lines for points.

Analysis: Generate Future Topography, Assess Risks

Once the equation for each point was been defined the data in the spreadsheet was linked back to the spatial layer. The values are used to define a future correction layer such that the equation (Y = 0.000005 X^2 – 0.2345 X + 229; Figure 10) is used to find the difference between the future year (X) elevation and the MBT (MBT_{MSL} – Y = Future $Elevation_{MSL}$). In GIS terms the correction layer is subtracted from the MBT in MSL datum to arrive at an MSL elevation for the year chosen (Figure 11).

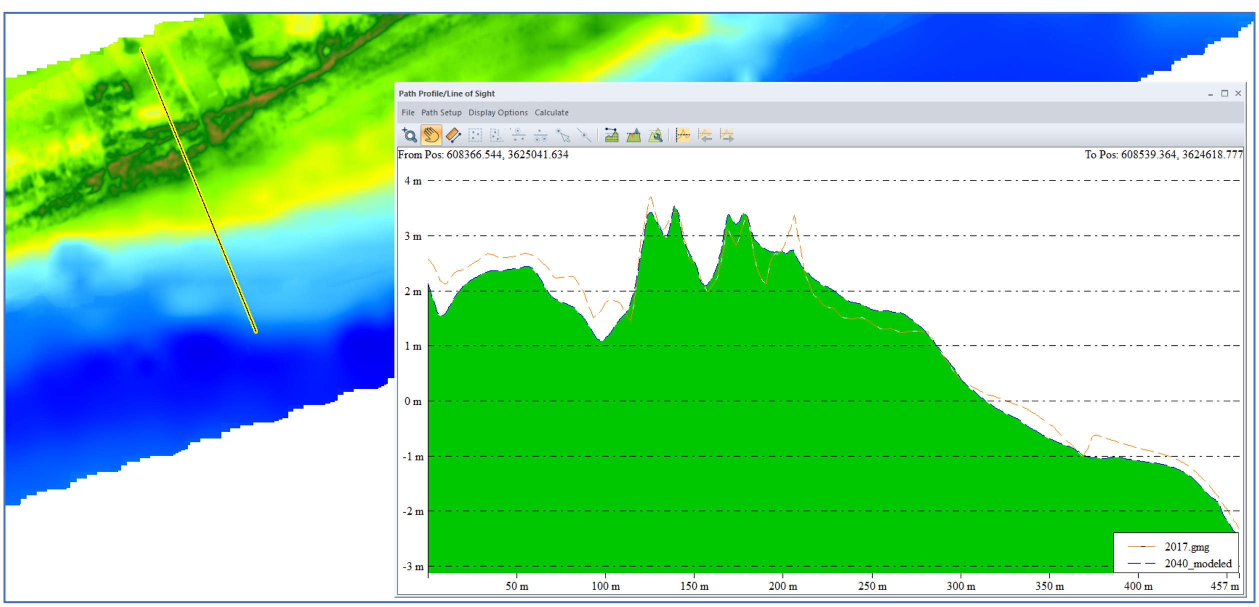

Figure 11. Profile across the shoreline and the difference between 2017 (dashed red line) and the modeled 2040 surface (green area)

Analysis

The analysis is limited by the fact that the future DEM is a model. Although it is an empiric model, it still must be viewed as 'wrong'. To help bring more solidity to an analysis there are past data to measure the range of errors and those values can help estimate a range of likelihoods. So, and important aspect of this type of model is that error values (measured vs. modeled for each measured time) can be used to put some level of confidence to the ensuing comparisons and volume calculations.

Apart from defining the expected change in profile volumes in the coming years, the example below includes the use of a 2020 future surface to compare shoreline location predictions with the present (May, 2020) shoreline. This is a more advanced way to measure shoreline change since slope is included via the modeled topography.

In this case the surveyed high-water line (1.04 m NAVD88 based on the local tide gage at high tide) was compared to the 2020 theoretical surface and the standard error of the technique. The 1.04 m contour line was compared to the underlying 2020 topography and the difference in values (diff = 1.04 – 2020 surface) was then assessed against the standard error surface (Figure , which was also computed at 5m spacing, using a Z score (diff/standard error). A difference of more than 2 standard deviations (+/-) was considered a significant change in shoreline behavior from previous trends (Figure 12).

Figure 12. Recent shoreline colored by change significance on 2019 CIR (NAIP) imagery. Red parts of the shoreline indicates significant erosion, green significant accretion, and blue a location with no significant variation from the historic trends.

The highlighted areas (Figure 12) with significant deviation from the trends are consistent with similar differences in the underlying 2019 image. The red area was field visited and the change in trends is clear (Figure 14). The green area – significant accretion – was flagged as highly accretionary in the most recent Sullivan's Island Beach Report[3]

[3] 2020 Beach Monitoring Survey, https://sullivansisland.sc.gov/government/plans-reports-and-surveys

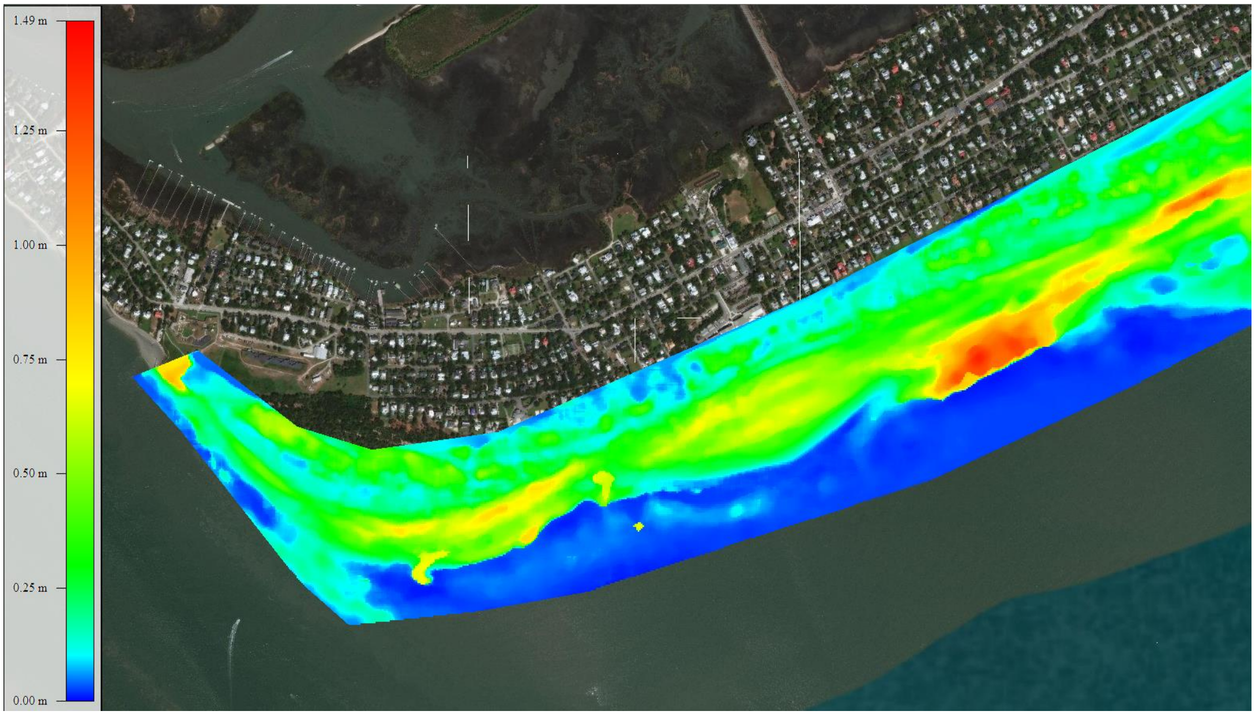

Figure 13. Standard error surface derived from the differences between the modeled elevations for each year there was lidar data.

Figure 14. Area of significant shoreline change (erosion) in Figure 12. The buried engineered pile (probably a relic of an earlier storm) is extended seaward about 10 feet and 2-3 feet above active beach profile.

Final Thoughts

Sullivan's Island provides a unique situation where the shoreline has accreted along most of the island. This allows a look back at the subsurface geology developed under previous conditions both in real data (imagery and shorelines) and with synthetic data (historic topography). The underlying idea of this analysis technique is the cyclic nature of the shoreline: the conditions that caused it to prograde in the past (Charleston Jetties) will change at some point (SLR and dredging?) and the pendulum will swing back towards a previous equilibrium. That said, in the longer-term model predictions, the shoreline at Sullivan’s island is fairly stable, so even with SLR it is not expected that the shoreline will resemble the 1958 shoreline any time soon.

Like any model the results should be used within reason. This model’s results are an indication of the possible outcomes and are intended to be useful not specifically correct. The appealing aspect is that the model can grow and capture more recent changes as they are experienced and measured. The historic information is not going to change – it forms the backbone of the future learning curve.