5.0 OCEAN TIDES AND STORMS

Appendix B describes water levels and storm history proximate to Beaufort Inlet. In brief, tides are semidurnal with ocean mean and spring ranges of about 3.7 feet and 4.3 feet, respectively. Current sea level rise is estimated as about 3.7 mm per year.

Between 1851 and 2004, storms passing within 75 nautical miles of Morehead City have included 42 hurricanes and 54 tropical storms. While the frequency of storms has varied over this period – including numerous storms since 1996 relative to an abeyance of storms during 1987-1995 -- there does not appear to be a statistically significant difference in the overall occurrence of storms between pre-project and post-project conditions. (See ***Figure 18***, below.)

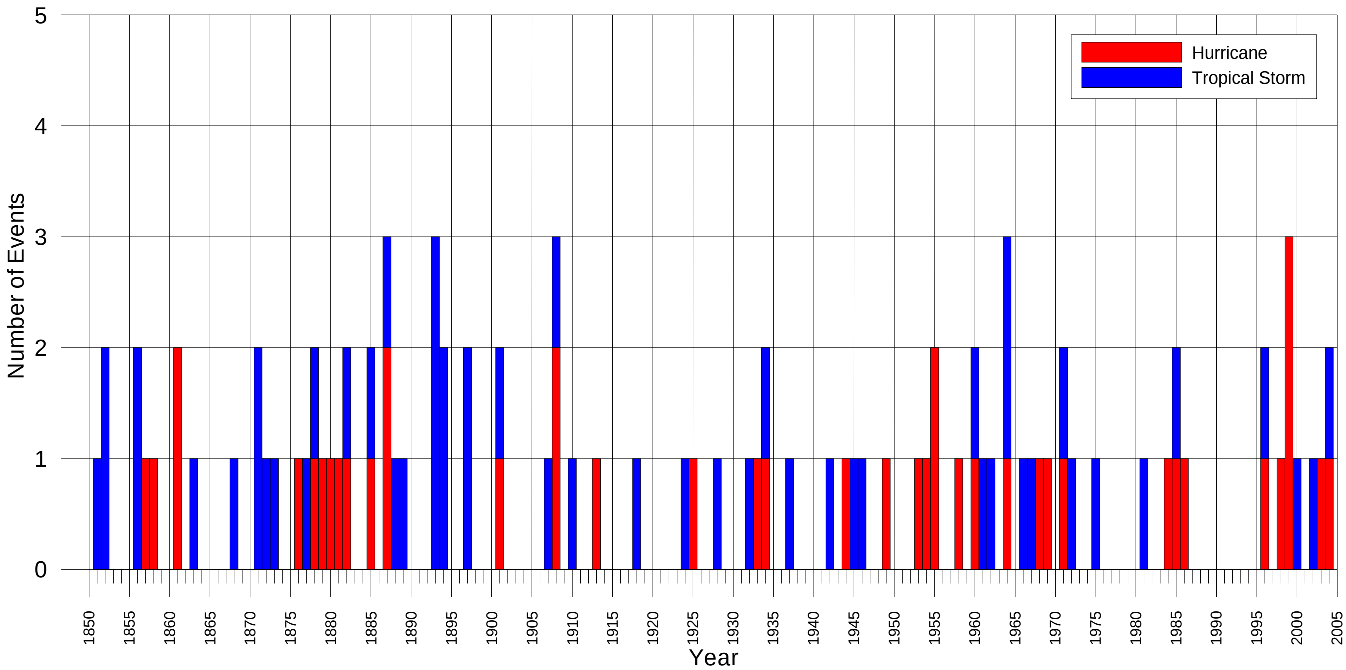

Figure 18: Occurrence of tropical storms within 75 n.miles of Morehead City, 1851-2004.

The area is also subject to extra-tropical nor'easters; however, the effects of these storms' waves is limited by the sheltering effects of the Cape Lookout shoals. Short-period southwest waves typically dominate the summer months and are of relatively moderate or low energy. The net effect of waves from tropical storms can be from either east or west, as a function of the storms' passage. Wave statistics for the site are described in ***Appendix E*** and also summarized in the following section.

6.0 WAVE ENERGY AND LITTORAL TRANSPORT PATTERNS

6.1 Overview

A detailed computer analysis was undertaken of wave refraction and the resultant longshore sediment transport potential for both pre-project (c. 1900) and existing (c. 2004) conditions. The analysis utilized the most recent 20-year wave hindcast data for the area (1980-1999), specifically weighting the wave statistics from five stations offshore of the coastline at Cape Lookout and westward along the study area. Three high-resolution bathymetric grids were developed to develop wave refraction patterns from easterly through southwesterly waves. The effect of northeasterly storm waves was also considered.

In total, the transformation of 45 representative wave cases of varying height, direction and period was examined for both pre-project and existing conditions[12]. For each wave case, the breaking height, angle, and longshore sediment transport potential were computed at 50-m spacing along the shoreline. The breaking wave angle was computed relative to the local shoreline orientation, which was separately enumerated at each grid cell for pre-project and existing conditions.

For each of the 45 wave cases, the computed breaking wave energy and longshore sediment transport potential were weighted by the average-annual occurrence of each wave case. The results were summed to develop an estimate of the average annual wave energy and sediment transport potential along the shorelines of both pre-project and existing conditions. The shoreline study area extended along all of Bogue Banks and most of Shackleford Banks -- noting that the results are less reliable approaching the extreme western and eastern ends of the study area (Bogue Inlet and Barden Inlet, respectively).

Changes in wave height across the ebb tidal shoal, from pre-project to existing conditions, were also identified for several typical wave cases. These included changes in wave height across the inlet throat and along the navigation channel. Future potential wave height changes were also computed for projected 15- and 30-year reductions in the inlet's ebb shoal elevations, based upon the historic trends of ebb shoal deflation.

Details of the wave refraction and littoral transport analyses are presented in ***Appendix E*** of this report.

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[12] The analysis used WIS hindcast data from the Corps' Coastal Hydraulics Laboratory, the model STWAVE for wave transformation, and the CERC Formula to estimate longshore transport. Details are presented in Appendix E.

6.2 Input Wave Conditions

Figure 19, below, illustrates the average annual occurrence of wave heights and directions – called a "wave rose" -- from one of the hindcast data locations used for the wave refraction and littoral transport study. The wave rose on the left is from hindcast data used in the Corps' Section 111 study (USACE 2001). The wave rose on the right is from revised hindcast data used in the present study. Both represent the same location offshore of Beaufort Inlet and are for the approximate same time period (±5 years); and both were published by the Corps of Engineers' Coastal Hydraulic Laboratory.

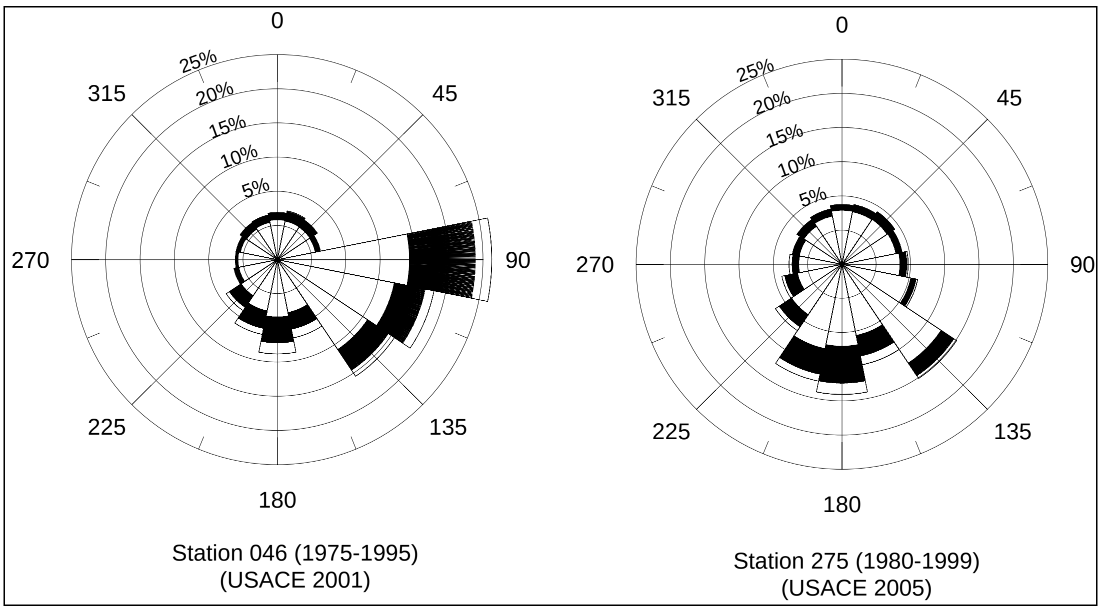

Figure 19: Wave height roses for the same hindcast location used in the Corps' Section 111 Study (at left) and for the present study (at right). The latter is the most recent, revised hindcast data, published by the Corps' Coastal Hydraulic Laboratory in 2005.

Compared with the data used in the Corps' Section 111 study, the revised hindcast data -- shown at right and used in the present study (along with four other adjacent stations along the study area shoreline) -- shows significantly less energy from the east and greater energy from the south and southwest. This is presumably because the revised hindcast data more accurately reflects the sheltering of east and northeast waves by the shoals of Cape Lookout.[13] The overall occurrence of wave heights is about the same. Wave periods (not shown) are shorter in the revised hindcast.

[13] The recent hindcast computations were performed by an independent subcontractor, using much higher grid resolution and an updated numerical wave model.

In the Corps' Section 111 study, one would expect that the use of the previous wave data – which features extraordinary dominance of waves from the east – would result in very strong east-to-west littoral transport. Instead, the Corps' study predicts a relatively *modest* westerly transport that is generally similar to the present study. This result is perplexing because the Corps' study relied upon [incorrect] wave data that are very different than the present study.

6.3 Longshore Transport Potential – Existing Conditions

Figure 20, on the following page, depicts the average-annual longshore sediment transport potential computed along the study area shoreline for existing conditions (c. 2004). The values do not necessarily represent the actual amount of sand that is transported alongshore – instead, the values represent the potential transport that would be driven by incident waves in the presence of adequate sand supply. The effects of tidal currents are not included. Because of inherent limitations to the predictive formulae, the absolute magnitudes of the transport potential are less certain than the alongshore trends (gradients and direction) of transport.

The results indicate an overall net westerly-directed littoral drift. Along Bogue Banks, there is a fairly balanced east-west littoral drift, but with westerly-directed transport being net dominant along most of the island. Along Shackleford Banks, the net potential transport is predicted to be strongly to the west, with a relatively small easterly-directed component.

West of the inlet, along Bogue Banks, a *nodal point* in longshore transport is predicted at about 12,500 feet (2.4 miles) west of the inlet. Physically, this point corresponds to eastern Atlantic Beach, between the Triple S and Oceanana Piers. East of this point, net transport potential is computed to accelerate rapidly toward the east (toward the inlet), reaching over 500,000 cy/yr at the Fort Macon State Park boundary and continuing at this rate to the inlet. West of this point, transport potential is computed to accelerate more modestly toward the west, reaching about 70,000 cy/yr on alongshore average, then decelerating along western Atlantic Beach into Pine Knoll Shores.

This region of eastern Atlantic Beach and Fort Macon along which the transport diverges to the west and east is expected to be chronically erosional. In reality, the location of this "divergent node" varies and usually encompasses a broad reach of shoreline moreso than a discrete point.

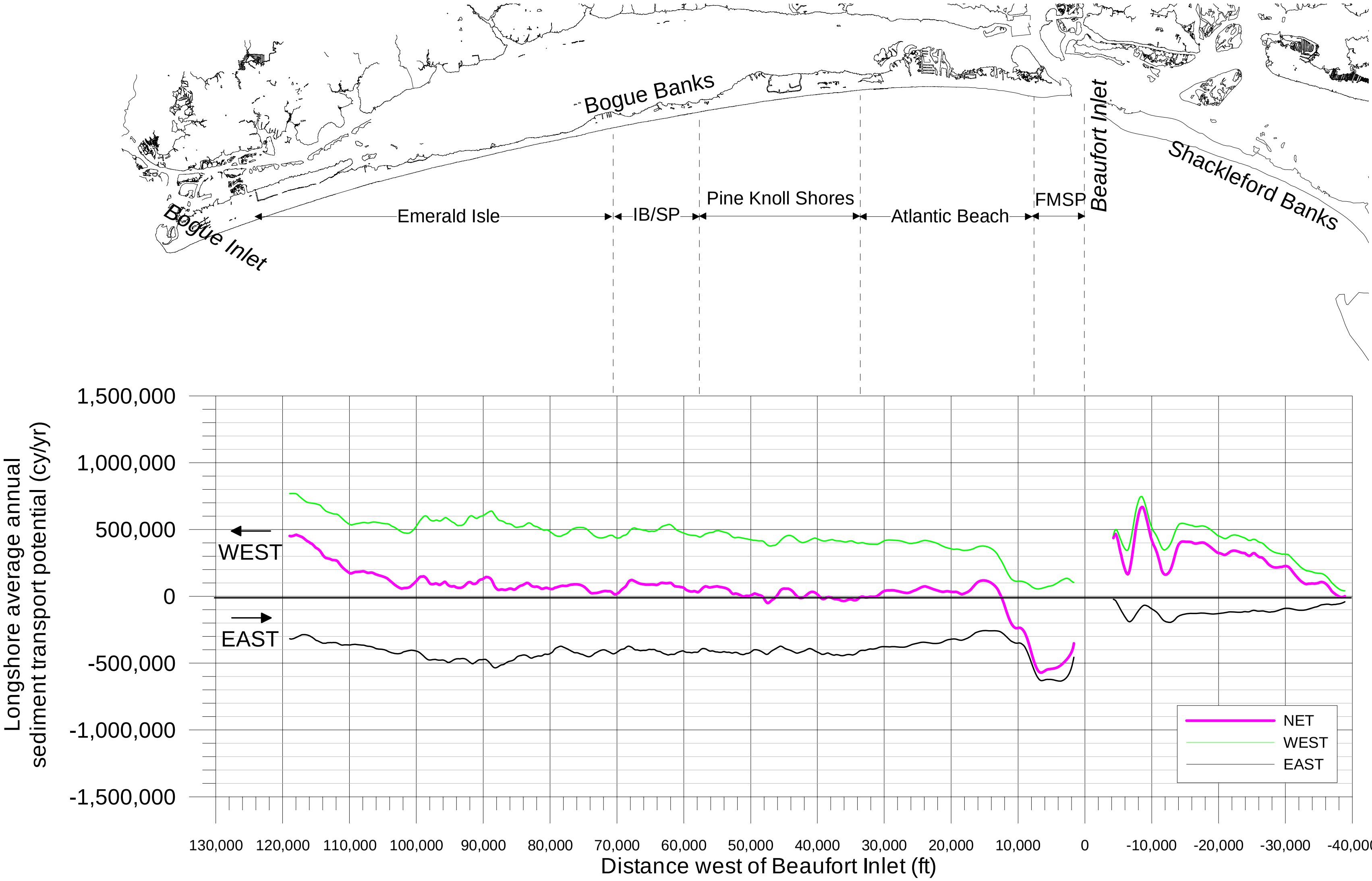

Figure 20: Average annual longshore transport potential computed for existing conditions (c. 2004).

The net westerly transport potential is computed to be relatively modest along most of Pine Knoll Shores (PKS) and then to gradually accelerate to about 100,000 cy/yr along western PKS into Indian Beach/Salter Path, where it continues along most of Emerald Isle. Along western Emerald Isle, within about 3.8 miles of Bogue Inlet, the net westerly transport potential accelerates significantly toward the inlet. (Results in this area, especially in magnitude, are less certain because of the coastline curvature and the distance from the principal study area.)

Overall, along most of Bogue Banks, the gross transport potential is very high relative to the net transport: that is, there is about 800,000 to 1,000,000 cy/yr combined east-west transport potential versus about 100,000 cy/yr net. This means that there is a large -- but nearly equal -- volume of sand moving both east and west along the shoreline throughout the year. In an equilibrium condition, this would result in only minor net transport and shoreline changes. However, in a perturbed condition – where there is a sediment sink at one end of the system (such as via dredging at Beaufort Inlet) -- the system can become unbalanced. Easterly-transported sand that is "trapped" by the inlet and dredging is no longer available for westerly-transport. The result is net erosion to the beach system.

The effect is analogous to marbles rolling back and forth in a pan. In a balanced system (with no holes), the marbles move back and forth with no net change. In an unbalanced system (with a hole, or "sink", at one end), marbles can fall out of the pan at one end and are no longer available to roll back to the other end. The impact of the pan's hole is upon the *total* ("gross") amount of marbles moving in the system; the impact is not limited to the net movement of the marbles. In this way, an improved inlet can act as a "sink" to the *gross* transport rate directed toward the inlet – not just the net transport rate.

From Figure 20, the *gross* transport potential directed toward the inlet is on the order of 600,000 cy/yr from the west (Bogue Banks) and 500,000 cy/yr from the east (Shackleford Banks). The combined value – 1,100,000 cy/yr – is the same magnitude as the current rate of maintenance dredging of the federal navigation project.

The rates of transport potential toward the inlet depend upon the locations which are selected along the adjacent islands. The potential sand transport into the inlet is not limited to the ends of the islands; instead, sand transport between the islands and the inlet can occur across the entire region at which the ebb tidal platform attaches to the adjacent shorelines. By inspection of the computed transport patterns and the inlet bathymetry, this region spans from about 12,500 ft (2.4 miles) west to 11,000 ft (2.1 miles) east of the inlet.

A significant result of the analysis is that sand placed within at least 2.4 miles west of the inlet, along eastern Bogue Banks, can be expected to be directly transported back to the inlet. From Section 3.5 (page 17), this comprises at least 4.15 Mcy – or about 38% -- of the net beach-compatible volume of sand placed upon Bogue Banks as beach disposal from the federal navigation project.

6.4 Longshore Transport Potential – Pre-Project vs. Existing Conditions

Figure 21, on the following page, compares the computed longshore transport potential for pre-project conditions (c. 1900) and existing conditions (c. 2004). The results are shown for only a subset of the study area. There are no discernible changes beyond the alongshore limits shown in the figure.

The contrast between the pre-project and existing transport patterns includes all of the effects of the nearshore and offshore dredge disposal, the deepened navigation channel, the change in shoreline orientations and the western accretion of Shackleford Banks – all of which were modeled in the existing conditions (c. 2004). The pre-project conditions are based upon the 1900 bathymetric survey data and shoreline geometry.

Changes in transport potential – from pre-project to existing conditions – extend to about 24,000 ft (4.5 miles) west and 20,000 ft (3.8 miles) east of the inlet. The former corresponds to central Atlantic Beach, about 1.3 miles west of Sportsman Pier. From pre-project to existing conditions, the most notable changes include:

- A slight eastward shift of the nodal point (transport "reversal") -- from about 14,500 ft west to 12,500 ft west of the inlet
- A *decrease* in easterly "reversal" transport along eastern Atlantic Beach, but a significant *increase* in easterly "reveral" transport along the entire Fort Macon State Park shoreline.
- At the inlet mouth (i.e., near the ends of the adjacent islands), the *gross* transport directed toward the inlet increased from about 150,000 cy/yr to about 600,000 cy/yr on the west side. It decreased from about 700,000 cy/yr to about 500,000 cy/yr on the east side.
- The *net* longshore transport potential directed toward the inlet, near the inlet mouth, increased from about 150,000 cy/yr to 450,000 cy/yr on the west side. It decreased from about 650,000 cy/yr to 450,000 cy/yr on the east side.

Thus, near the inlet, there were significant *increases* in transport potential directed from Bogue Banks into the inlet (on the order of at least +300,000 cy/yr). And, there were apparent *decreases* in transport potential directed from Shackleford Banks into the

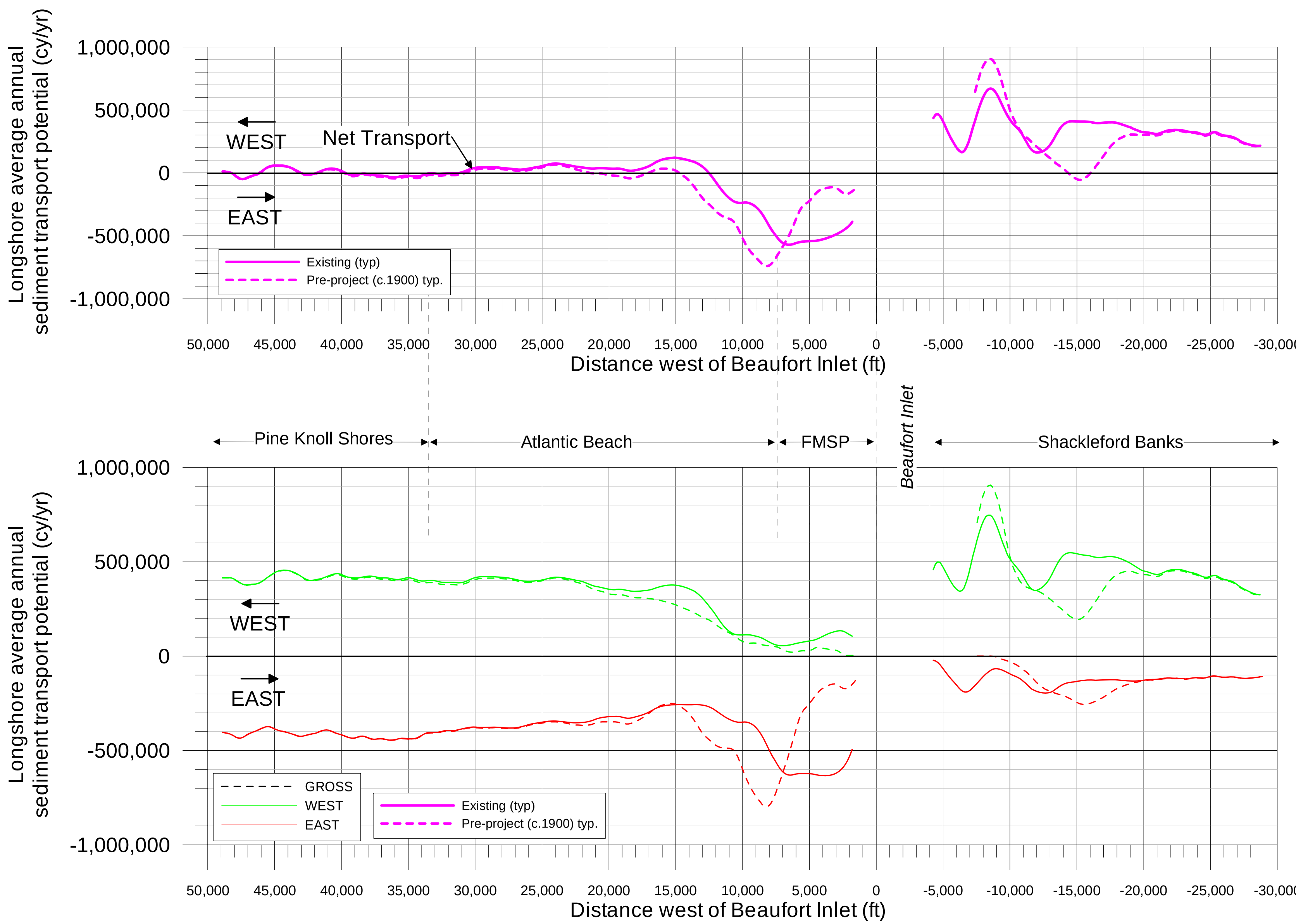

Figure 21: Average annual longshore transport potential computed for pre-project (c. 1900) and existing conditions (c. 2004).

Inlet (on the order of about -200,000 cy/yr). Again, defining discrete values or changes of transport potential depend upon the location near the inlet; but the values noted above reflect the trend, or order of magnitude, of the computed transport changes between pre-project and existing conditions.

6.5 Comparison with Corps' Section 111 Study

The results of the present study are generally similar to the transport potential computed by the Corps' Section 111 study (USACE, 2001). Overall, as in the present study, the Corps' study predicted a general net westerly-directed transport along Shackleford Banks and Bogue Banks. Both studies predict an easterly-directed reversal in transport within about 2.4 miles west of the inlet.

From pre-project to existing conditions, both studies conclude that significant changes in transport potential extend to about central Atlantic Beach (4.5 miles west of the inlet), but the Corps' study additionally computed minor changes (slight reductions in net westerly transport) extending all the way through Pine Knoll Shores, up to 10.5 miles west of the inlet. [This result is somewhat suspect because of the unusual way in which the Corps' study "seamed" results together from one alongshore grid to another.]

Both studies computed a similar 2000-ft eastward shift in the 'nodal' point of transport reversal at Atlantic Beach, but the Corps' study did not compute an increase in easterly-directed transport along the entirety of Fort Macon State Park. [This is because the Corps' study apparently did not change the shoreline orientation between existing conditions and pre-project conditions.]

Both studies' transport predictions for Shackleford Bank were similar, except that the Corps did not appear to model the significant difference in the island's westerly extents between pre-project and existing conditions.

The Corps' study did not illustrate alongshore variations in breaking wave energy, for either pre-project or existing conditions. These results, from the present study, are presented below.

6.6 Alongshore Wave Energy – Pre-Project versus Existing Conditions

Figure 22 compares the average annual breaking wave energy computed along the shorelines for both pre-project and existing conditions. Changes extend to about 20,000 ft (3.8 miles) east and west of the inlet. Significant increases in wave energy are evident

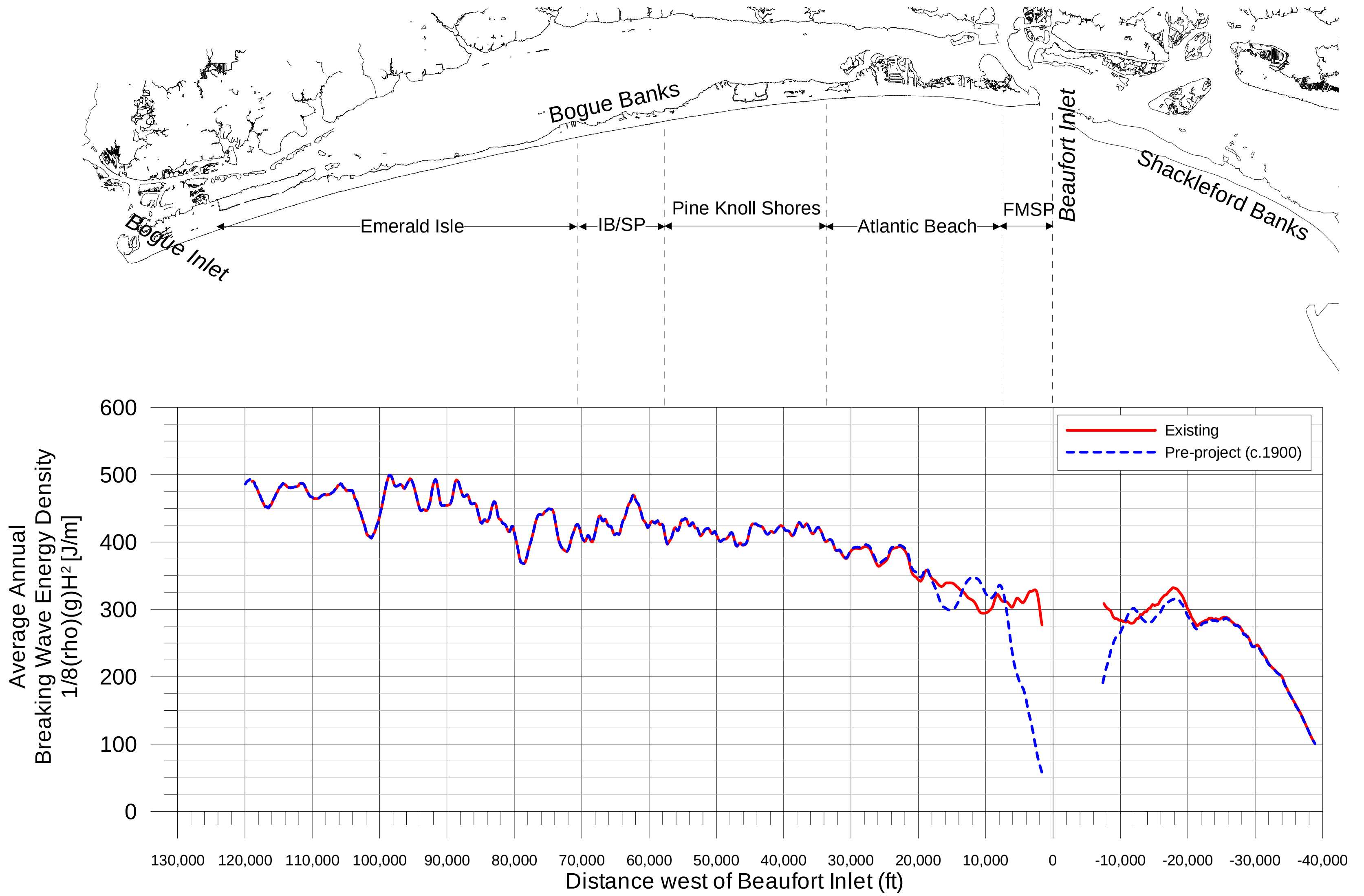

Figure 22: Average annual breaking wave energy density for pre- and post-project bathymetries.

within about 7000 ft (1.3 miles) east and west of the inlet – particularly along the entire length of the Fort Macon State Park shoreline. From pre-project to existing conditions, the total increase in breaking wave energy along the Bogue Banks shoreline was about 3.2 times greater than along the Shackleford Banks shoreline. Alternately stated, about 76% of the energy increase is associated with the Bogue Banks (western) side of the inlet.

Figure 23 depicts planform changes in wave height from pre-project to existing conditions for a typical wave condition from the southeast. Additional results are illustrated in ***Appendix E***, pages E-38 through E-43.

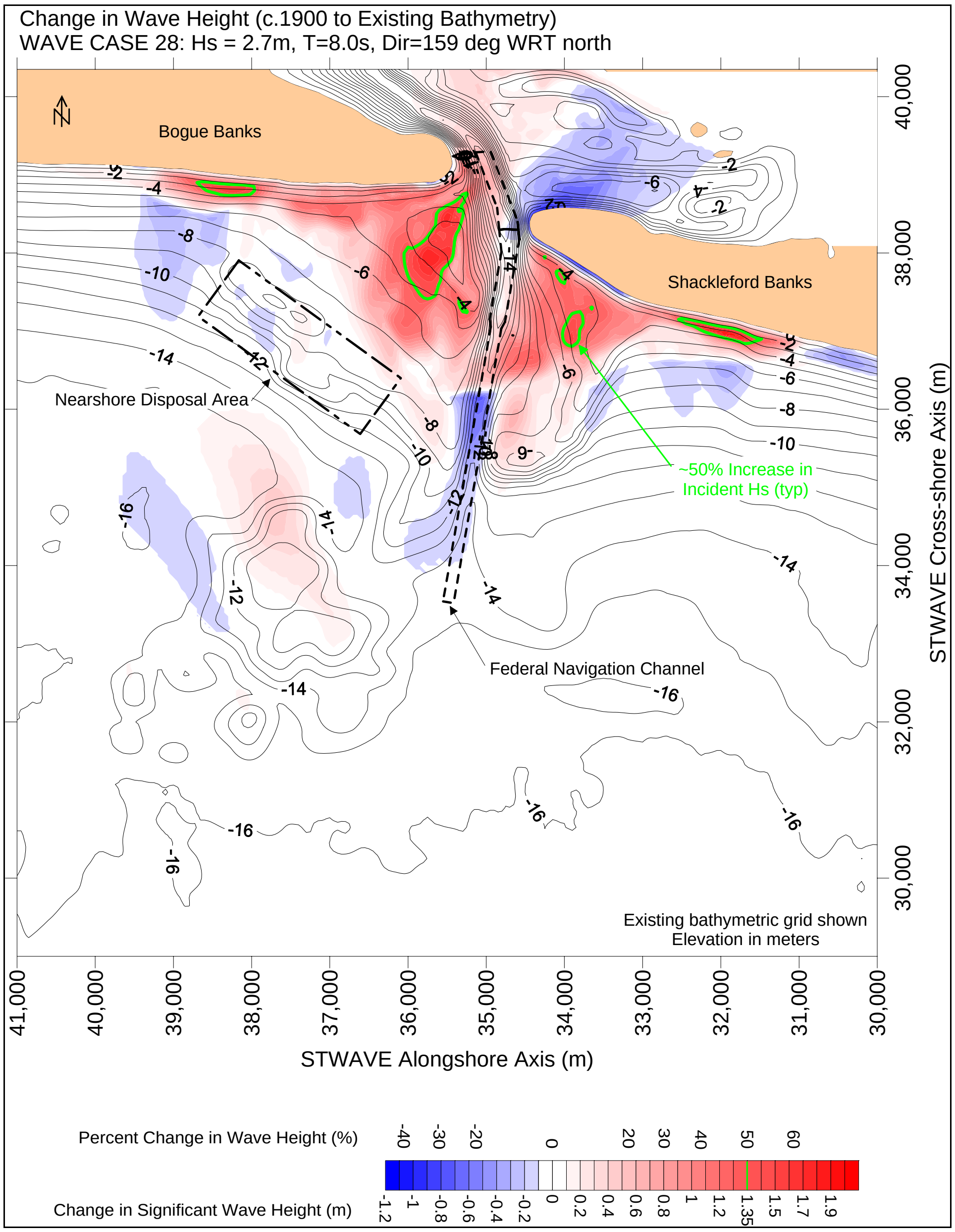

Figure 23: Change in wave height for wave case 28 – south southeast wave.

6.7 Wave Height Changes at the Inlet Throat and Navigation Channel

Deflation of the ebb tidal shoal has increased wave energy entering the inlet throat as well as that along the navigation channel, and along the adjacent shorelines. Continued deflation of the ebb tidal shoal is predicted to result in additional increases of wave energy in these areas. Increases in wave height are greatest along the western (Bogue Banks) side of the inlet.

As a typical example, ***Figure 24*** depicts the computed wave heights across the inlet throat and along the channel axis for a 5-ft sea condition from the south-southwest. Results are shown for pre-project (c. 1900) and existing-conditions. Results are also predicted for future conditions, simulating 15-years and 30-years of continued ebb shoal deflation, based upon the historic trends of bathymetric changes along the east and west lobes of the ebb shoal. ***Figure 25***, following page, illustrates the location of the two sections along which these wave height computations were made.

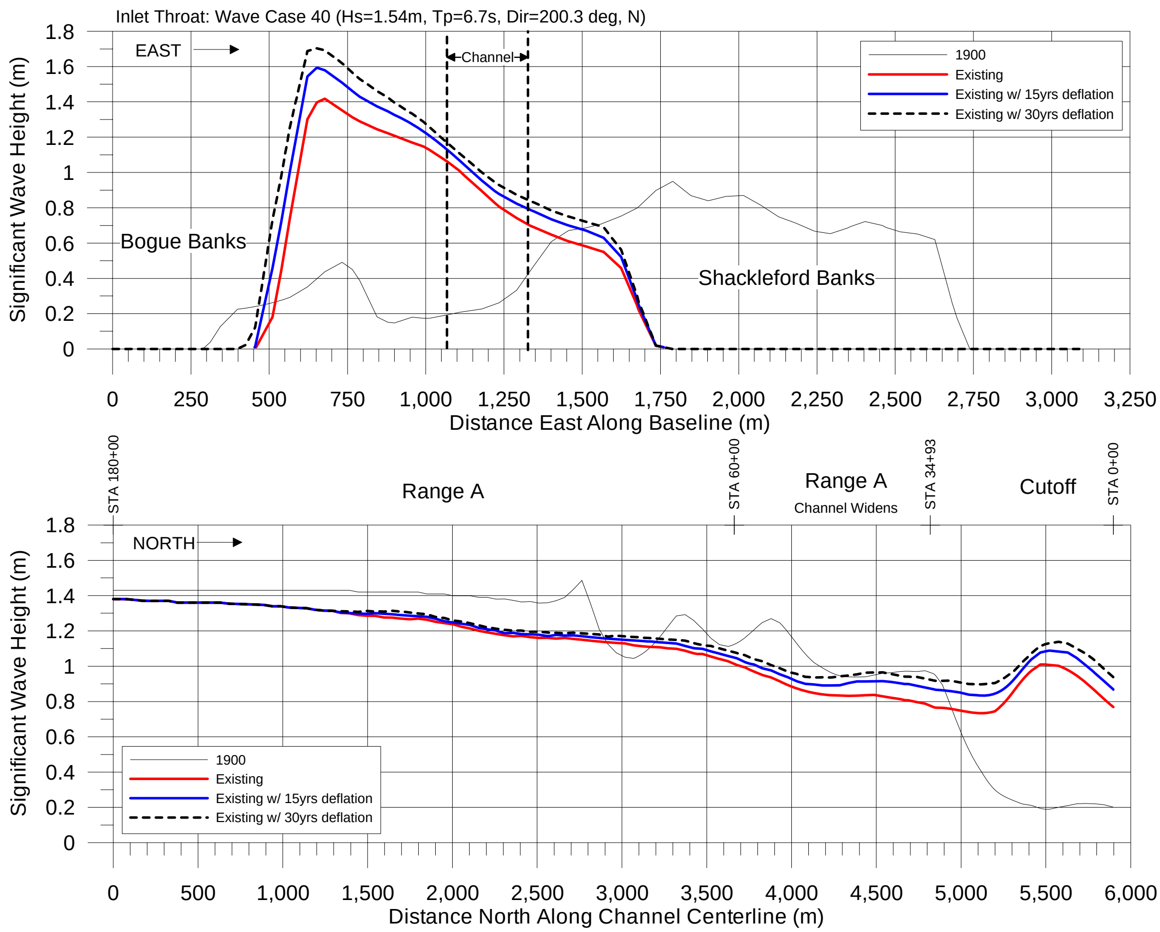

Figure 24: Wave heights across the inlet throat (upper figure) and along the navigation channel (lower figure) computed for 1900, existing, 15-year future, and 30-year future conditions. In this example, the incident wave direction is from the south-southwest.

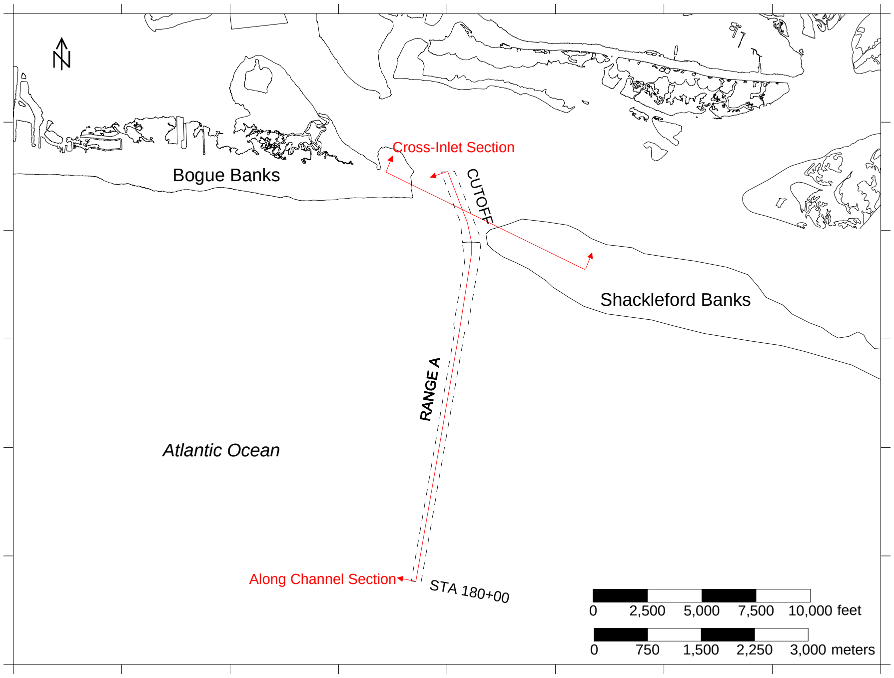

Figure 25: Section-locations corresponding to the wave heights shown in Figure 24, above.

From Figure 24, for this south-southwest wave condition, the wave height across the inlet mouth, at the channel, increased by a factor of about 4 from pre-project to existing conditions. Wave energy was greatly increased along the eastern tip of Bogue Banks – consistent with that shown in Figures 22 and 23. Wave energy decreased to the east, along Shackleford Banks, because of the growth of this island into the inlet throat since pre-project conditions. Along the navigation channel, moving toward the inlet (from left to right in the figure), the wave heights are decreased because of the deeper shoal and channel elevations. However, approaching the inlet mouth (at the junction of the Range A and Cutoff Channel), the wave height is dramatically increased.

The 15- and 30-year future projections predict continuing increase in wave heights -- by about 10% for each case -- as the ebb shoal continues to deflate. Results for other wave directions are similar (see ***Appendix E***, pp. E-54 to E-59).

The increases in wave height along the navigation channel – and particularly at the inlet throat, where vessels must maneuver between Shackleford and Bogue Banks – can be expected to adversely affect navigation. Additionally, increased wave heights entering the inlet can be reasonably expected to adversely impact the interior bay and estuary. These impacts could include portions of the Rachel Carson National Estuarine Research Reserve. This reserve encompasses nearly 2700 acres leeward and east of the inlet (***Figure 26***), and includes marshlands and islands comprising habitat to over 200 species of birds.

Figure 26: Boundaries of the Rachel Carson National Estuarine Research Reserve within the interior waters of Beaufort Inlet. (Figure is from North Carolina National Estuarine Research Reserve Program.)