APPENDIX A WAVE & SEDIMENT MODELS

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1.0 INTRODUCTION

The purpose of this Appendix is to document the data sources, approach, methods, and results of modeling studies supporting the Engineering Report. The studies documented here include: hydrodynamic and wave transformation models covering the region between Cape Lookout and Bear Island; GIS based analysis of historical changes in Bogue Inlet channel and shoreline morphology; and coupled wave, hydrodynamic, sediment transport, and morphodynamic models focused on Bogue Inlet.

The overall study area consists of the barrier islands of Carteret County and adjacent tidal waters from Cape Lookout in the east to Bear Island in the west, including Bogue Sound and the nearshore waters to a depth of approximately -30 meters NAVD88.

Unless otherwise noted, all units in this Appendix are in the metric system, and all elevations are referenced to the North American Vertical Datum of 1988 (NAVD88). All horizontal coordinates are referenced to Universal Transverse Mercator (UTM) Zone 18N, WGS 1984 horizontal datum.

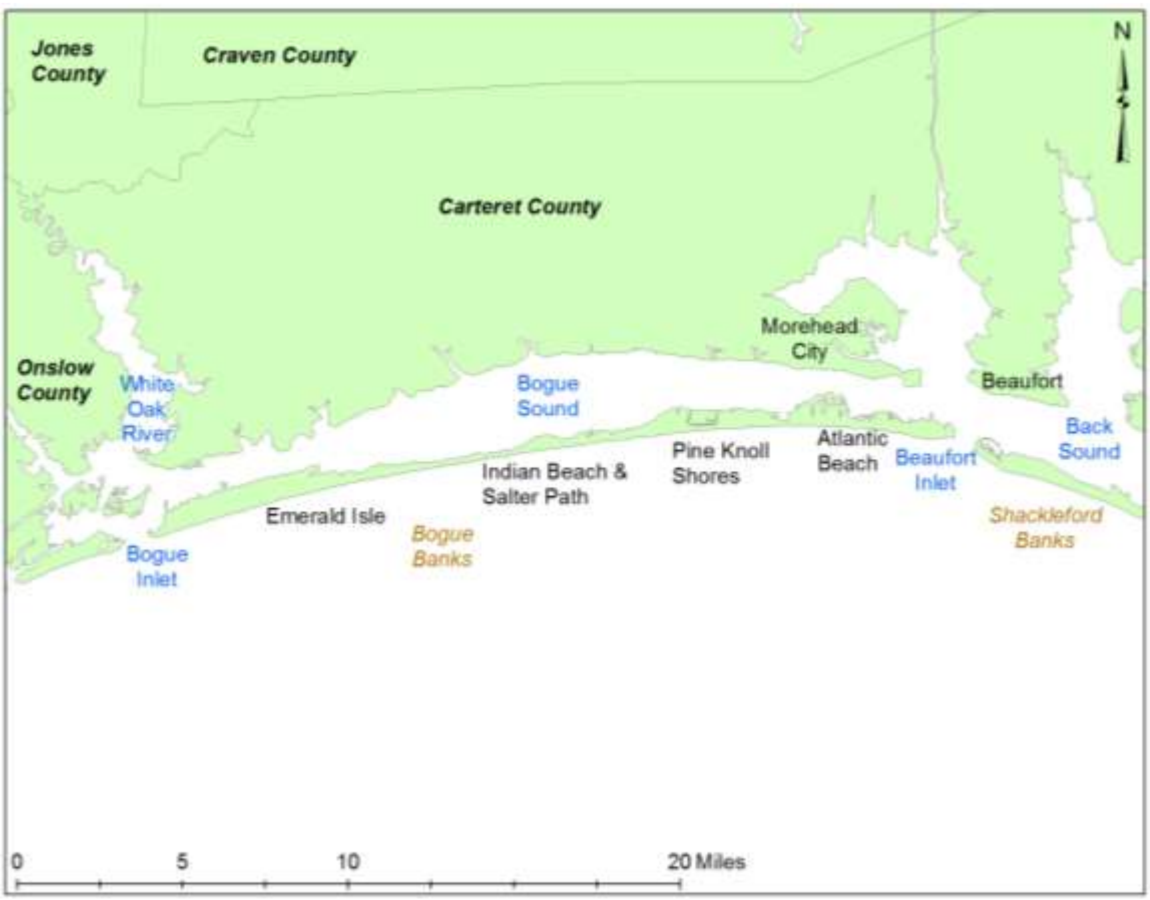


Figure 1-1: Study area of Bogue Banks and Bogue Inlet, Carteret County, NC

2.0 STUDY APPROACH

The study consists of an analysis of Bogue Inlet channel morphology, as it is relevant to future coastal planning along the Bogue Banks coastline. The component of the study actually focused on Bogue Inlet relies on a separate, larger-scale regional numerical model of waves and tidal hydrodynamics that force the local sediment transport processes along Bogue Banks and within Bogue Inlet. The regional model provides boundary conditions to the separate local-scale numerical models of Bogue Inlet.

The approaches taken to the local-scale study is described below.

2.1 Bogue Inlet local-scale study approach

The purpose of the present study of Bogue Inlet is to understand the range of historical migration and orientation of the ebb and flood channels, and to translate that understanding into guidance for planning future maintenance of the ebb and/or incipient flood channels. This component of the Plan is focused on preventing the natural channel migration from unacceptably eroding the western end of Bogue Banks and the eastern end of Bear Island.

The present study primarily utilizes indicators of inlet channel and shoal morphology measurable from georeferenced historical aerial and satellite imagery and historical bathymetric surveys to develop these guidelines.

The empirical / analytical study is supplemented with a limited series of numerical morphodynamic model simulations. The local numerical model consists of dynamically coupled two-dimensional (2-D) depth-integrated waves and hydrodynamics, which drive quasi-three-dimensional (Q3D) sand transport calculations. The sand transport calculations cause changes in the model bathymetry, which are then automatically fed back to the subsequent wave, flow, and transport calculations. The purposes of the numerical model portion of the study are:

- to understand sediment transport pathways within the inlet and its shoals; and
- to investigate “tipping points” that may exist – i.e. inlet ebb channel positions or orientations which would indicate more likely acceleration of migration toward the barrier islands.

3.0 WAVE AND TIDE CLIMATE

The morphology of Bogue Inlet is dependent upon sediment transport due to tidal currents through the inlet and wave action on the shoal / channel complex and adjacent beaches. In order to study the inlet's morphology using numerical models, it is necessary to develop a finite set of wave and tide conditions that can be considered representative of the important sediment transport processes. In the present case, since it is important to study the combined action of tidal currents and waves over long periods of time, a "representative annual" time series of offshore waves has been superimposed on a representative time series of tidal water levels and currents. The offshore waves and tidal boundary conditions used to force the numerical models, along with the data used to calibrate the hydrodynamic model, are based on historical measured data from the sources shown in Figure 3-1 and described below.

Figure 3-1: Wave and Water Level Data Locations

3.1 Wave Climate

Relevant wave data in the project vicinity consist of three directional wave buoys that have been operated at various times by the National Data Buoy Center (NDBC) and the USACE Wave Information Studies (WIS) wave hindcast simulation archive. The NDBC measurements include wave height, period, and direction at approximately hourly intervals (with gaps) over various periods of time since 2003, as described below. The WIS archive contains simulated wave height, period, and direction at three-hour intervals over a period of 20 years from 1980 to 1999 (inclusive).

3.1.1 NDBC Buoy #41035 – Onslow Bay Inner

The National Data Buoy Center (NDBC) maintains two directional waverider buoys very close to the study area. The closest buoy to Bogue Banks is #41035 (Onslow Bay Inner), located approximately 16.5 miles southwest of Bogue Inlet and in a water depth of approximately 10 meters. The data record spans August 1, 2005 – August 22, 2011. The record includes a significant gap between October 15, 2009 – April 15, 2010. The buoy appears to have gone offline on August 22, 2011, just before Hurricane Irene's landfall, and it has been offline since that date. As shown in Figure 3-2, waves at this buoy are predominantly from the south and southeast sectors, with measured significant wave heights predominantly between 0.5 and 1.5 meters. Measured significant wave heights exceed 2.5m approximately 0.14% of the time.

3.1.2 NDBC Buoy #41036 – Onslow Bay Outer

NDBC buoy #41036 (Onslow Bay Outer) is located approximately 32.5 miles south-southwest of Bogue Inlet and in a water depth of approximately 31 meters. The data record utilized spans July 2006 – September 2011. The record includes significant number of missing time steps, including large gaps from mid-August through mid-October 2006, and mid-January through November 2010. As shown in Figure 3-3, waves at this buoy are predominantly from the southeast through the east-northeast sectors, with measured significant wave heights predominantly between 0.5 and 2.5 meters. Measured significant wave heights exceed 2.5m approximately 7.3% of the time, and they exceed 3.5m approximately 2.4% of the time.

3.1.3 NDBC Buoy #41013 – Frying Pan Shoals

NDBC buoy #41013 (Frying Pan Shoals) is located significantly further from the project area, at approximately 92 miles southwest of Bogue Inlet and in a water depth of approximately 24 meters. The data record utilized spans November 2003 – September 2011. The record includes significantly less missing time steps than NDBC #41036, and it also includes waves from Hurricane Ophelia in September 2005. Notable gaps in this buoy's record include late-December 2003 – March 2004; January 2005; late-March to July 2005; and January to mid-April 2007. As shown in Figure 3-4, waves at this buoy are predominantly from the southeast through the northeast sectors, with measured significant wave heights predominantly between 0.5 and 2.5 meters. Measured significant wave heights exceed 2.5m approximately 5.7% of the time, and they exceed 3.5m approximately 1.0% of the time.

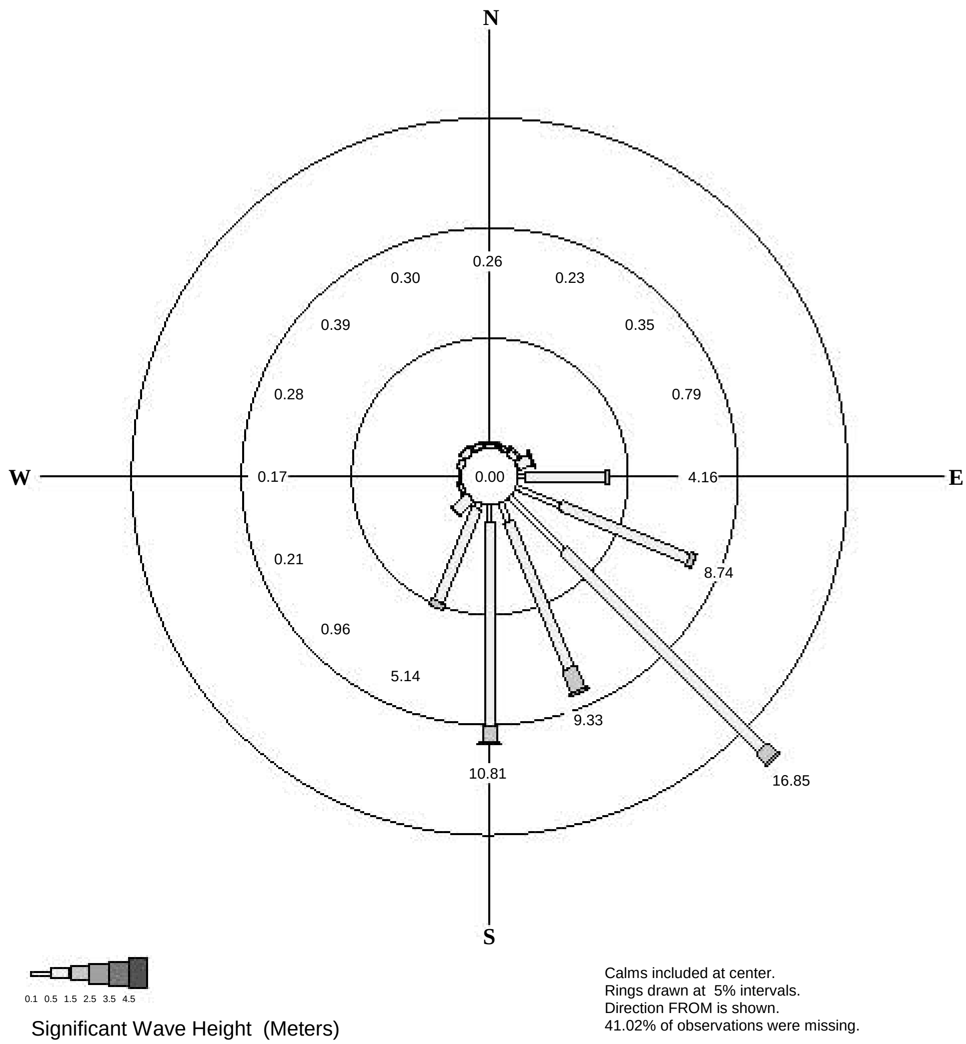
The recorded waves at the Frying Pan Shoals buoy are, in general, very similar in directional distribution (% occurrence) and in range of significant wave heights to those at Onslow Bay Outer. The primary difference in the records is that the Onslow Bay Outer rose shows a relatively high percentage (approximately 10%) of waves occurring from the northwesterly directions (compared to 6% at Frying Pan Shoals). The significant waves heights from the northwest quadrant (i.e. traveling from onshore to offshore) at the Onslow Bay Outer buoy seem unreasonably large at $H_s > 3.5$ m. However, the present study is not particularly interested in waves traveling *from* northwest, but in waves approaching Bogue Inlet and Bogue Banks from offshore (i.e. the northeast through southeast quadrants), and these northwest originating waves do not affect the modeling or other aspects of the study.

3.1.4 USACE Wave Information Studies (WIS) Hindcast Data

Longer-term hindcast wind and wave time series are available from several USACE WIS output stations in the project vicinity. The WIS station nearest in position and water depth to NDBC buoy #41036 (Onslow Bay Outer) is WIS Atlantic hindcast station #63287 in a water depth of approximately 95 feet (29 meters).

The WIS hindcast program simulated operational and storm waves over 20 years from 1980 to 1999 (inclusive), and for this reason the WIS data was used for conducting extreme value analysis on wave heights offshore of Bogue Banks.

Joint Frequency Distribution (Annual)
Station 41035 - Onslow Bay Inner
Period of observations 2005-2011



PERCENT OCCURRENCE: Significant Wave Height (Meters)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
N	0.04	0.20	0.01	0.01	0.00	0.00
NNE	0.05	0.16	0.02	0.00	0.00	0.00
NE	0.06	0.23	0.06	0.00	0.00	0.00
ENE	0.08	0.64	0.05	0.01	0.00	0.00
E	0.28	3.69	0.19	0.00	0.00	0.00
ESE	2.19	6.30	0.25	0.00	0.00	0.00
SE	3.46	12.69	0.65	0.04	0.00	0.00
SSE	0.95	7.17	1.10	0.11	0.00	0.00

TOTAL OBS = 82739 MISSING OBS = 33940

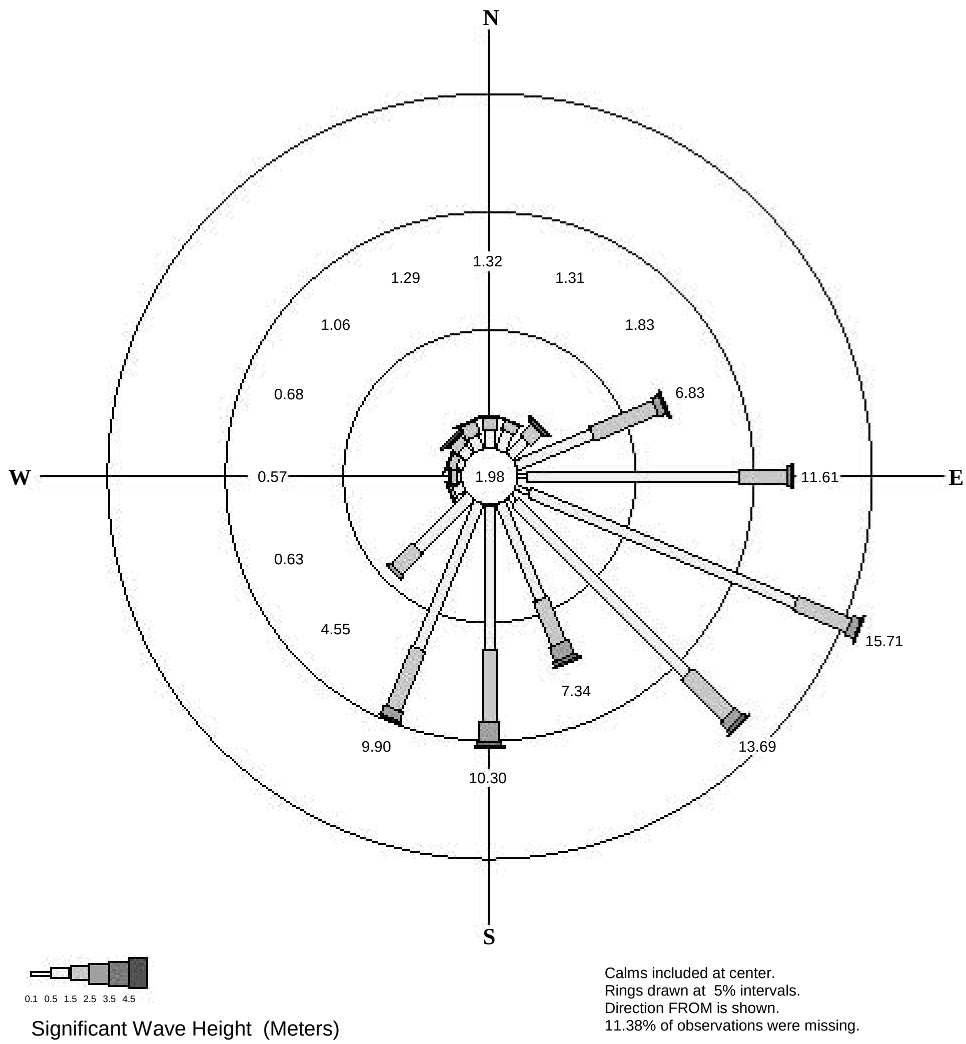
PERCENT OCCURRENCE: Significant Wave Height (Meters)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
S	0.78	9.26	0.72	0.04	0.01	0.00
SSW	0.27	4.59	0.28	0.00	0.00	0.00
SW	0.07	0.86	0.03	0.00	0.00	0.00
WSW	0.03	0.18	0.01	0.00	0.00	0.00
W	0.02	0.15	0.00	0.00	0.00	0.00
WNW	0.04	0.24	0.00	0.00	0.00	0.00
NW	0.08	0.30	0.01	0.00	0.00	0.00
NNW	0.08	0.21	0.01	0.00	0.00	0.00

CALM OBS = 1 PERCENT CALM = 0.00

Figure 3-2: Onslow Bay Inner Wave Rose (August 2005 – August 2011)

Joint Frequency Distribution (Annual)
Station 41036 - Onslow Bay (NC) Outer
Period of observations 2006-2011



PERCENT OCCURRENCE: Significant Wave Height (Meters)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
N	0.01	0.73	0.54	0.04	0.00	0.00
NNE	0.00	0.86	0.42	0.02	0.01	0.00
NE	0.00	0.98	0.66	0.08	0.09	0.03
ENE	0.03	3.49	2.89	0.32	0.07	0.03
E	0.40	8.94	2.05	0.19	0.03	0.00
ESE	0.66	12.17	2.44	0.38	0.05	0.01
SE	0.36	10.27	2.44	0.42	0.17	0.02
SSE	0.04	4.41	2.01	0.65	0.18	0.06

TOTAL OBS = 72034 MISSING OBS = 8199

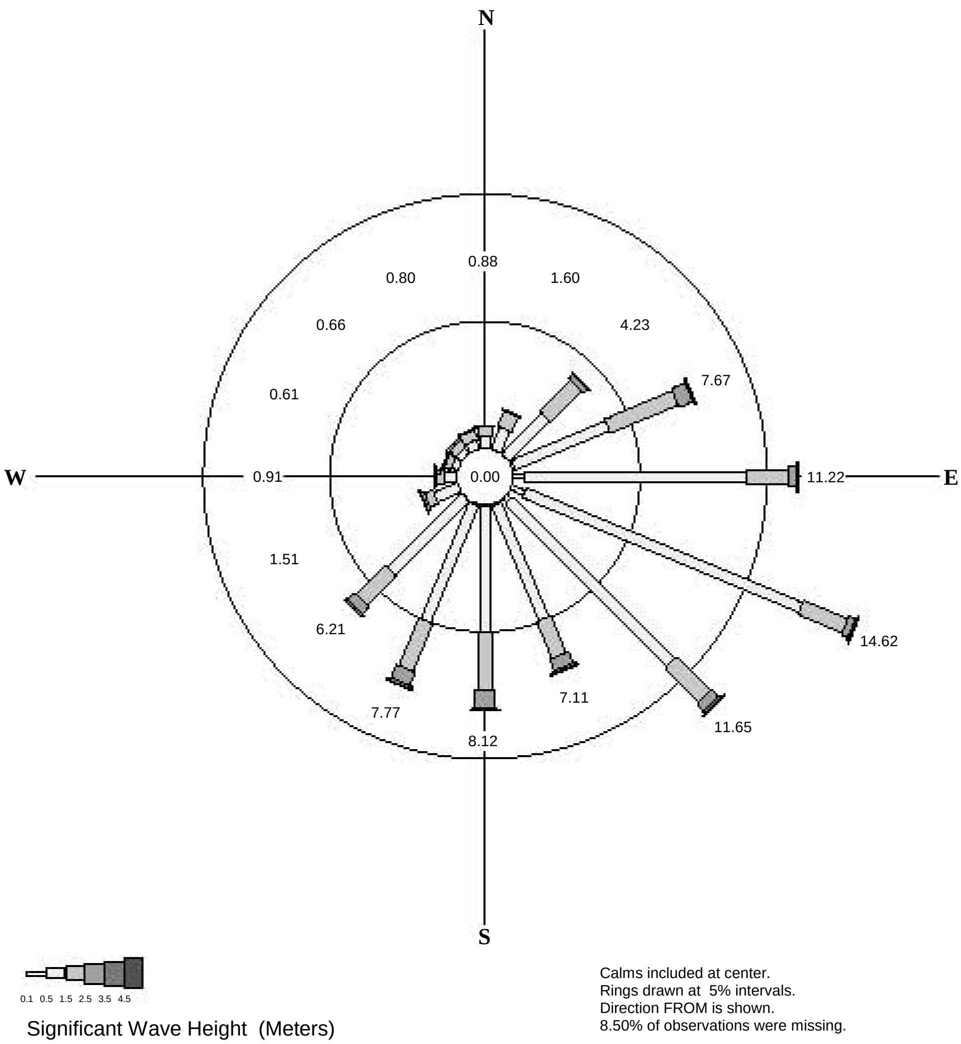
PERCENT OCCURRENCE: Significant Wave Height (Meters)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
S	0.02	6.08	3.05	0.91	0.18	0.05
SSW	0.01	6.69	2.74	0.41	0.04	0.00
SW	0.00	3.15	1.26	0.14	0.00	0.00
WSW	0.00	0.46	0.14	0.02	0.01	0.00
W	0.00	0.23	0.23	0.09	0.01	0.00
WNW	0.00	0.28	0.34	0.03	0.02	0.01
NW	0.00	0.49	0.43	0.05	0.04	0.05
NNW	0.00	0.64	0.59	0.04	0.01	0.01

CALM OBS = 1429 PERCENT CALM = 1.98

Figure 3-3: Onslow Bay Outer Wave Rose (July 2006 – September 2011)

Joint Frequency Distribution (Annual)
Station 41013 - Frying Pan Shoals (NC)
Period of observations 2003-2011



PERCENT OCCURRENCE: Significant Wave Height (Meters)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
N	0.01	0.49	0.36	0.02	0.00	0.00
NNE	0.01	0.92	0.64	0.03	0.00	0.00
NE	0.01	2.24	1.72	0.24	0.02	0.00
ENE	0.10	4.03	2.88	0.58	0.07	0.01
E	0.41	8.75	1.70	0.25	0.08	0.03
ESE	0.59	11.79	1.89	0.27	0.07	0.02
SE	0.25	9.00	1.88	0.41	0.09	0.02
SSE	0.08	4.86	1.57	0.48	0.09	0.03

TOTAL OBS = 61458 MISSING OBS = 5223

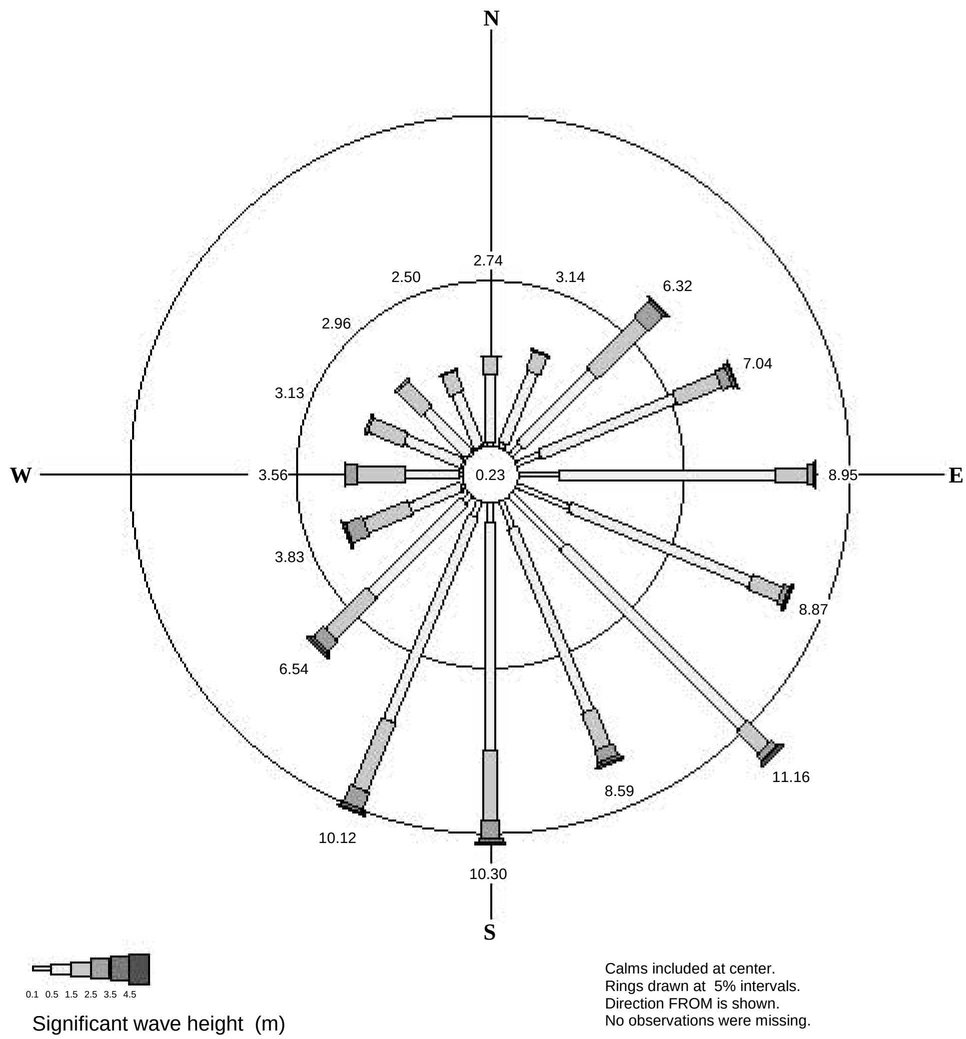
PERCENT OCCURRENCE: Significant Wave Height (Meters)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
S	0.06	4.93	2.29	0.70	0.12	0.02
SSW	0.07	4.97	2.04	0.56	0.12	0.01
SW	0.05	4.11	1.64	0.35	0.06	0.00
WSW	0.02	1.00	0.35	0.13	0.01	0.00
W	0.00	0.46	0.33	0.10	0.02	0.00
WNW	0.00	0.28	0.26	0.05	0.00	0.01
NW	0.00	0.32	0.28	0.05	0.00	0.00
NNW	0.01	0.36	0.40	0.03	0.00	0.00

CALM OBS = 1 PERCENT CALM = 0.00

Figure 3-4: Frying Pan Shoals Wave Rose (November 2003 – September 2011)

Joint Frequency Distribution (Annual)
Station 63287 - WIS
Period of observations 1980-1999



PERCENT OCCURRENCE: Significant wave height (m)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
N	0.14	2.04	0.54	0.01	0.00	0.00
NNE	0.18	2.33	0.59	0.03	0.00	0.00
NE	0.44	3.05	2.10	0.64	0.07	0.01
ENE	0.78	4.40	1.42	0.32	0.10	0.02
E	1.19	6.51	1.01	0.16	0.06	0.01
ESE	1.75	5.88	0.97	0.17	0.07	0.03
SE	2.26	7.61	0.94	0.21	0.08	0.06
SSE	0.90	5.99	1.19	0.37	0.11	0.04

TOTAL OBS = 58438 MISSING OBS = 0

PERCENT OCCURRENCE: Significant wave height (m)
LOWER BOUND OF CATEGORY

DIR	0.1	0.5	1.5	2.5	3.5	4.5
S	0.58	6.88	2.10	0.55	0.16	0.04
SSW	0.51	6.68	2.24	0.55	0.11	0.03
SW	0.30	3.93	1.73	0.44	0.11	0.03
WSW	0.12	1.66	1.44	0.55	0.06	0.01
W	0.09	1.65	1.39	0.41	0.02	0.00
WNW	0.08	1.86	1.14	0.06	0.00	0.00
NW	0.06	1.84	1.03	0.03	0.00	0.00
NNW	0.08	1.74	0.66	0.03	0.00	0.00

CALM OBS = 136 PERCENT CALM = 0.23

Figure 3-5: WIS Station #63287 Wave Rose (January 1980 – December 1999)

3.1.5 Representative offshore waves for two-dimensional beach and inlet modeling

For the two-dimensional coupled wave, flow, and sediment transport modeling portions of the study, it was necessary – for computational simulation time considerations – to produce a "representative annual" wave climate that could be represented as an hourly time series of approximately 1.5 months in duration. The period between June 2007 – June 2008 at the Frying Pan Shoals buoy was determined to be a sufficiently representative year for conducting the wave transformation and sediment transport model simulations.

The primary advantage to using the Frying Pan Shoals buoy as the representative measured offshore wave climate for the present study is that this record covers the longest time period of measured wave data in the area, and it captures tropical and extratropical storm wave events from two years prior to the 2005 Bogue Inlet channel relocation through the present day, with data gaps primarily in winter and spring months (thus avoiding major gaps in tropical storm seasons).

The Frying Pan Shoals wave rose shows an increased occurrence of waves from the northeast quadrant (13%) over the Onslow Bay Outer rose (9%), though the significant wave heights are similar for waves from the northeast. In contrast, occurrence of waves from the southern quadrant at Frying Pan Shoals (21%) is less than the 26% indicated by the Onslow Bay Outer rose. Taken together, these statistics suggest that the overall wave climate at Frying Pan Shoals is biased somewhat counterclockwise compared to the wave climate at the Onslow Bay Outer buoy.

Though waves occurred from all directional sectors, only those most relevant to sediment transport at Bogue Inlet and along Bogue Banks were actually simulated. The buoy #41013 time series was filtered to extract waves between 53 ^{o}N and 217 ^{o}N. The series was further filtered to remove records with H_s < 2m, as smaller offshore waves would have less influence than large waves on sediment transport in the project area.

Wave model simulations considered whether any significant bias is seen in the nearshore at Bogue Inlet and Bogue Banks between offshore boundaries using Frying Pan Shoals data vs. Onslow Bay Outer data. Figure 3-6 shows wave roses for the representative year time period from the Frying Pan Shoals and the Onslow Bay Outer NDBC stations. The roses show similar distributions (band widths) of wave heights in each band. The directional range of the Frying Pan Shoals data is broader than that at Onslow Bay Outer. The Frying Pan Shoals rose shows more than 10% of wave heights greater than 2.0 meters approaching from east-northeast, a primary difference from Onslow Bay Outer. The sector with most wave height observations in the Frying Pan Shoals data is south, while the peak sector at Onslow Bay Outer is south-southeast. Finally, more and larger waves approach Frying Pan Shoals from south-southwest than at Onslow Bay Outer.

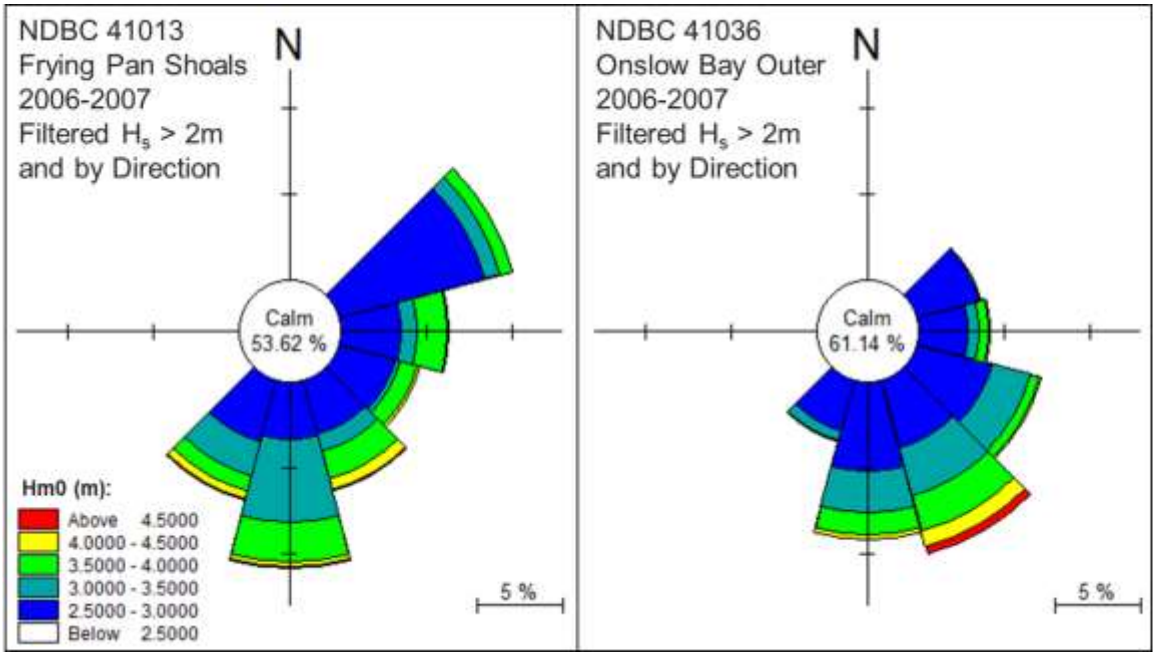


Figure 3-6: Wave Roses at Regional Model Boundary (Years 2006 – 2007)

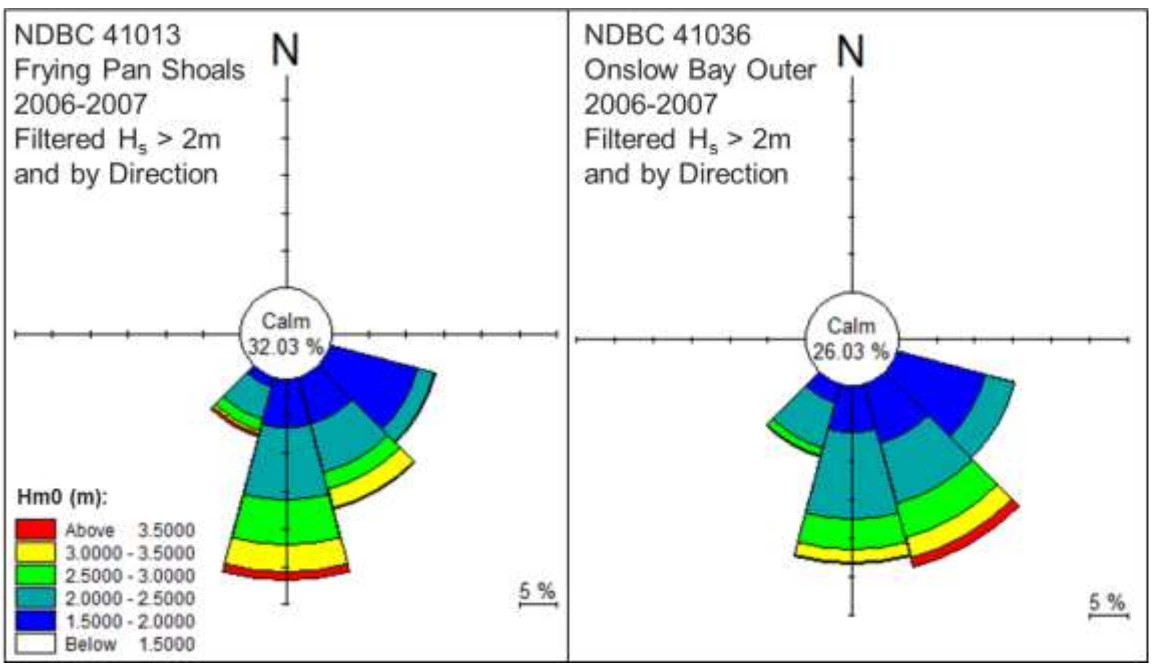


Figure 3-7: Wave Roses Outside Bogue Inlet Ebb Shoal (Years 2006 – 2007)

Each of the data sets in Figure 3-6 were simulated in the regional wave transformation model, and the results just outside the Bogue Inlet ebb shoal are presented in rose form in Figure 3-7. The roses of nearshore, transformed wave heights and directions indicate much less difference at Bogue Inlet between the two starting data sets. Similar distributions of wave heights are seen between the two data sets. The Frying Pan Shoals-based results still show a southerly directional peak sector, while the Onslow Bay Outer-based results are more from the south-southwest. If anything, this bias would be expected to drive sediment transport more in a west-to-east direction over and around the ebb shoal and adjacent shoreline.

Overall, a comparison of the nearshore results from separate models with boundary conditions starting from Frying Pan Shoals and Onslow Bay Outer filtered wave data sets indicates that little difference is expected between the two sets of results. It is therefore judged appropriate to develop the representative wave climate model inputs based on the more complete record of data available from Frying Pan Shoals.

3.1.6 Summary of Wave Climate

The annual wave climate affecting coastal hydrodynamic and sediment transport processes along Bogue Banks was evaluated using NDBC measured and Atlantic WIS hindcast wave data. Different data sources were utilized for different purposes. The nearest offshore wave buoy (Onslow Bay Outer) was used as the primary source of historical time series data to develop inputs for long-term shoreline evolution modeling and historical storm inputs for beach profile evolution modeling. The next nearest wave buoy (Frying Pan Shoals) was used to fill gaps in and extent the record from the Onslow Bay Outer buoy. The two data sets are judged to be sufficiently similar to each other to allow this mixing of the data sets for the present purposes.

The offshore wave heights, periods, and direction data sets developed from these sources were transformed to nearshore positions using a MIKE 21 SW spectral wave model (Chapter 5.0) prior to application in other models.

Offshore significant wave heights are greater than 4.5 m (14.8 feet) between 15% and 25% of the time in the NDBC and WIS data sets. The vast majority of waves approach from the east-northeast through south-southwest directions. The NDBC buoys' measured wave data indicate a noticeably higher percentage of waves occurring from east through southeast, while the longer term model hindcast WIS record indicates a more even spread of wave occurrence between east and south-southwest.

The Onslow Bay Outer NDBC buoy #41036 data was used as the primary source of offshore wave data for developing and running GENESIS and SBEACH models for historical time periods. Where necessary, the Frying Pan Shoals (NDBC #41013) and WIS data sets were used to fill gaps and extend this record to cover additional time periods.

The Frying Pan Shoals NDBC buoy #41013 data between June 2007 – June 2008 was used as a "representative annual" offshore wave climate for developing condensed wave cases for the coupled wave/ flow/ sediment transport/ morphodynamic model simulations.

Due to its longer and more complete (no gaps) time coverage, the Atlantic WIS Station #63287 data set was used as the primary source for computing extreme wave heights in development of design storm data sets for several statistical "return periods."

3.2 Tides and Currents

3.2.1 NOAA Tide Gauge #8656483 – Beaufort

The only presently-operating NOAA tide gauge in the immediate study area is located at Beaufort, NC. Verified six-minute and hourly water level measurements, with associated predicted tidal water levels, are readily available from NOAA's CO-OPS program website for the time period December 1995 – present.

NOAA's published tidal datum sheet indicates a range of 1.078 m (3.54 ft) between MHWW and MLLW, with a range of 0.948 m (3.11 ft) between MHW and MLW. The Beaufort tide station is located well within the harbor at Beaufort Inlet, and as such does not accurately represent tidal water levels along the open Atlantic coast of Bogue Banks or at the Bouge Inlet channel and ebb shoal. However, the Beaufort tide gauge data provides an applicable data set for inferring the effects of coastal storms (e.g. surge over predicted astronomical tides) and for validating numerical model simulated water levels.

3.2.2 NOAA Tide Gauge #8656590 – Atlantic Beach Triple-S Pier

The only open-coast NOAA tide gauge listed by NOAA's CO-OPS program in the immediate study area was located in Atlantic Beach at the Triple-S Pier. Verified hourly water level measurements are readily available from NOAA's CO-OPS program website for the time period December 1975 – June 2000; however, no data exists in the record between December 1983 – September 1998. Thus the Atlantic Beach tide gauge is not available for directly analyzing water levels from recent tropical and extratropical storms of interest.

NOAA's published tidal datum sheet indicates a range of 1.264 m (4.14 ft) between MHWW and MLLW, with a range of 1.113 m (3.65 ft) between MHW and MLW. The Atlantic Beach Triple-S Pier tide station was located along the open Atlantic coast of Bogue Banks, and is useful for inferring the effects of coastal storms during its limited recent history of operation and for validating numerical model simulated water levels. Figure 3-8 shows the relationships of tidal datums MHHW, MLLW, and MSL in feet relative to NAVD88 at the Beaufort and Atlantic Beach Triple-S Pier tide stations based on NOAA's 1983-2001 tidal epoch.

The mean tide range at the Atlantic Beach Triple-S Pier tide gauge is approximately 117% of the mean tide range at the Beaufort tide gauge. The ratio of measured water levels Atlantic Beach to those at Beaufort increases to just over 120% (in general) for significant coastal storm surge events.

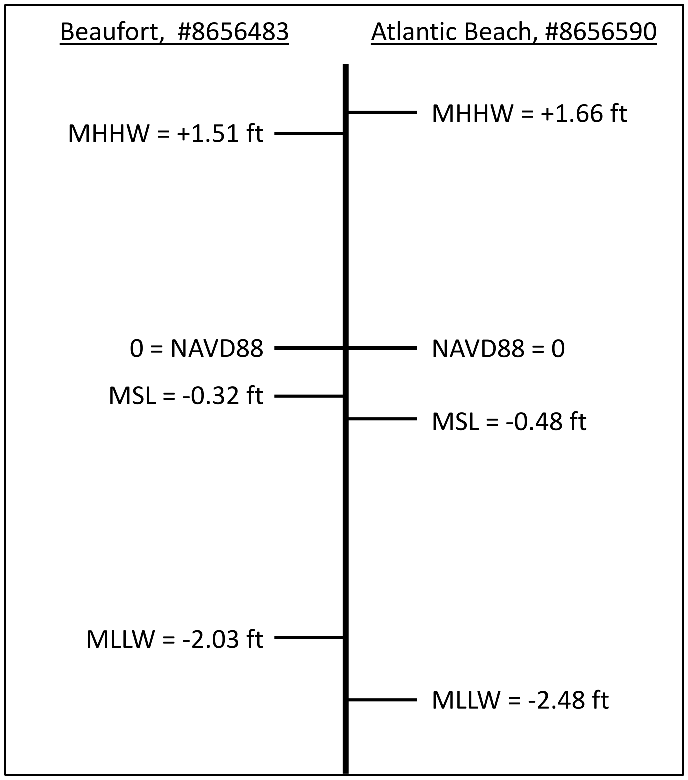


Figure 3-8: Selected Tidal Elevation Datums With Respect to NAVD88 at Beaufort and Atlantic BeachTriple-S Pier

3.2.3 Bogue Inlet field measurements

Coastal Science & Engineering (CS&E) conducted field flow measurements on a transect across the Bogue Inlet main ebb channel using a digital Marsh-McBirney Model 201 flowmeter on June 27, 2005. The transect spanned both the “old” and “new” inlet channels existing at the time. Tidal water surface elevations were read from a tide staff (reference elevation leveled in using RTK-GPS) at The Point on Emerald Isle.

The measurements were conducted over a full tide cycle, from low tide at 6:40 a.m. to high tide at 12:52 p.m. to low tide at 6:50 p.m. (times approximated). A tide range of approximately 1.22m (4 ft) was measured by CS&E during the flow measurement period. Peak discharges of between approximately 850 m^3/sec (30,000 ft^3/sec) during flood tide and 1,200 m^3/sec (42,400 ft^3/sec) during ebb tide were measured across the transect.

4.0 BOGUE INLET ANALYTICAL STUDY

4.1 Purpose and Definitions

The study of Bouge Inlet's channel morphology – past, present, and estimates of future behavior – has to date relied most heavily on analysis of observed channel positions and alignments observable from overhead imagery (aerial and satellite, referred to in this report as "aerial") and partial hydrographic surveys. The present work to define reasonable limits and thresholds for triggering future Bogue Inlet channel modification / relocation continues to rely primarily on observable historical observed inlet morphology.

The historical data have been reviewed again in the Analytical stage of this study. The Numerical Modeling component has been added in this phase of study to supplement (e.g. to test, support, expand upon) knowledge gained and recommendations from analysis of the historical data; schematic representations of different types of inlet channel configurations are also based on the analytical study findings.

The analytical study was begun by tracing the inlet geometry components defined below from historical aerial imagery. Figure 4-1 show the delineation of analytical study components from a 1938 aerial photo of Bogue Inlet, with definitions:

- Reference Line / Calculation Point = A line oriented as nearly parallel to the shoreline of Bogue Banks and Bear Island (somewhat away from the immediate inlet shape effects) as could be practically determined from the combined years of available aerial photos. The endpoints of the Reference Line were set to represent lateral (east-west) positions of consistent vegetation on Bogue Banks and Bear Island across most of the historical images. The Reference Line is used as a standard for measuring the angle (skew) made by the various channel components described below; a skew angle of 90 degrees from the Reference Line would be normal to the Reference Line. The Reference Line Calculation Point is used as a standard for measuring lateral (shore-parallel) distances between the Main Channel and the Bogue Inlet / Bear Island shorelines in each photo year.

- Bogue Inlet Shoreline = Apparent high-water shoreline position (Bogue Banks and Bear Island shoulders) observable from the aerial photos.

- Main Channel Centerline = Polyline traced through the apparent center of the most likely main ebb channel of the inlet in each photo year.

- Main Channel Skew = One or two straight line segments schematized from the more sinuous main channel centerline in each photo year. The skew lines are used for calculating a single representative skew angle with respect to the reference line; two skew lines are provided to allow for significant differences in skew landward of the reference line vs. seaward of the reference line.

- White Oak Channel Centerline = Polyline traced through the apparent center of the most likely White Oak River channel (channel running west around Dudley Island) in each photo year.

- White Oak Channel Skew = One line segment schematized from the more sinuous White Oak channel centerline ***close to its junction with the main ebb channel*** in each photo year.

- Bogue Sound Channel Centerline = Polyline traced through the apparent center of the most likely Bogue Sound channel (Atlantic Intracoastal Waterway channel running east around Dudley Island) in each photo year.

- Bogue Sound Channel Skew = One line segment schematized from the more sinuous Bogue Sound channel centerline ***close to its junction with the main ebb channel*** in each photo year.

- CW = Clockwise, used in this discussion to describe rotation of the skew lines with respect to a line normal (perpendicular) to the Reference Line.

- CCW = Counterclockwise, used in this discussion to describe rotation of the skew lines with respect to a line normal (perpendicular) to the Reference Line.

4.2 Results and Discussion

Figure 4-1 through Figure 4-17 each show a single year's aerial photo and the traced inlet shorelines, channel centerlines, and channel skew lines. The first few dates are separated by more than 5 years in each case, from 1938 to 1949 to 1956. In 1938, the main ebb channel was hard against the Bear Island shoreline with an extreme clockwise skew angle (relative to the reference line). Only a single apparent main channel existed, and the White Oak River and Bogue Sound channel connected smoothly into the main ebb channel. A long spit existing between present-day limits of Emerald Isle and the submerged shoals of the inlet.

The earliest dates are separated by more than 5 years in each case, from 1938 to 1949 to 1956. In 1938, the main ebb channel was hard against the Bear Island shoreline with an extreme clockwise skew angle (relative to the reference line). Only a single apparent main channel existed, and the White Oak River and Bogue Sound channel connected smoothly into the main ebb channel. A long spit existing between present-day limits of Emerald Isle and the submerged shoals of the inlet.

In 1949, the Bogue Banks spit had largely eroded and a second channel had formed on the far east side of the inlet. This was judged to be the main ebb channel from the 1949 photos due to the more apparent connectivity of this eastern channel with the waters of Bogue Sound. The White Oak River channel appears to be choked with shoals (the centerline and skew angle were difficult to determine), and it does not appear to connect directly with either of the main observable channels through the inlet. It is worth noting that a third channel may be appearing (or disappearing) more toward the center of the inlet in the 1949 photo.

In 1956, the main ebb channel appears to have migrated to (or a new one developed in) the center of the inlet, and its orientation was rotated CCW from the normal to the reference line. Though apparently in the center of the inlet at the time, the 1956 channel position is approximately 1,800 feet west of the authorized (2005) relocated inlet channel position. The White Oak River and Bogue Sound channels connected to the main channel in a fashion similar to that observed in the present-day inlet configuration.

The main ebb channel position did not change significantly between 1956 and 1960, though the skew angle rotated significantly, to a position well CW of the reference line normal. A long spit had formed off of Bear Island – the outline of which may be seen as shoals in 1956.

By 1971, the main channel appears to have migrated at least 1,000 feet eastward and reoriented to a severe CCW skew angle. However, the 1971 photo is especially dark and low in contrast, and it is very difficult to discern where the actual position and extents of the ebb channel lie in this photo.

Though also dark and low-contrast, the 1976 photo suggests that the main ebb channel shifted slightly west of the 1971 channel position and that it was oriented slightly CCW of the reference line normal. The White Oak River and Bogue Sound channels appear to be well-connected to the main ebb channel.

Between 1976 and 1987, the main ebb channel had migrated 1,500 feet eastward, and the skew orientation was again significantly CCW from the reference line normal. The White Oak River channel was well-defined, as was the Bogue Sound channel, and both back channels connected smoothly to the main ebb channel. A large spit had formed on the east end of Bogue Banks, but oriented far more shore-normal than shore-parallel. (This spit feature continued to exist through to the present-day, at times with channels carved through it near the Coast Guard station.) The 1987 channel position was as far eastward as any of the previous photo dates indicated, and further east than all but the 1949 channel.

By the 1992 photo date, the ebb channel had migrated a further 1,000 feet eastward toward Bogue Banks, and the landward segment's skew was more CCW than in 1987. The 1992 channel was located approximately 1,000 further east than on any of the previously discussed dates, and the channel continued to migrate eastward from 1992 to 2004, though at a notably slower annual rate of change. The main ebb channel position changed little between 1998 and 2004, and the skew remained extremely CCW to the reference line normal from 1987 to 2004.

It is worth noting that the period between 1987 and 2004 was the most "stable" period with respect to skew angle in the limited history of the inlet observable from these combined 17 aerial photo snapshots. The ebb channel position moved only 500 feet from 1998 to 2004, though man-made efforts to protect the developed portions of Emerald Isle (and possibly the geology underlying this historically more stable portion of Emerald Isle) may have been responsible for preventing further eastward movement.

The inlet's main ebb channel was relocated in 2005. No aerial photos were available in the data set from immediately pre- or post-construction of the relocation project. In the 2006 photo (Figure 4-12) the relocated main ebb channel is seen approximately 3,000 feet west of its 2004 position. The pre-construction ebb channel can also still be seen against the western end of Emerald Isle; that remnant channel was left by the relocation project to fill in naturally over time.

The alignment of the Authorized Channel constructed in 2005 aligned more directly with the Bogue Sound channel (also the Atlantic Intracoastal Waterway connection) than with the White Oak River channel. The skew of both the landward and seaward segment of the Authorized Channel were nearly normal (slightly CW) to the reference line. Over the next several years, from 2006 to 2011, the main ebb channel's connection with the White Oak River channel appears to have deepened, and the skew of the main ebb channel's landward segment progressively rotated more CCW to align more smoothly with the White Oak River channel. The White Oak channel skew rotated more CW, further connected with the main ebb channel. At the same time, the seaward segment of the main ebb channel rotated more CW (a configuration predicted by the numerical model study, described elsewhere in this report), and the "curved" ebb channel began to migrate eastward again toward Bogue Banks. The connection point between the White Oak, Bogue Sound, and main inlet ebb channels has not migrated eastward to the extent that the main channel mid-point has migrated, and the landward segment of the main channel has elongated since 2006.

As of mid-2011, the main ebb channel had migrated approximately 1,100 feet from the position of the Authorized Channel centerline (in 6 years), and it was still approximately 1,700 feet from its furthest eastward 2004 position. If it continues along this track, it might be expected that the 2004 position would be reached in another 6 to 8 years, or 14 years from relocation to the Authorized Channel. One of the questions that the numerical model portion of this study attempts to answer is whether there is a "tipping point" in one or more channel geometry parameters, or in a combination of parameters such as landward skew + seaward skew, beyond which the eastward (or westward) migration of main ebb channel is likely to be reinforced and speed up (or else be unlikely to recover to a more mid-inlet position).

Through all of these years, it is possible that the orientation (skew) of the main ebb channel is heavily influenced by the relative fraction and intensity of ebb discharges coming from the White Oak River vs. those from the Bogue Sound side of Dudley Island. This may be a key factor in understanding the morphology of Bogue Inlet's channel and shoal system, but it is very difficult to discern from historical data, as no records have yet been found of flows in either of branches. This is a subject which the numerical modeling component of the study may attempt to address, in a later phase.

Table 4-1: Bogue Inlet Analytical Study Calculations from Historical Imagery

Year	[1]Width feet	[2]Dist. to Bear Island feet	[2]Dist. to Bogue Banks feet	[3]Ocean Segment Angle ºN	[3]Sound Segment Angle ºN
1938	3,413	788	2,625	217	18
1949	9,640	6,919	2,721	187	28
1956	6,195	3,552	2,642	153	333
1960	3,870	792	3,078	178	15
1971	3,767	1,741	2,026	120	308
1976	6,511	2,735	3,776	156	326
1987	4,587	2,900	1,688	125	282
1992	5,547	5,205	342	128	305
1998	7,028	6,623	404	136	289
2003	7,349	6,871	479	138	294
2004	6,592	6,264	328	142	291
2006	5,724	2,553	3,171	175	332
2007	4,364	1,875	2,489	179	333
2008	4,113	1,497	2,617	176	328
2009	3,317	1,086	2,231	185	324
2010	3,878	2,794	1,084	173	313
2011	4,058	3,371	687	180	310

[1]Width measured between apparent Bear Island and Bogue Banks inlet shoulder shorelines.

[2]Distance from channel centerline to either Bear Island or Bogue Banks apparent shorelines.

[3]Azimuth in degrees relative to true North. Perpendicular to Reference Line has an azimuth of 161 ºN.

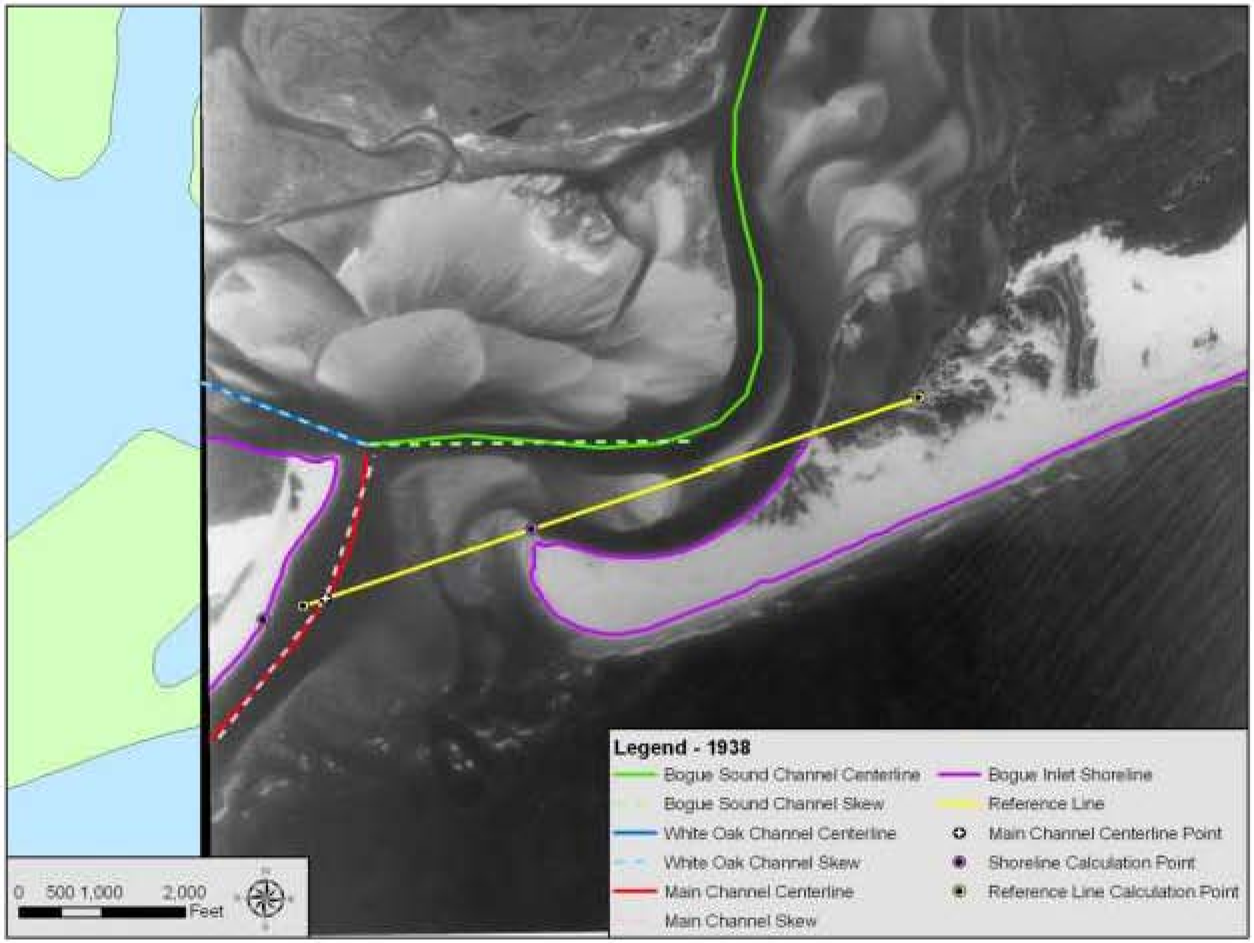


Figure 4-1: Bogue Inlet Analytical Morphology Parameters from 1938 Aerial Photo

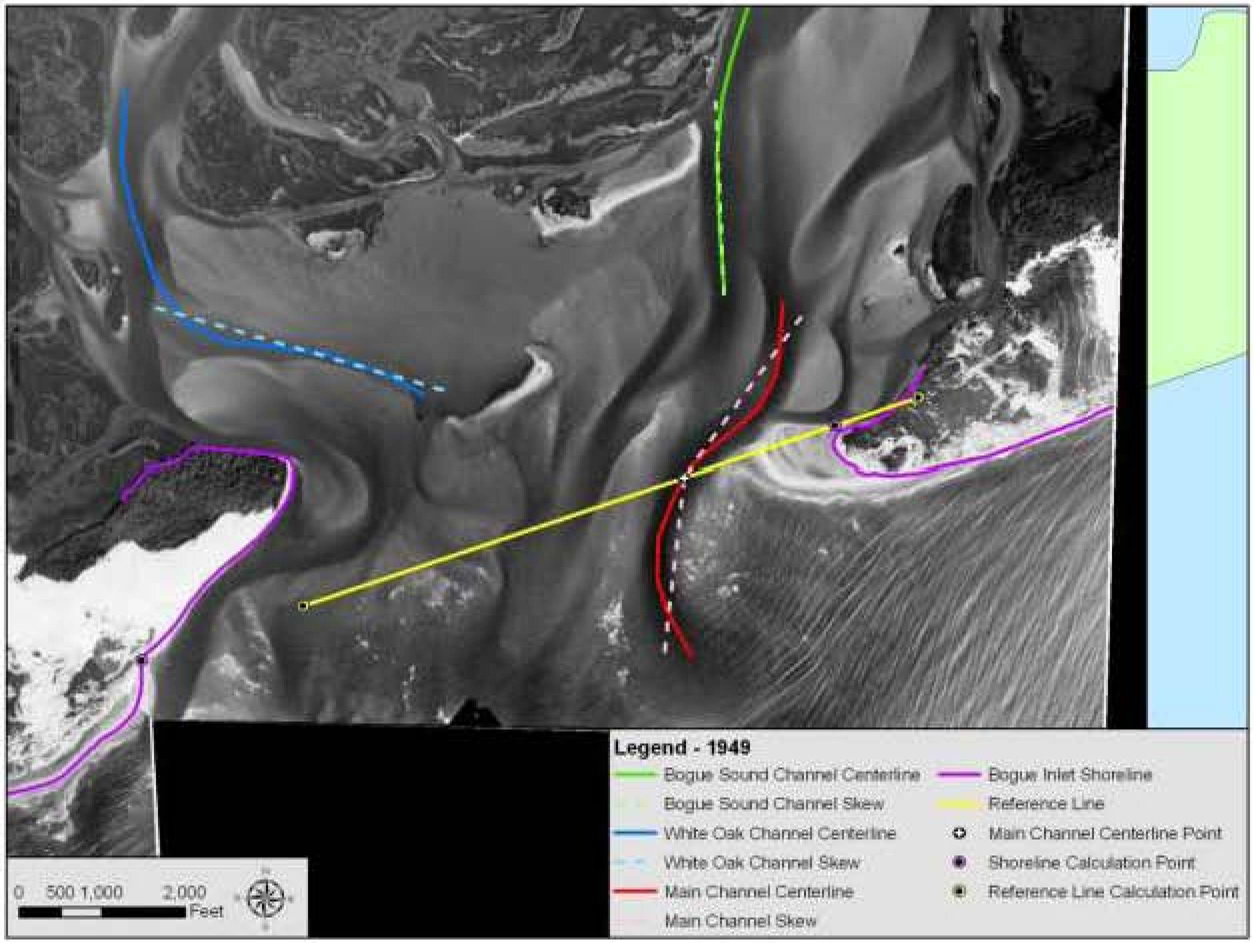


Figure 4-2: Bogue Inlet Analytical Morphology Parameters from 1949 Aerial Photo

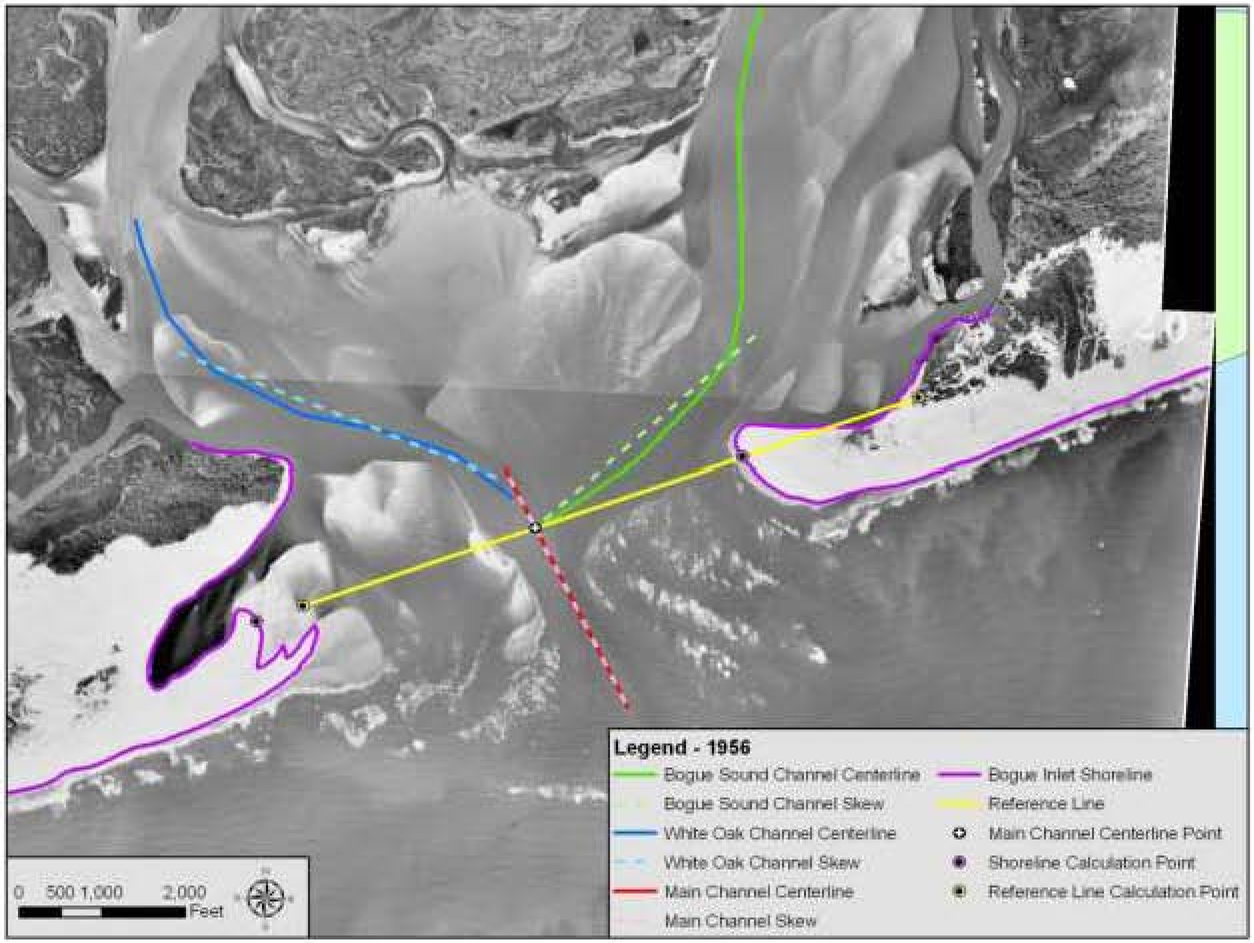


Figure 4-3: Bogue Inlet Analytical Morphology Parameters from 1956 Aerial Photo

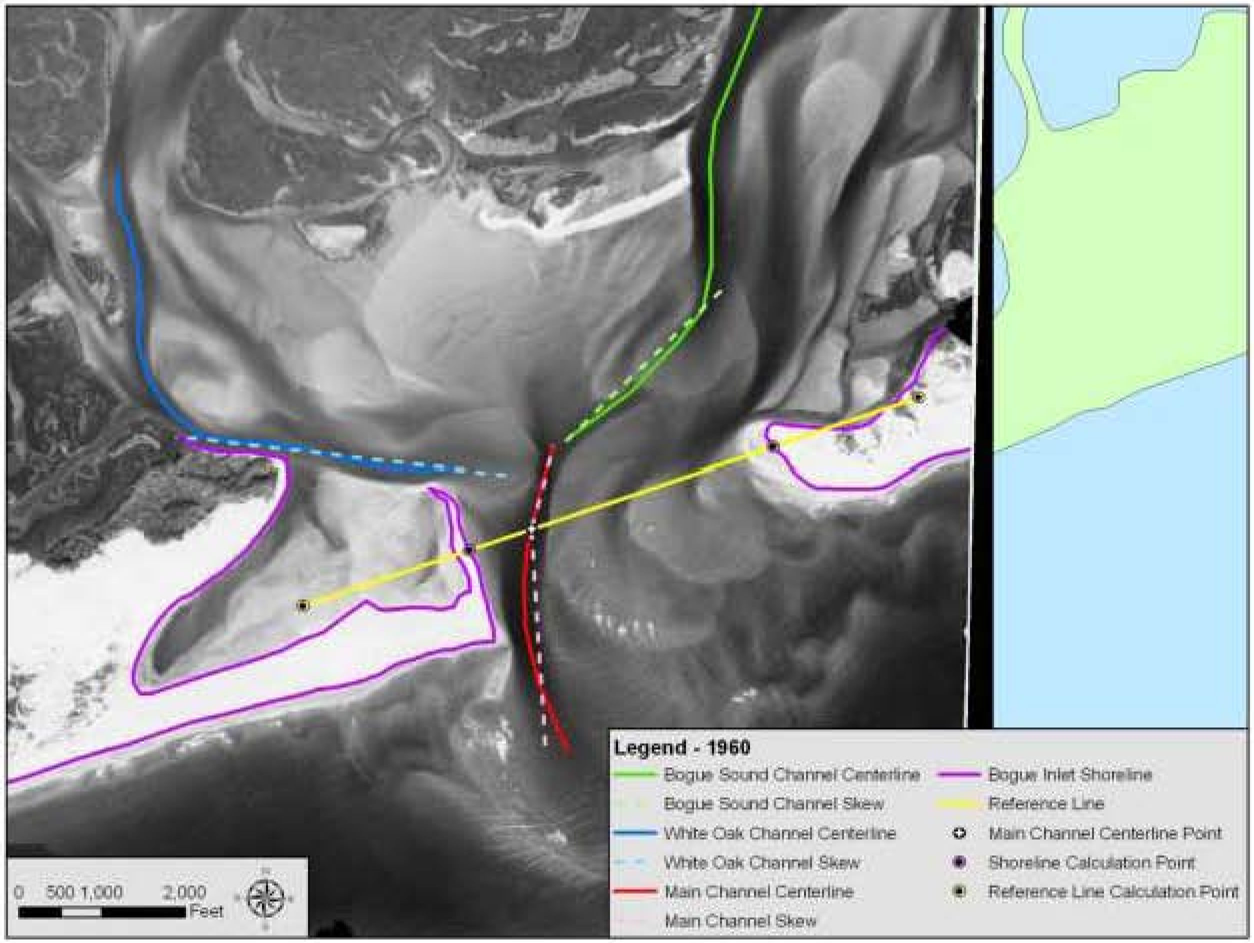


Figure 4-4: Bogue Inlet Analytical Morphology Parameters from 1960 Aerial Photo

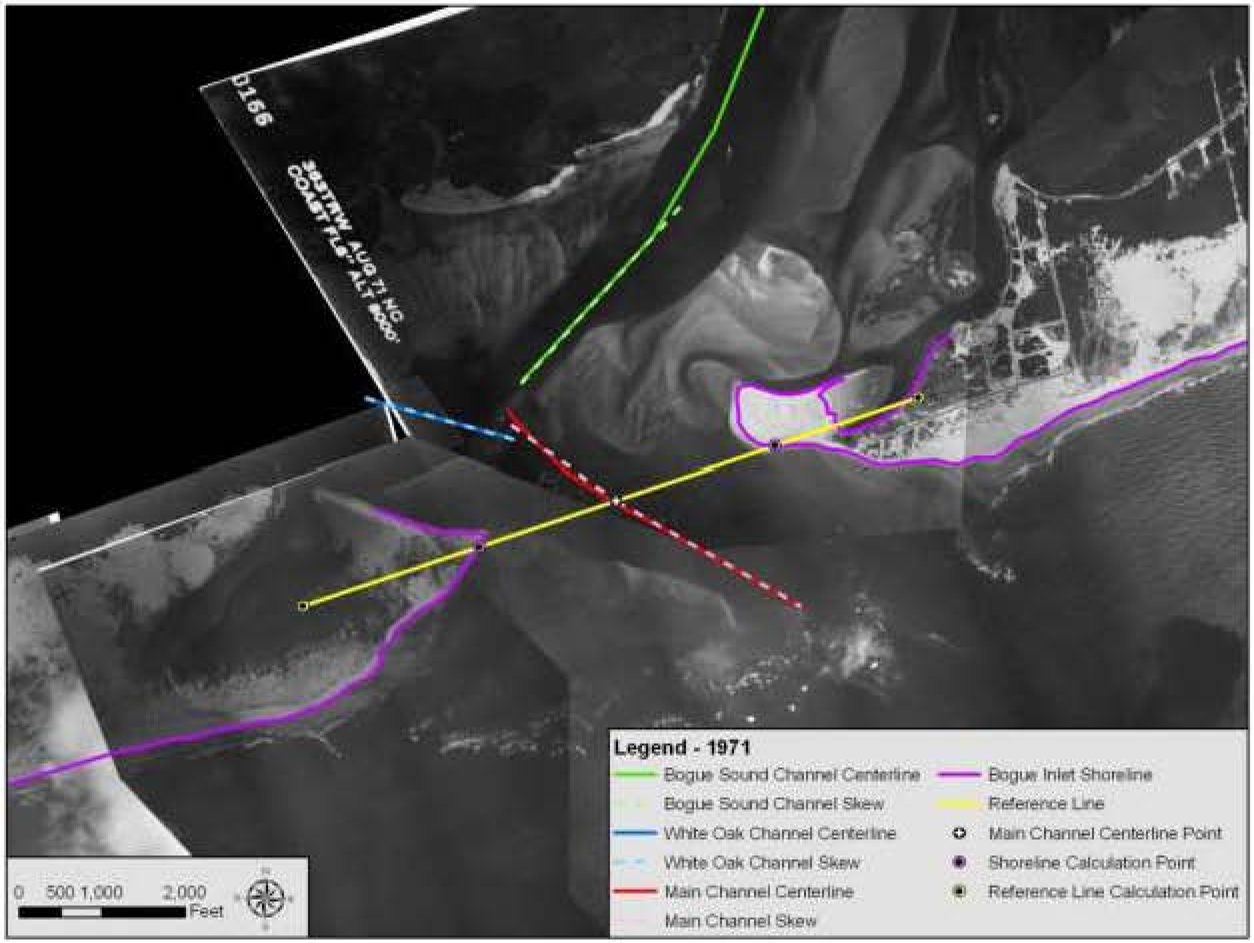


Figure 4-5: Bogue Inlet Analytical Morphology Parameters from 1971 Aerial Photo

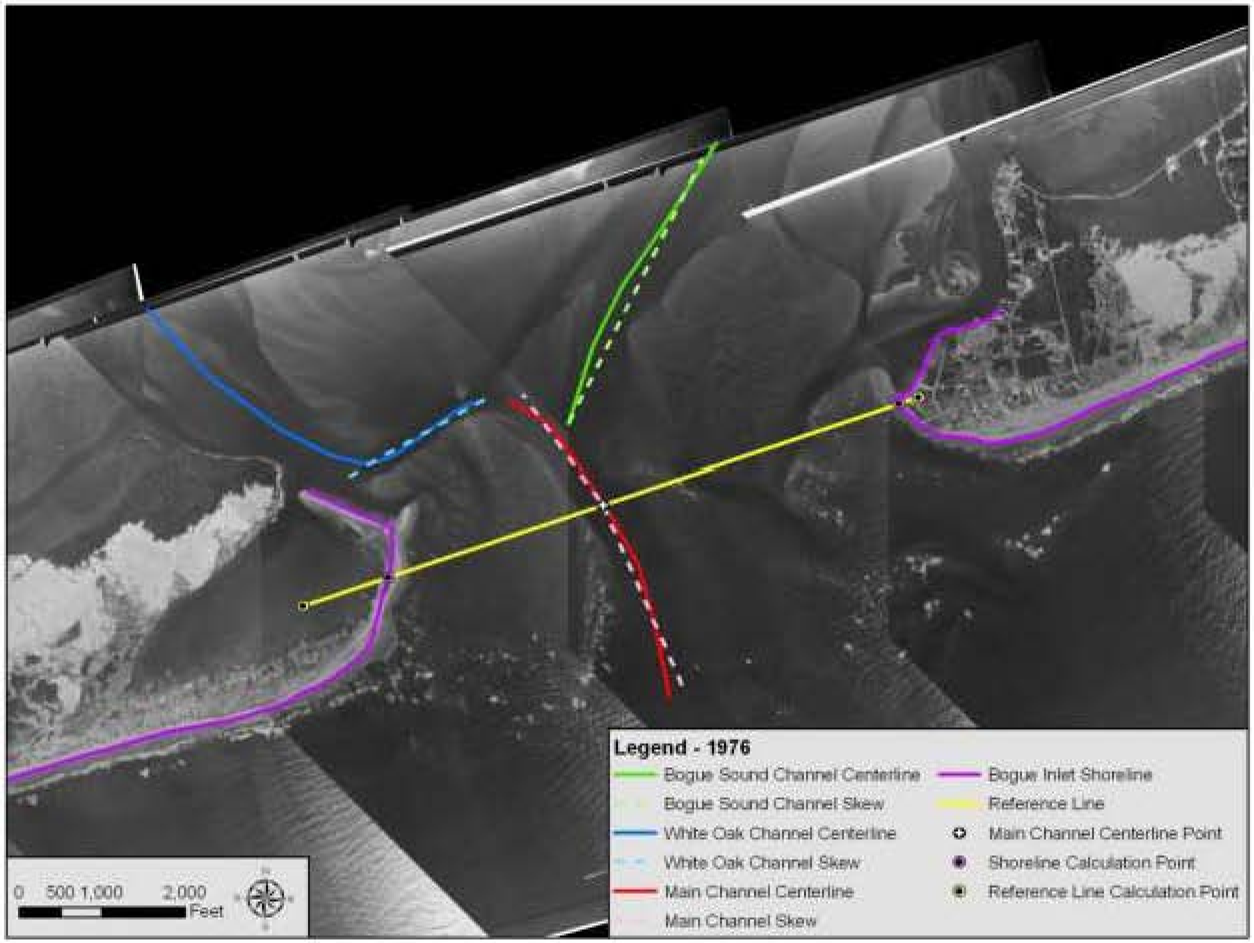


Figure 4-6: Bogue Inlet Analytical Morphology Parameters from 1976 Aerial Photo

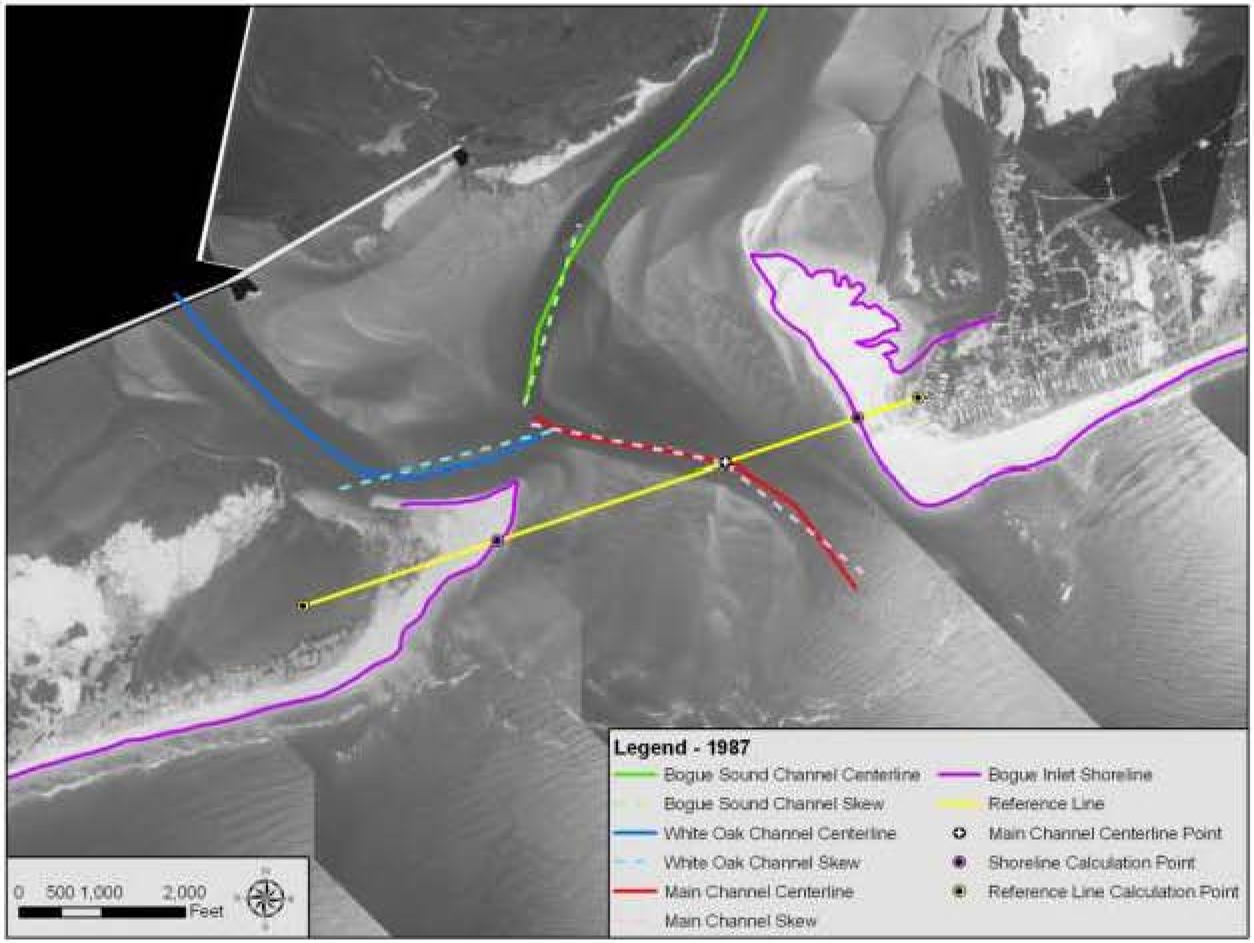


Figure 4-7: Bogue Inlet Analytical Morphology Parameters from 1987 Aerial Photo

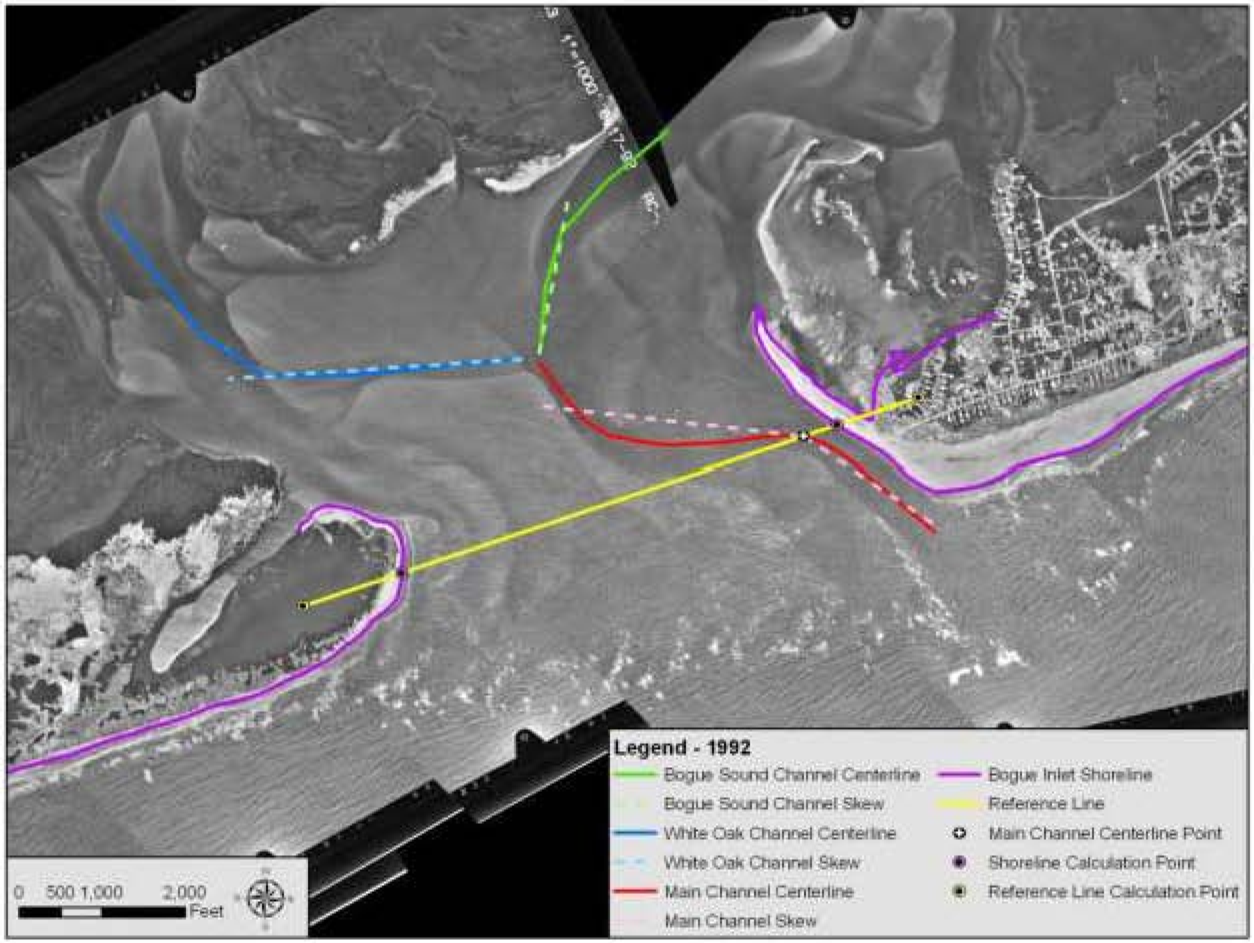


Figure 4-8: Bogue Inlet Analytical Morphology Parameters from 1992 Aerial Photo

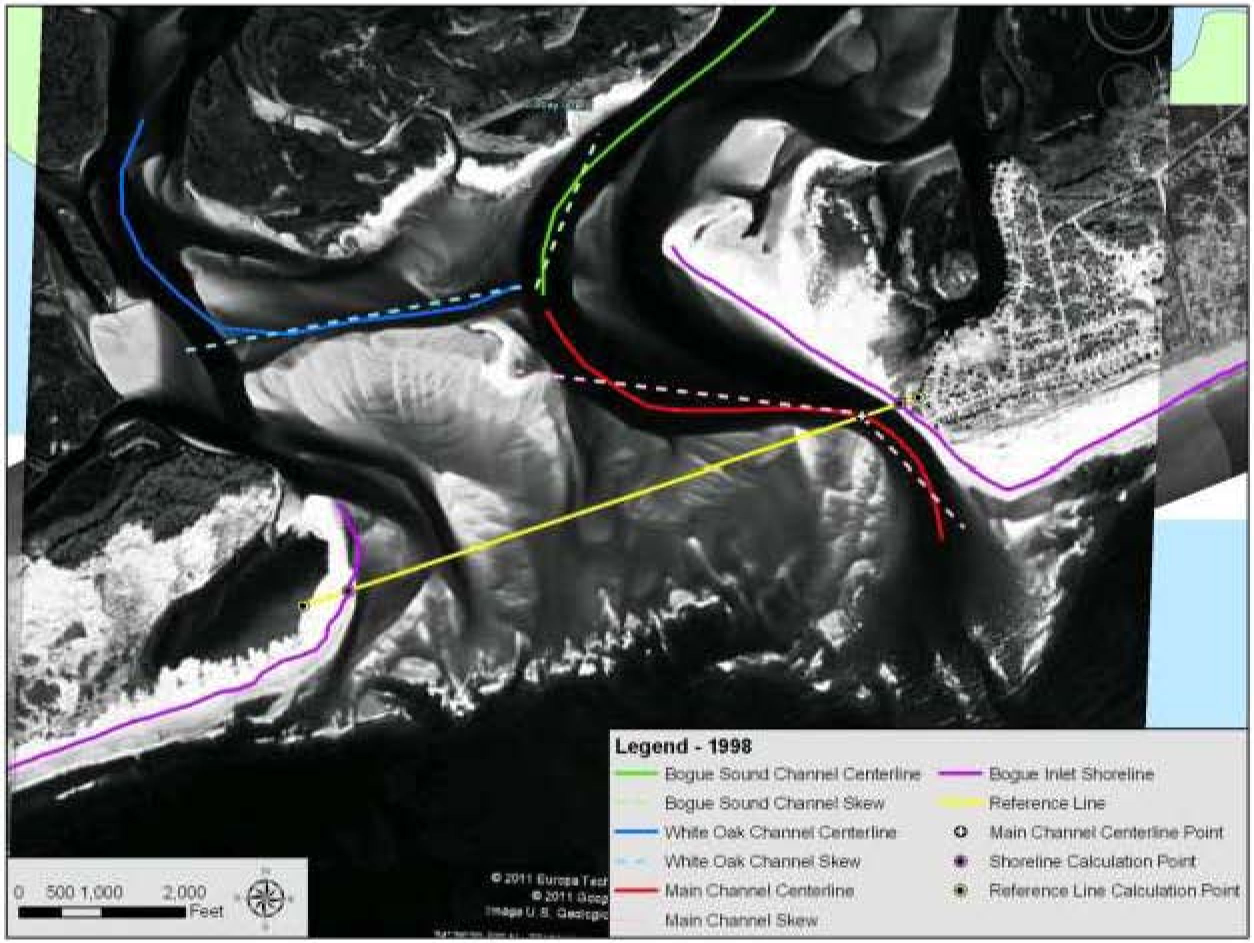


Figure 4-9: Bogue Inlet Analytical Morphology Parameters from 1998 Aerial Photo

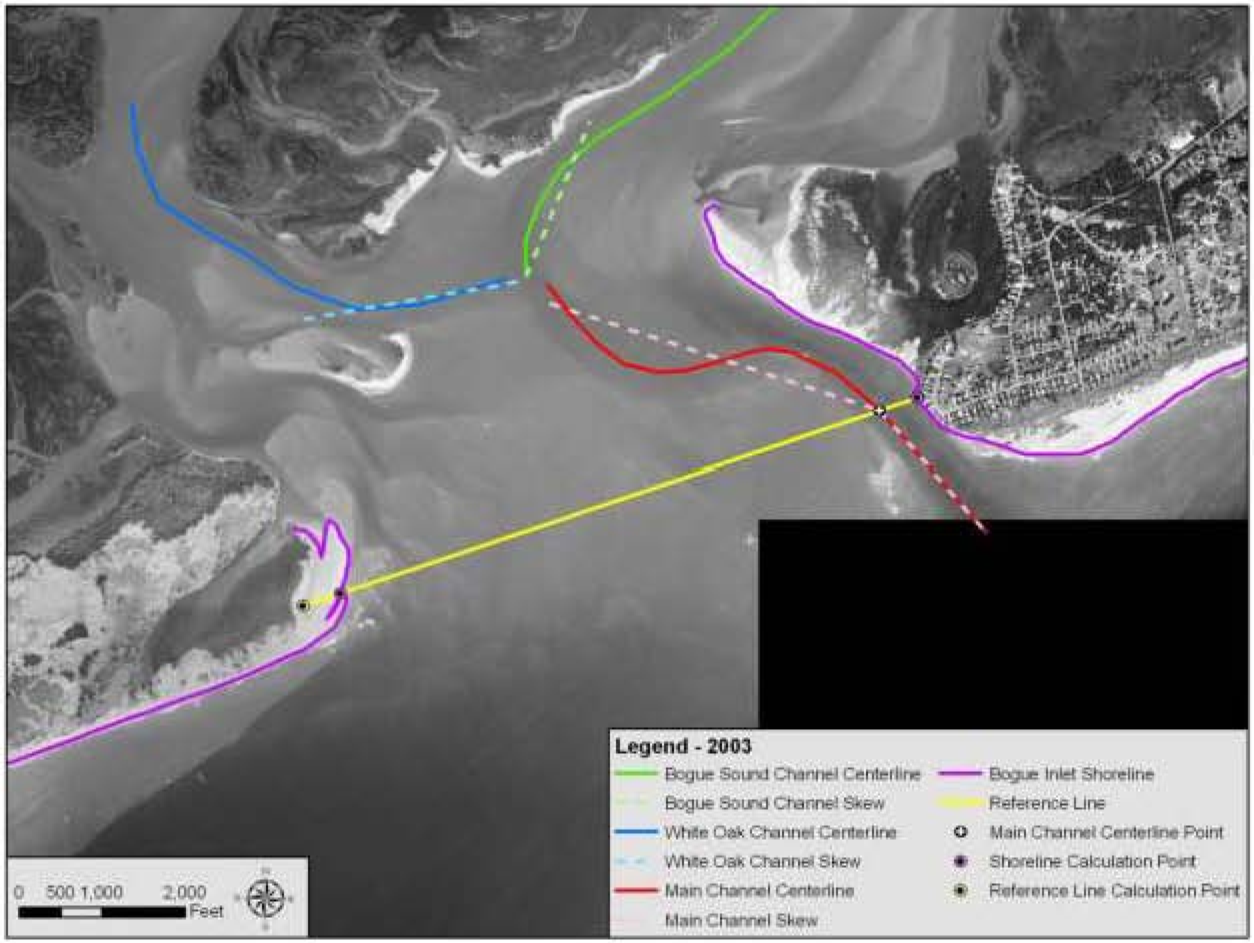


Figure 4-10: Bogue Inlet Analytical Morphology Parameters from 2003 Aerial Photo

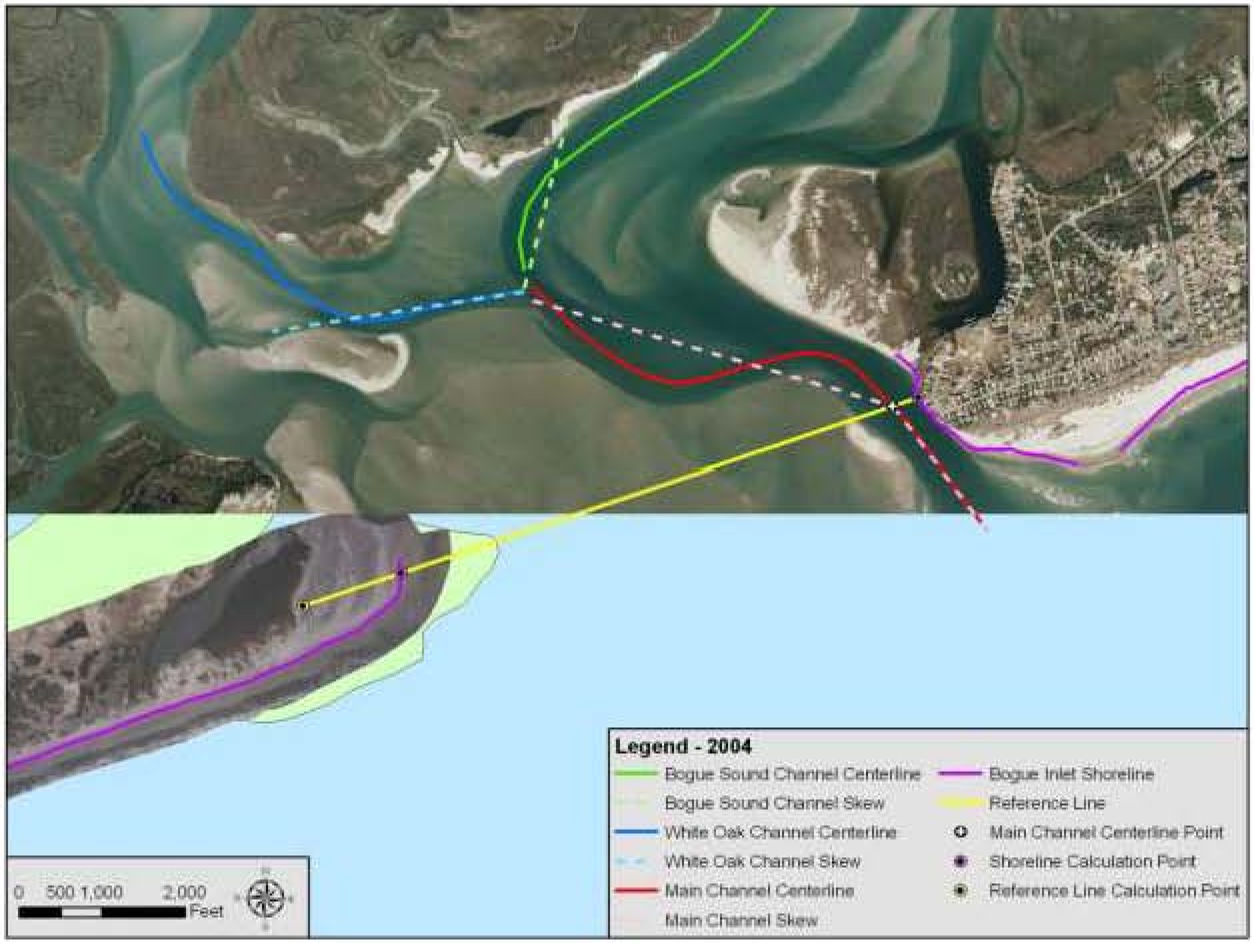


Figure 4-11: Bogue Inlet Analytical Morphology Parameters from 2004 Aerial Photo

Figure 4-12: Bogue Inlet Analytical Morphology Parameters from 2006 Aerial Photo

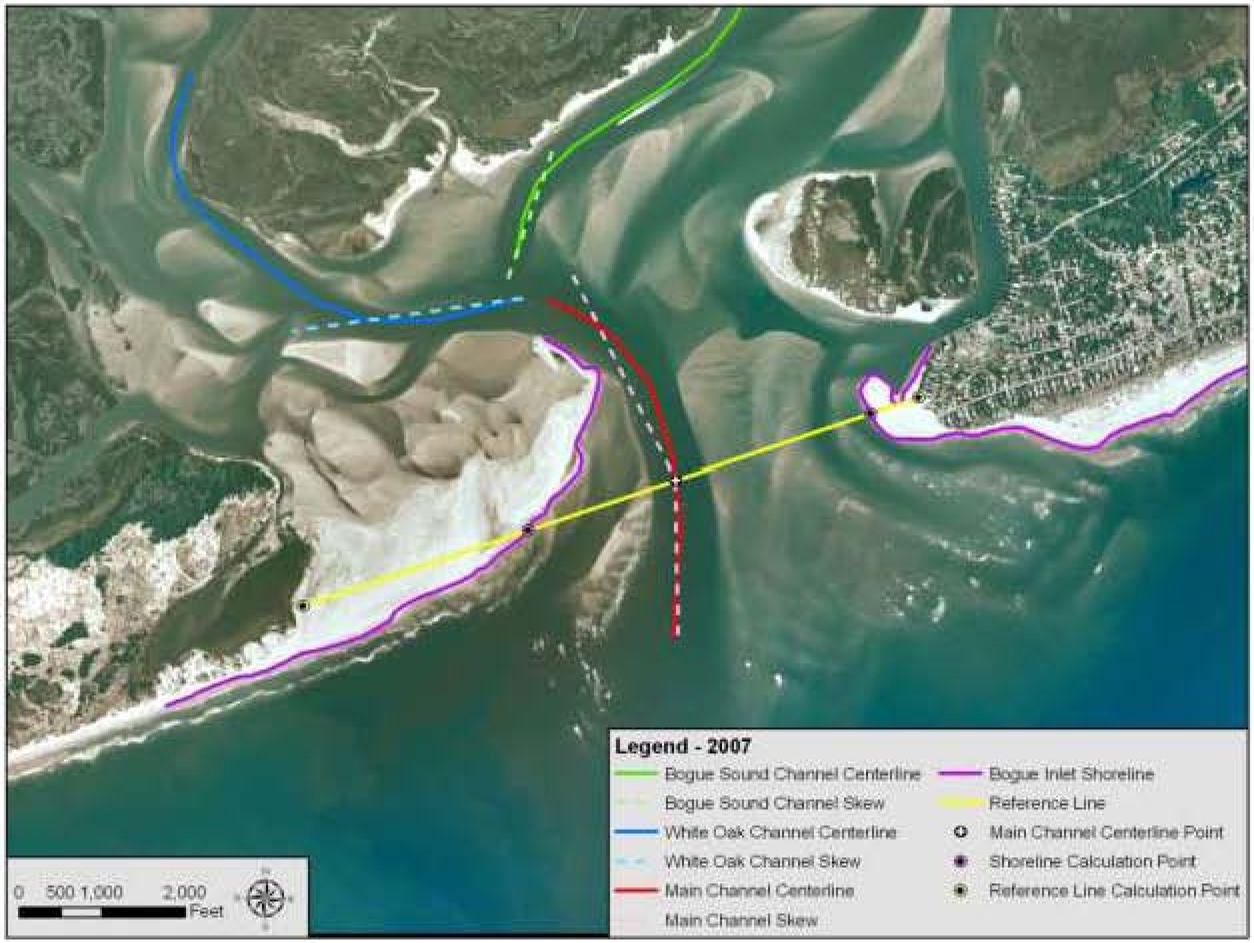


Figure 4-13: Bogue Inlet Analytical Morphology Parameters from 2007 Aerial Photo

Figure 4-14: Bogue Inlet Analytical Morphology Parameters from 2008 Aerial Photo

Figure 4-15: Bogue Inlet Analytical Morphology Parameters from 2009 Aerial Photo

Figure 4-16: Bogue Inlet Analytical Morphology Parameters from 2010 Aerial Photo

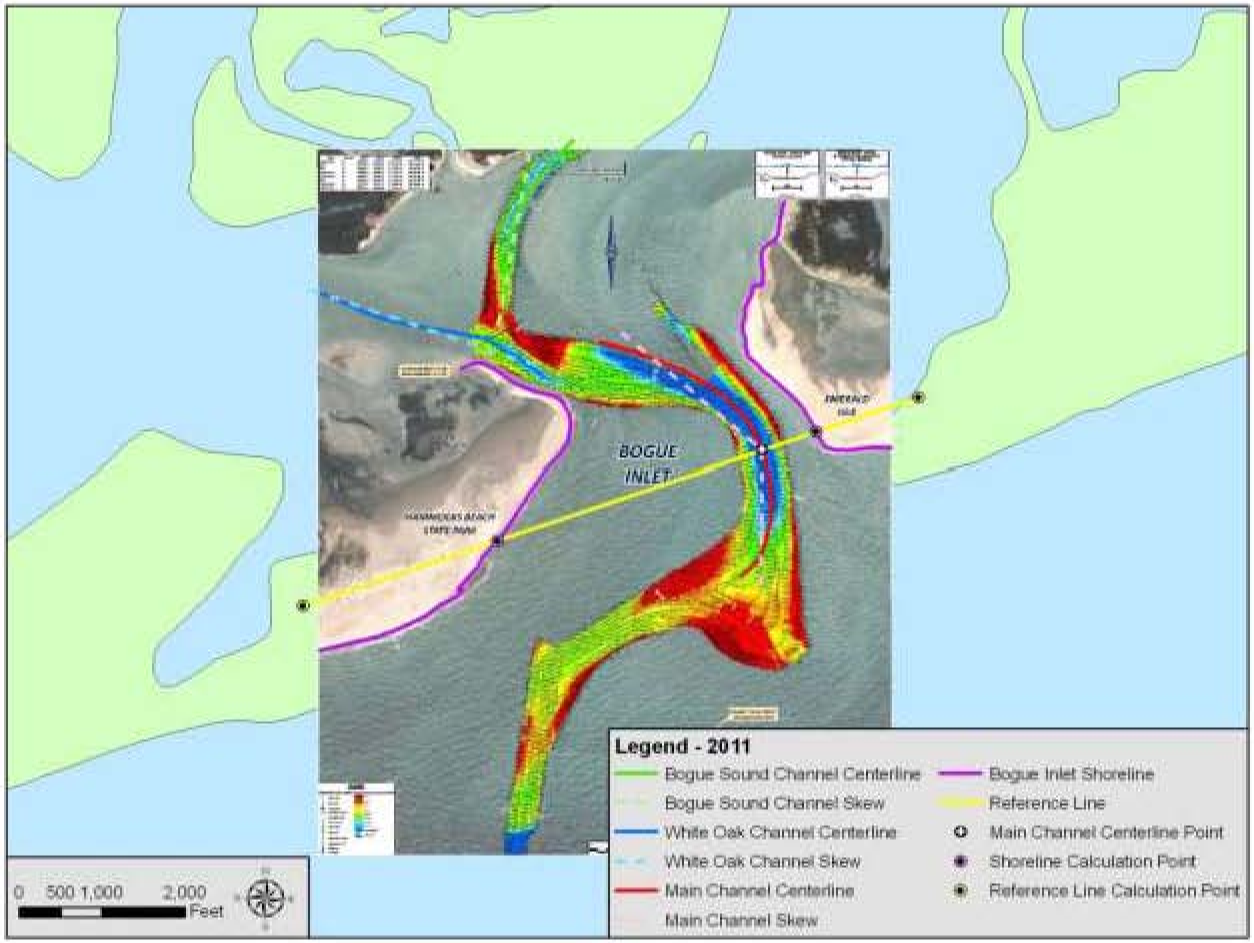


Figure 4-17: Bogue Inlet Analytical Morphology Parameters from 2011 Aerial Photo

While the position of the main ebb channel (and significant flood channel) is an important influence on ***contemporary*** erosion (i.e. at any given time) of Bogue Banks or Bear Island, the alignment of the main ebb channel is an important factor in estimating the ***future*** morphologic behavior of the inlet for management decisions. A primary goal of this study is to develop guidance for anticipating future inlet behavior in advance, so that appropriate mitigation measures can be employed proactively.

Figure 4-18 presents a summary map of the main ebb channel alignments discussed above. The channel alignments are presented as shaded lines, with line color varying steadily over time from 1938 (blue) to 2011 (red). The alignments of the ebb channels post-relocation are identified as orange to red lines in Figure 4-18. These several post-relocation alignments all have similar shapes – though different lateral positions – with CCW rotation from Authorized Channel landward of the reference and CW rotation seaward of the reference line.

The channel alignments can be grouped into a few types as shown in Figure 4-19, where:

- Type 1 (orange) – ebb channel is aligned significantly CW of the Authorized Channel landward of the reference line, indicating dominance of flows from Bogue Sound over flows from the White Oak channel.

- Type 2 (red) – ebb channel aligned significantly CCW of the Authorized Channel landward of the reference line, and moderately CCW of the Authorized Channel seaward of the reference line. This configuration indicates dominance of flows from the White Oak channel and/or significant influence of the spit off of Bear Island. The inlet channel was in a Type 2 configuration, positioned very close to the Bogue Banks shoreline, just prior to relocation in 2005. Type 2 alignments are seen alternating with Type 1 alignments in the 1930s – 1960s. In the more recent past, prior to relocation, the inlet appears to have been stuck in a Type 2 alignment. It is worth noting that Type 2 alignments have been exhibited over a wide range ebb channel inlet lateral positions since the 1960s.

- Type 3 (green) – ebb channel aligned moderately CCW of the Authorized Channel landward of the reference line, and moderately CW of the Authorized Channel seaward of the reference line. Type 3 configurations are observed only post-relocation, as the straight-aligned Authorized Channel begins to migrate. The angle between the landward and seaward portions of the ebb channel has been steadily increasing, as the landward portion rotates more CCW and the seaward portion rotates more CW.

- Type 4 (blue) – ebb channel aligned generally "straight" approximately in line with the Authorized Channel.

It is hypothesized that there may come a "tipping point" in the Type 3 morphology, where the angle between landward and seaward portions becomes unsustainable and the inlet possibly reverts to a Type 2 configuration (with accelerated migration toward Bogue

Banks). The numerical morphodynamic modeling component of this study investigates this hypothesis by running model simulations on schematized Type 2 and Type 3 inlet channel configurations. Sample schematized Type 2 and Type 3 configurations are shown over the historical channel alignments in Figure 4-20 and Figure 4-21, respectively. Figure 4-22 shows that the Authorized Channel configuration is used as a representative example of Type 1 ebb channel morphology.

Inlet channel alignment cases simulated in the numerical model study are discussed in greater detail in Chapter 6.6.

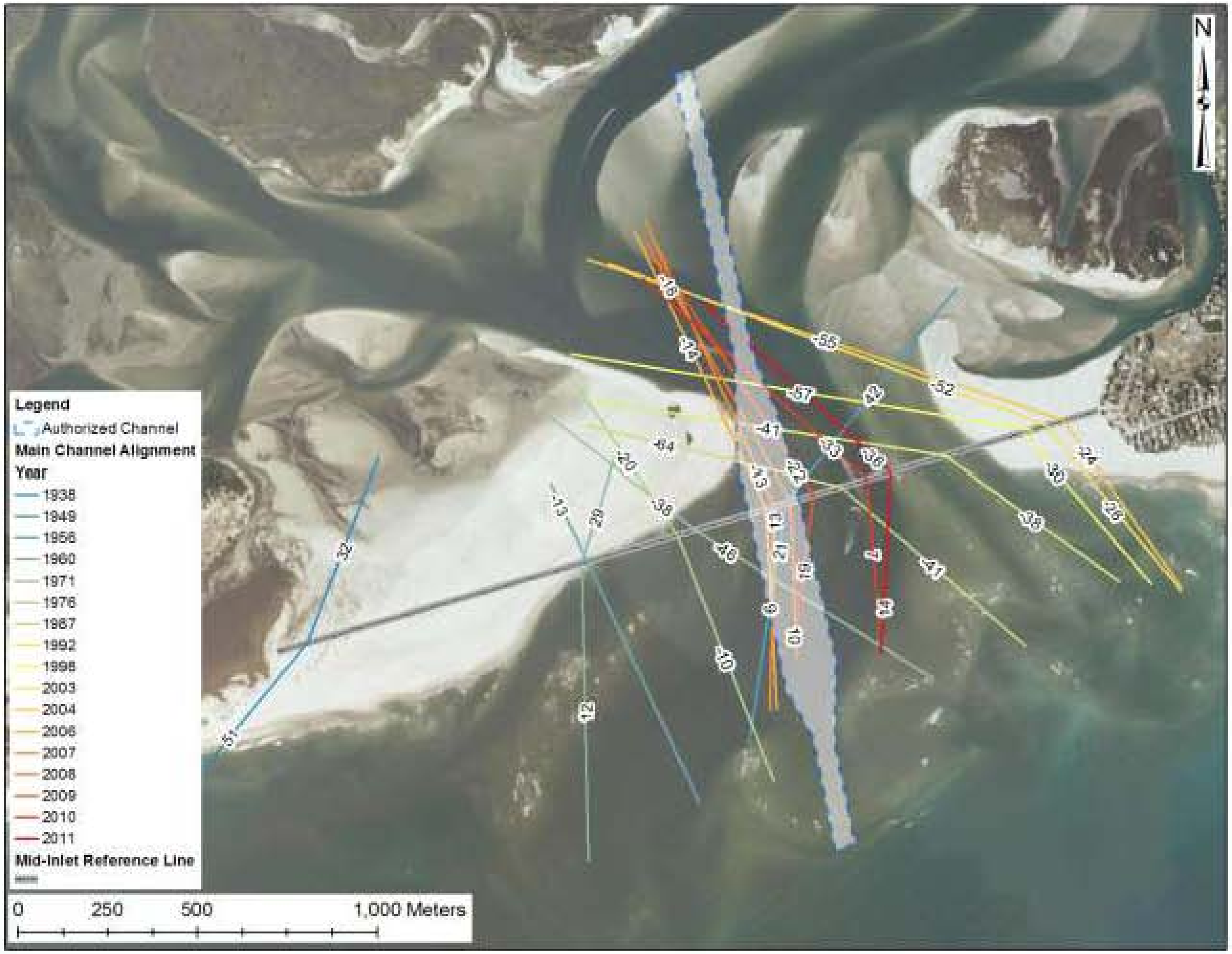


Figure 4-18: Historical Main Ebb Channel Alignments – By Year

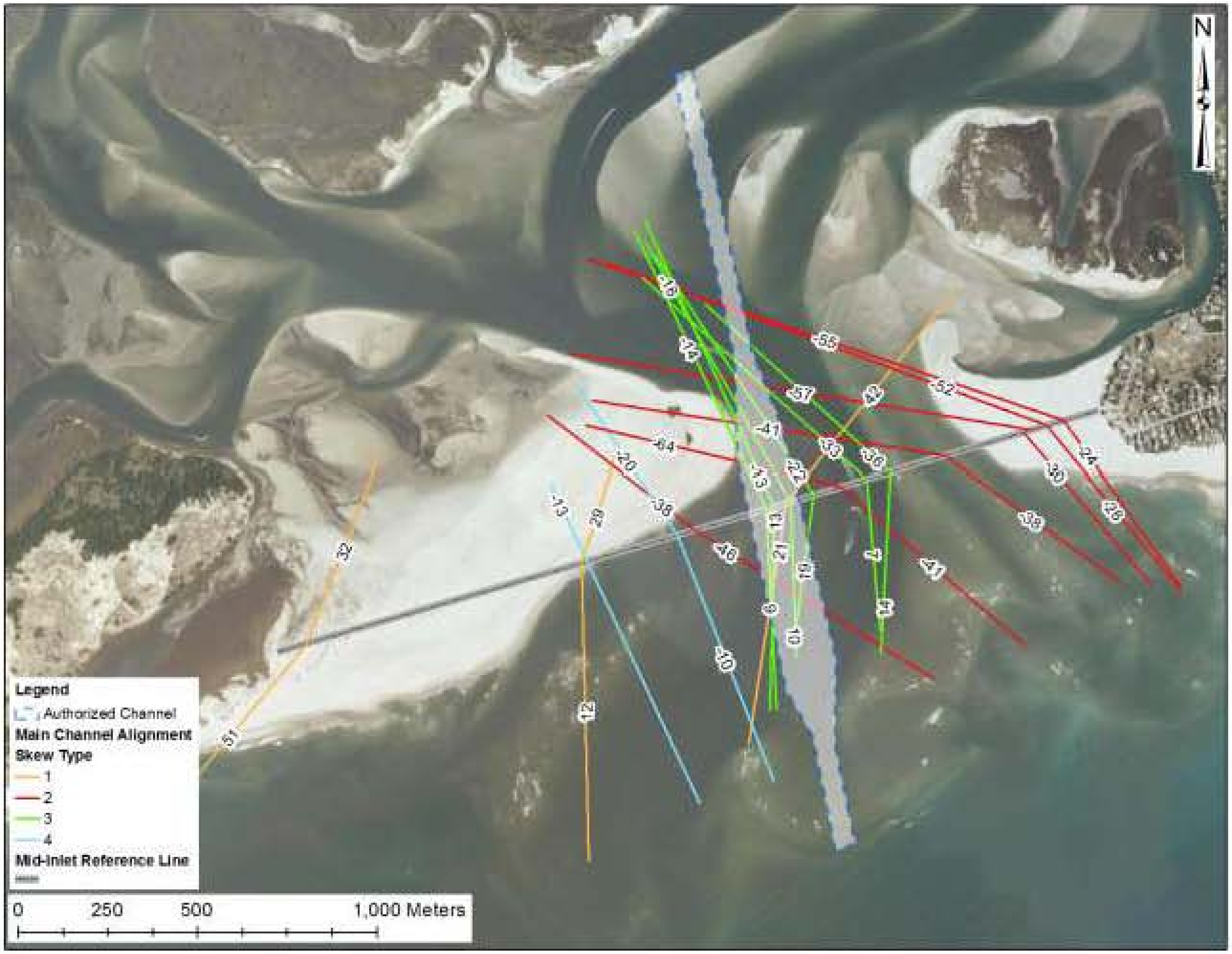


Figure 4-19: Historical Main Ebb Channel Alignments – By Alignment Type

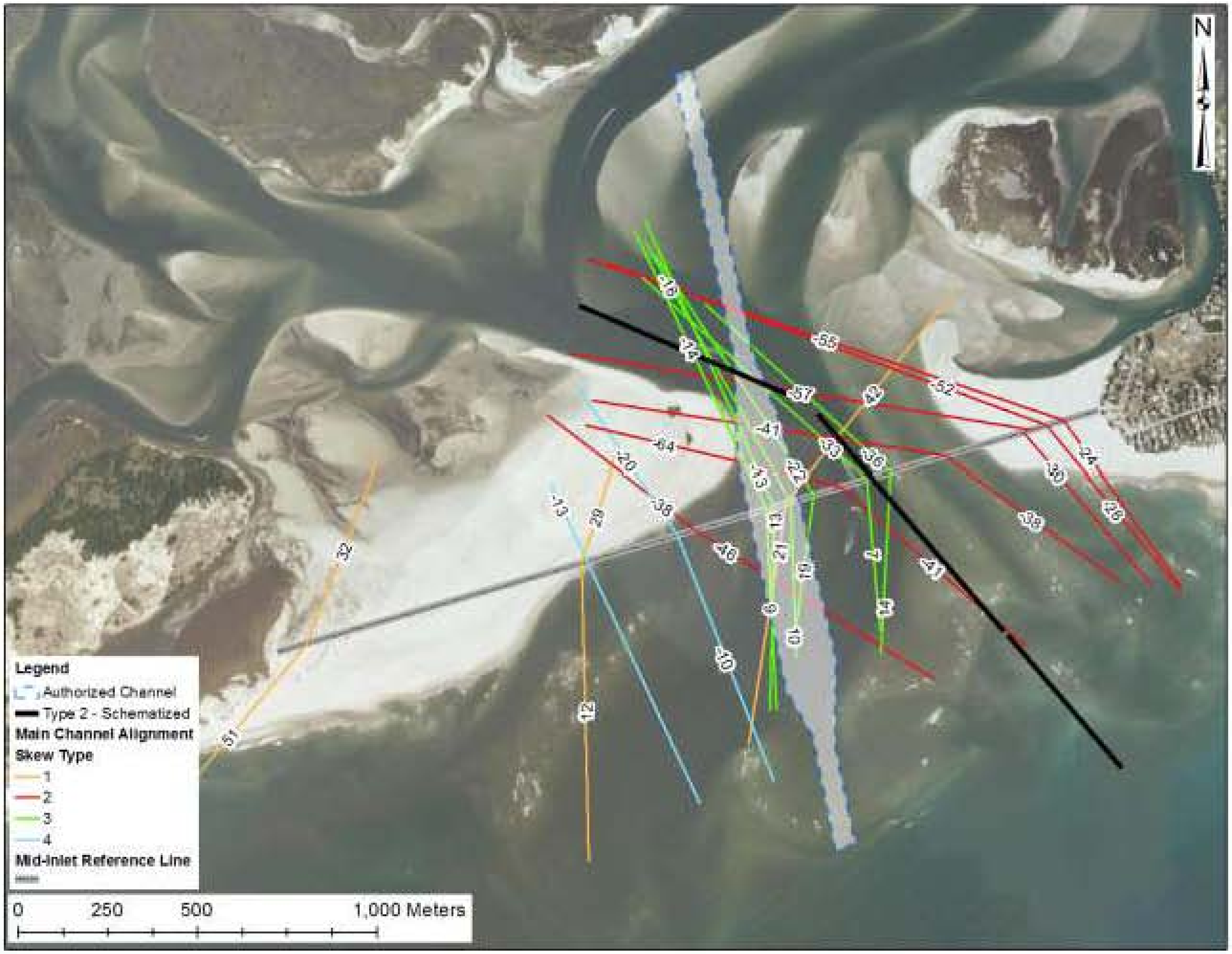


Figure 4-20: Schematized Main Ebb Channel Type 2 Over Historical Ebb Channel Alignments

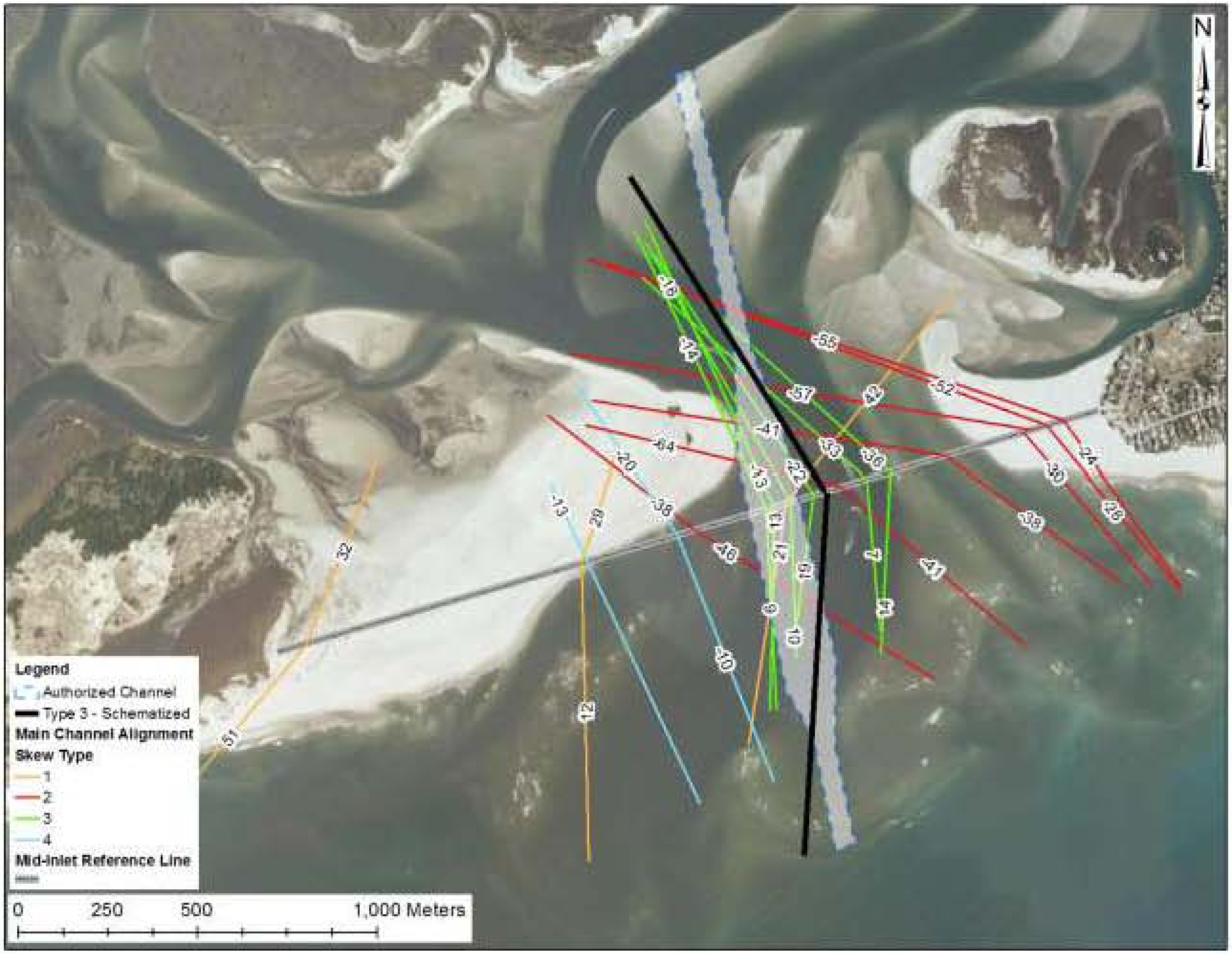


Figure 4-21: Schematized Main Ebb Channel Type 3 Over Historical Ebb Channel Alignments

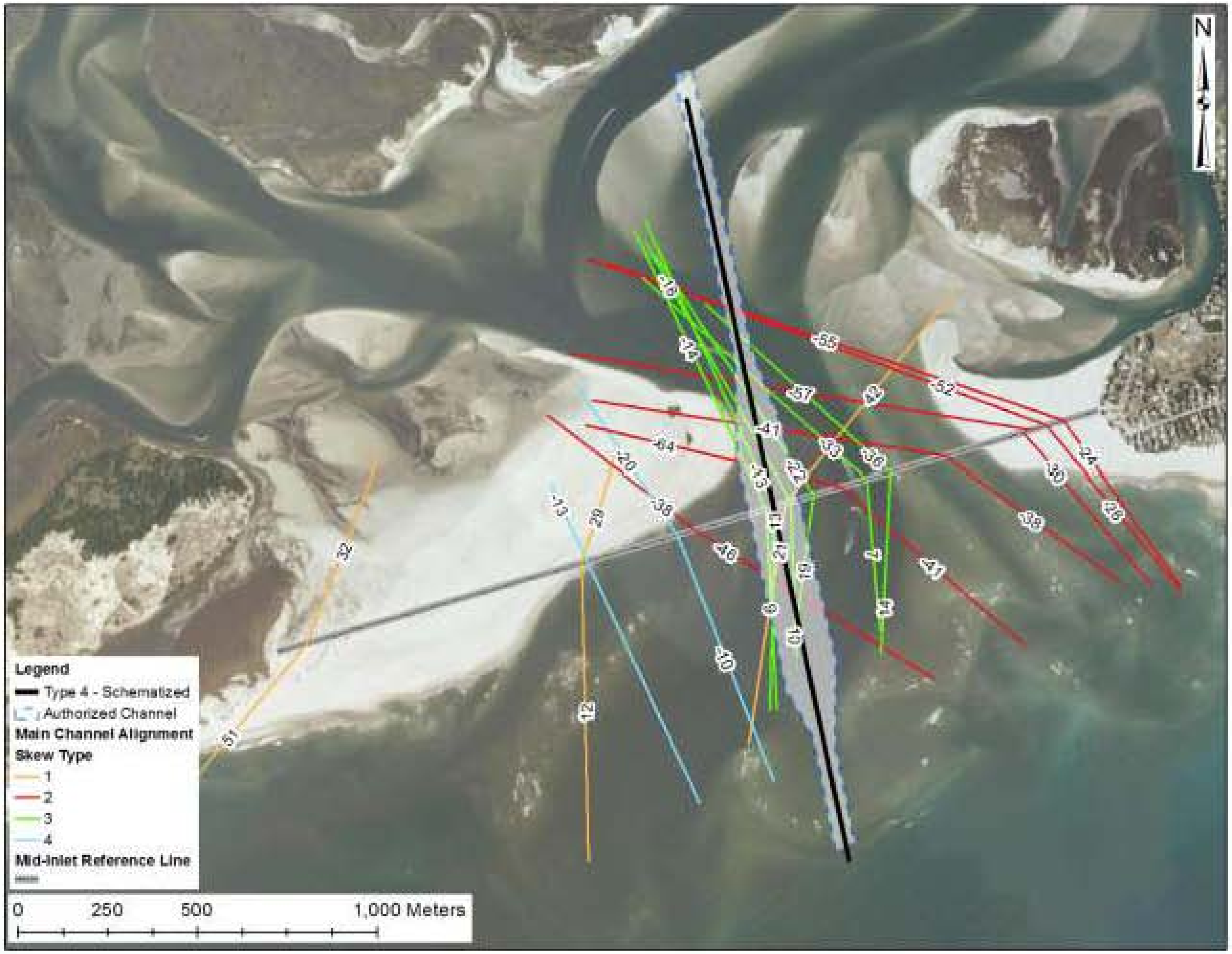


Figure 4-22: Schematized Main Ebb Channel Type 4 Over Historical Ebb Channel Alignments

5.0 ONSLOW BAY REGIONAL MODEL

5.1 Purpose

The purpose of the regional numerical model is to provide spatially-varying, time series boundary conditions of water level, flow (current vectors), and wave conditions to the Bogue Inlet and Bogue Banks local models. The regional model consists of dynamically coupled hydrodynamic and wave transformation models, developed as described below, which transform tidal water level signals and spectral wave field signals from "offshore" points (> 30m depth) to the project shorelines, inlet interiors, and sounds. The regional model results are in turn used as inputs to local model simulations of Bogue Inlet and the Bogue Banks shoreline and nearshore area. This regional-to-local nested model approach allows for greater computational efficiency by using a single large-area model to develop boundary conditions for multiple local-scale model areas, and by allowing detailed changes to be made to the local models (e.g. inlet channel alignments) without re-simulating the large regional areas that are not truly affected by the local changes.

The wave transformation component of the regional model also provides useful information on the spatial variability of the nearshore wave climate – transformed from offshore measured wave records – and gradients in wave energy that affect sediment transport processes along the Bogue Banks shoreline. This particular result of the regional model is discussed in the main Engineering Report along with the detailed Bogue Banks local model results.

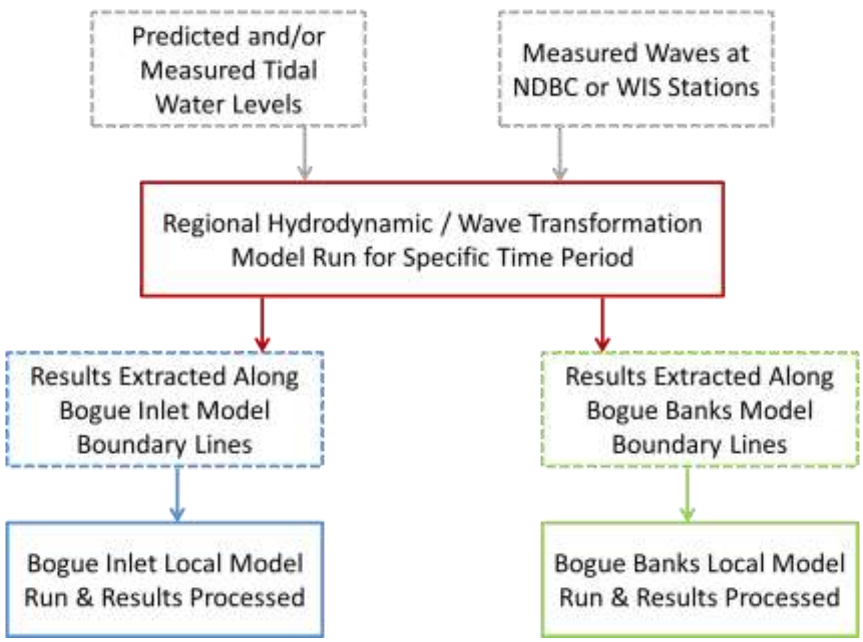


Figure 5-1: Flowchart of Regional to Local Model Offline Nesting

5.2 Methodology

The regional numerical model utilizes the MIKE 21 software environment, commercially licensed by DHI Water, Environment, and Health – formerly the Danish Hydraulic Institute (DHI). MIKE 21 contains many software modules for simulating flows, sediment transport, and dissolved constituent advection-dispersion through a 2-D (depth integrated) finite volume computational approach. A 2-D spectral wave action model is also included for simulating coastal and ocean wave generation and transformation.

The present regional model employs the MIKE 21 flexible mesh hydrodynamic (FM HD) and spectral waves (SW) modules. The simulations are run in an online-coupled framework allowing wave and flow calculations to be conducted simultaneously, so that feedback between the wave and flow processes are capture – e.g. changing tidal water depths affects wave transformation, and wave radiation stresses affect hydrodynamic currents in the wave breaking zone.

MIKE 21 FM HD consists of a finite volume/flexible mesh hydrodynamic program which solves the two-dimensional, incompressible, Reynolds averaged Navier-Stokes equations under the assumptions of Boussinesq and of hydrostatic pressure. The model solves for continuity, momentum, temperature, salinity, density equations and a turbulent closure scheme.

MIKE 21 SW is a spectral wave action model which simulates the following physical phenomena: wave growth by action of wind; non-linear wave-wave interaction; dissipation due to bottom friction; dissipation due to depth-induced wave breaking; refraction and shoaling due to depth variations; wave-current interaction. The directional decoupled parametric formulation of the software was applied in the present study to transform simple representations of the offshore wave climate to the nearshore area around Bouge Inlet and along Bogue Banks.

Complete descriptions of the MIKE 21 FM HD and MIKE 21 SW model basis and solution techniques are given in the *MIKE 21 Flow Model Module Scientific Documentation* (DHI, 2009a) and *MIKE 21 Spectral Wave Module Scientific Documentation* (DHI, 2009b).

5.3 Bathymetry Data

Bathymetry data used to develop and provide bed elevations to the regional model consist of multiple sources. Where local topographic and hydrographic survey data exist in efficiently usable form, those data sources were used directly by interpolating xyz point elevation data on the MIKE 21 computational mesh (grid). Local survey data utilized include a 2005 multi-beam hydrographic survey of Bogue Inlet and its flood and ebb shoals and 2009 topographic / hydrographic beach and nearshore survey profiles along the standard Bogue Banks monitoring program transects; both surveys were conducted by Geodynamics LLC.

Published digital navigational chart data were used to fill gaps where local survey data were not available – such as in the majority of Bogue Sound, the White Oak River, and similar enclosed waterways, and in ocean areas seaward of approximately 12 m water depth. The chart data were extracted from multiple years' charts, at varying scale and resolution, from the Jeppesen C-MAP commercial chart data archive through the MIKE CMAP (DHI, 2009c) software interface and license.

The model computations rely heavily on the bathymetry values assigned to each mesh element (grid cell). The use of multiple data sources from potentially many different years in which coastal bathymetric conditions may have been very different from each other places some limitations on the accuracy of the model computations. However, the local survey data covered the local areas of this study's focus completely, and it was possible to represent each local model area (Bogue Inlet and Bogue Banks nearshore) with a single, internally consistent bathymetry data source.

The primary limitation of using the C-MAP chart data for this study is that flows and water levels through Bogue Inlet are very sensitive to the bathymetric description of Bogue Sound – particularly the shoals, tidal wetland areas, and Dudley Island, and the White Oak River and Atlantic Intracoastal Waterway channels around Dudley Island. Very little elevation data were available for these areas, and model bathymetry development required significant assumptions and interpolations to describe these areas. In consequence, the bathymetry of these areas was somewhat of a model calibration parameter, as described below. The performance and reliability of future model simulations would be improved by obtaining reliable, recent elevation data describing these channel, island, sound and shoal features.

5.4 Model Development

5.4.1 Computational domain

Figure 5-2 shows the regional model extent and bathymetry in meters relative to NAVD88. The extent of the model domain was selected in order to capture the effects of Cape Lookout and its shoals on the regional circulation and wave transformation processes. The western extent of the model is set far enough away from Bogue Inlet to ensure that the boundary conditions do not unduly affect model results at the inlet. Bogue Sound and other connecting channels between the various inlets were also included.

Figure 5-3 is a closer view of the regional model domain that indicates the computational mesh resolution in the nearshore focus area of this study. Approximate model resolutions of various key areas are shown as text labels on Figure 5-3.

5.4.2 Hydrodynamic boundary conditions

The flow model was forced at the offshore boundary using astronomical tide water levels obtained from the Oregon State University (OSU) Atlantic Ocean Tidal Solution. This tidal database was developed by OSU by assimilating satellite altimetry data collected over numerous years into regional tidal databases using the Ocean Tidal Inversion Software (OTIS). Astronomical tide time series were generated from tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4) extracted around the perimeter of the regional model using a MATLAB tool developed by M&N coastal engineers.

The MATLAB tool is capable of adding surge effects onto the astronomical tide signal by extracting and comparing NOAA tide gauge data. This feature was utilized to develop tidal boundary conditions for selected storm-specific time periods, such as Hurricane Ophelia.

5.4.3 Wave boundary conditions

Spectral wave height, period, and direction descriptions were applied to the offshore boundaries of the regional model, based on time series of wave conditions from NDBC buoy #41013 Frying Pan Shoals (as described in Section 3.1.5).

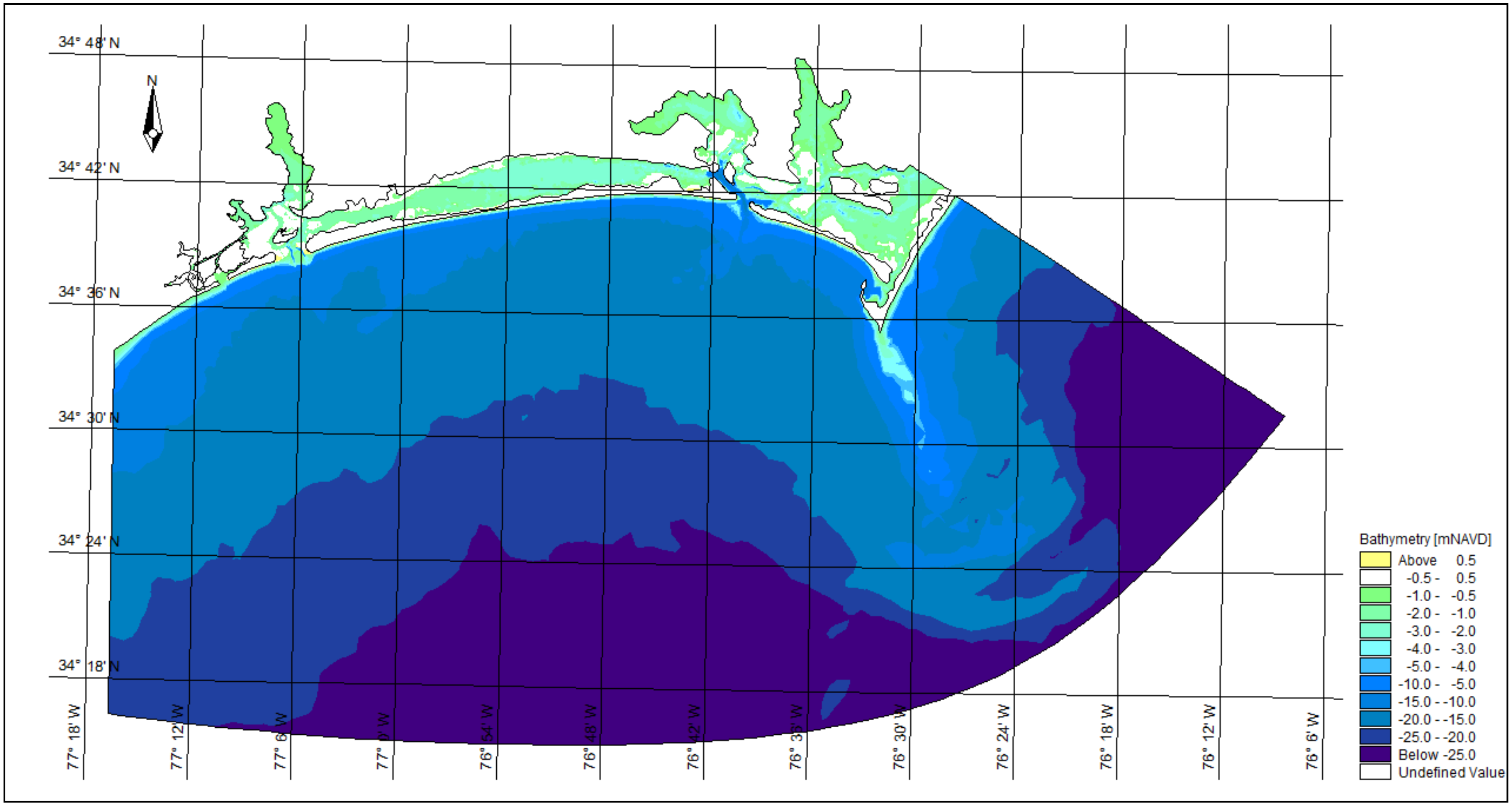


Figure 5-2: Regional Model Bathymetry

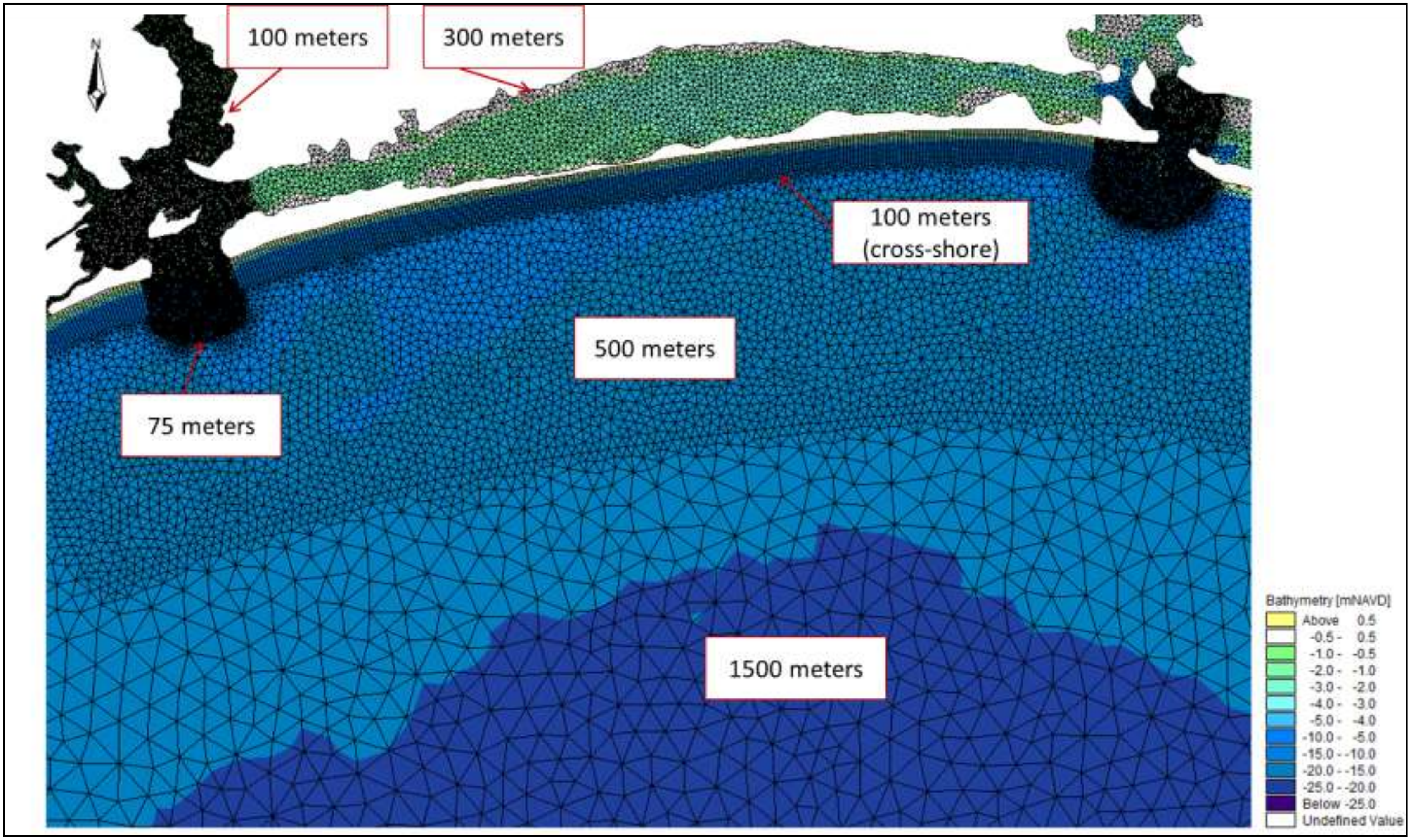


Figure 5-3: Regional Model Computational Mesh Between Bogue Inlet and Beaufort Inlet

5.5 Model Validation

Regional model simulations were conducted over time periods including both the NOAA tide gauge data (June 1999) and the CS&E Bogue Inlet field measurements (25 - 28 June 2005).

Key model parameters, such as bed roughness and eddy viscosity, were set initially based on software defaults values and previous experience. The resulting model water levels were plotted against NOAA measured and predicted water levels at Beaufort (Figure 5-4) and Atlantic Beach Triple S Pier (Figure 5-5) tide gauges. The initial model simulations compared well with the ***predicted*** NOAA tide gauge data (not available at Atlantic Beach), and not as well with the measured NOAA data. This is reasonable since the model was forced primarily using astronomical tide constituents that do not include meteorological effects.

The June 2005 model validation period was examined in validation of the regional model, but is more important to the Bogue Inlet local model, and discussed in Chapter 6.5.

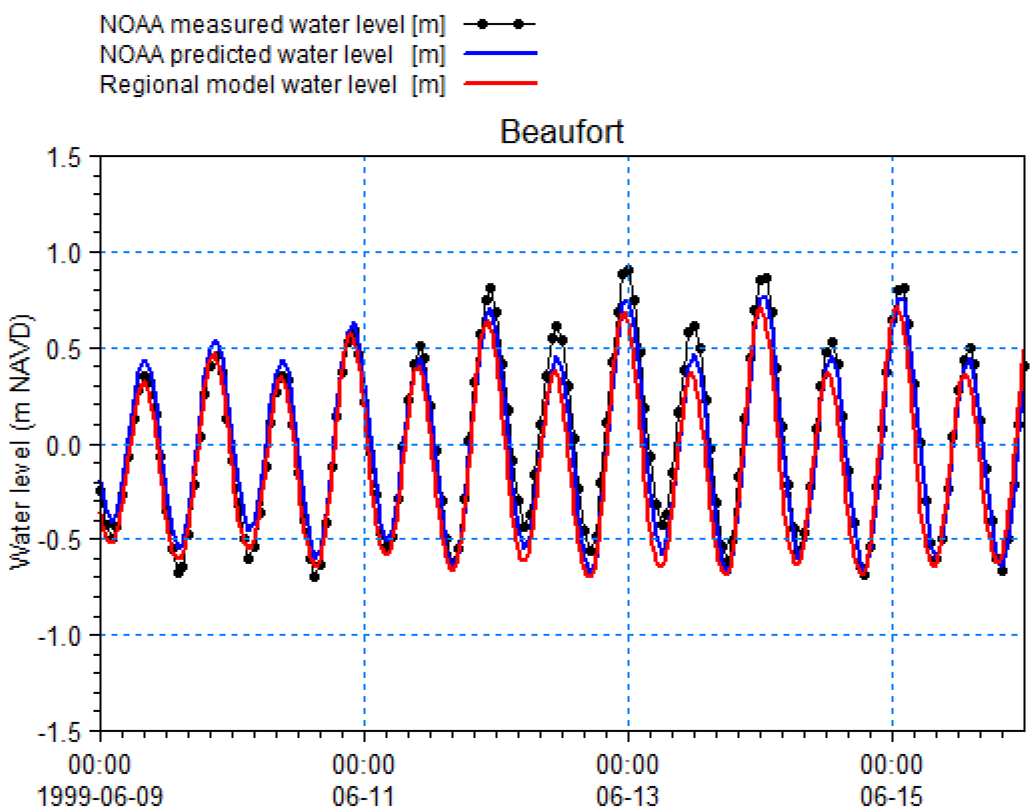


Figure 5-4: Regional Model Water Level vs. NOAA Beaufort Tide Gauge

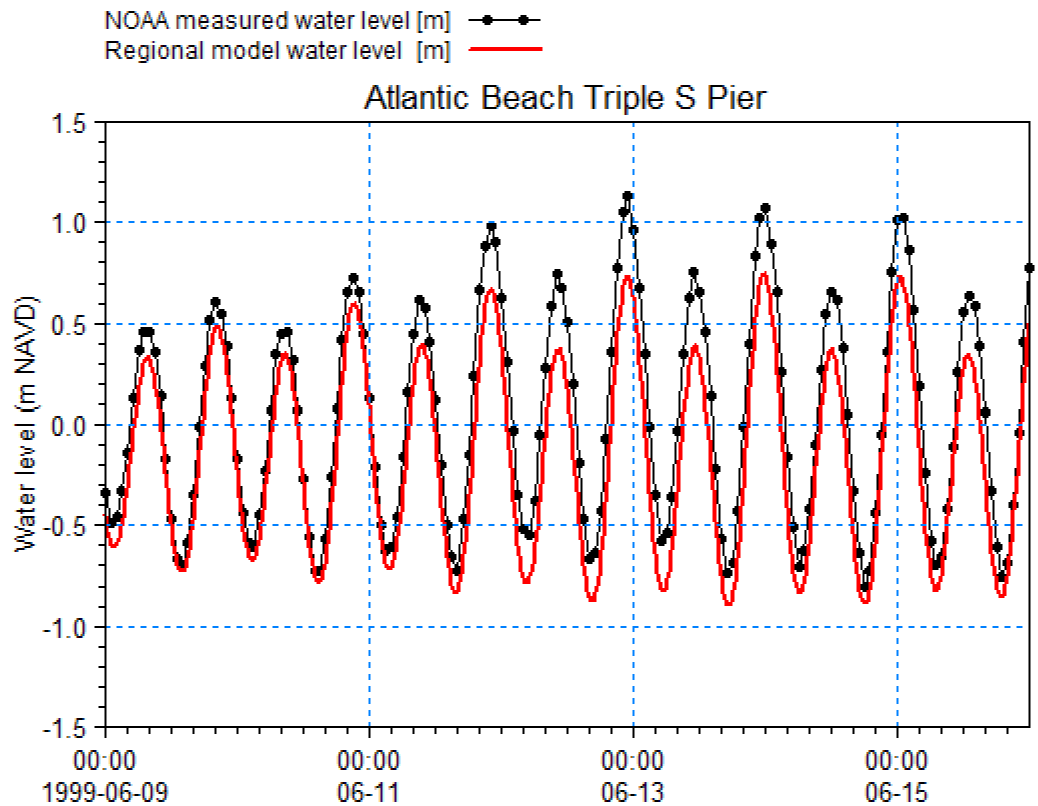


Figure 5-5: Regional Model Water Level vs. NOAA Atlantic Beach Tide Gauge

6.0 BOGUE INLET LOCAL MODEL

6.1 Purpose

The purpose of the numerical model portion of the Bogue Inlet study is to extend the analytical / empirical analysis of historical data. The local model provides additional information on sediment transport pathways within the inlet and its shoals. The morphological model results facilitate and investigation of whether “tipping points” may exist – i.e. inlet ebb channel positions or orientations which would indicate more likely acceleration of migration toward the barrier islands.

6.2 Methodology

The empirical / analytical study is supplemented with a limited series of numerical morphodynamic model simulations. The local numerical model consists of dynamically coupled two-dimensional (2-D) depth-integrated waves and hydrodynamics, which drive quasi-three-dimensional (Q3D) sand transport calculations. The sand transport calculations cause changes in the model bathymetry, which are then automatically fed back to the subsequent wave, flow, and transport calculations.

6.3 Bathymetry Data

The local Bogue Inlet model mesh bathymetry was based on the same sources as described for the regional model, above. The computational resolution of the local model is much finer than in the regional model, and it provides significantly more fidelity to the original 2005 surveyed multi-beam hydrographic data.

6.4 Model Development

6.4.1 Computational domain

Figure 6-1 shows the extents of the local Bogue Inlet computational domain, and the computational mesh resolution is illustrated in Figure 6-2. The extents of the domain were selected in order to allow relatively smooth transitions from regional model hydrodynamics (particularly in the sound and channels around Dudley Island) and to place the seaward boundaries far enough away from the areas of greatest interest to avoid artificial boundary forcing impacts. The 20m horizontal resolution within the inlet was selected to ensure that several computational points would exist across all significant channel features, while keeping the number of computational elements in a manageable range for simulation times and available computer hardware.

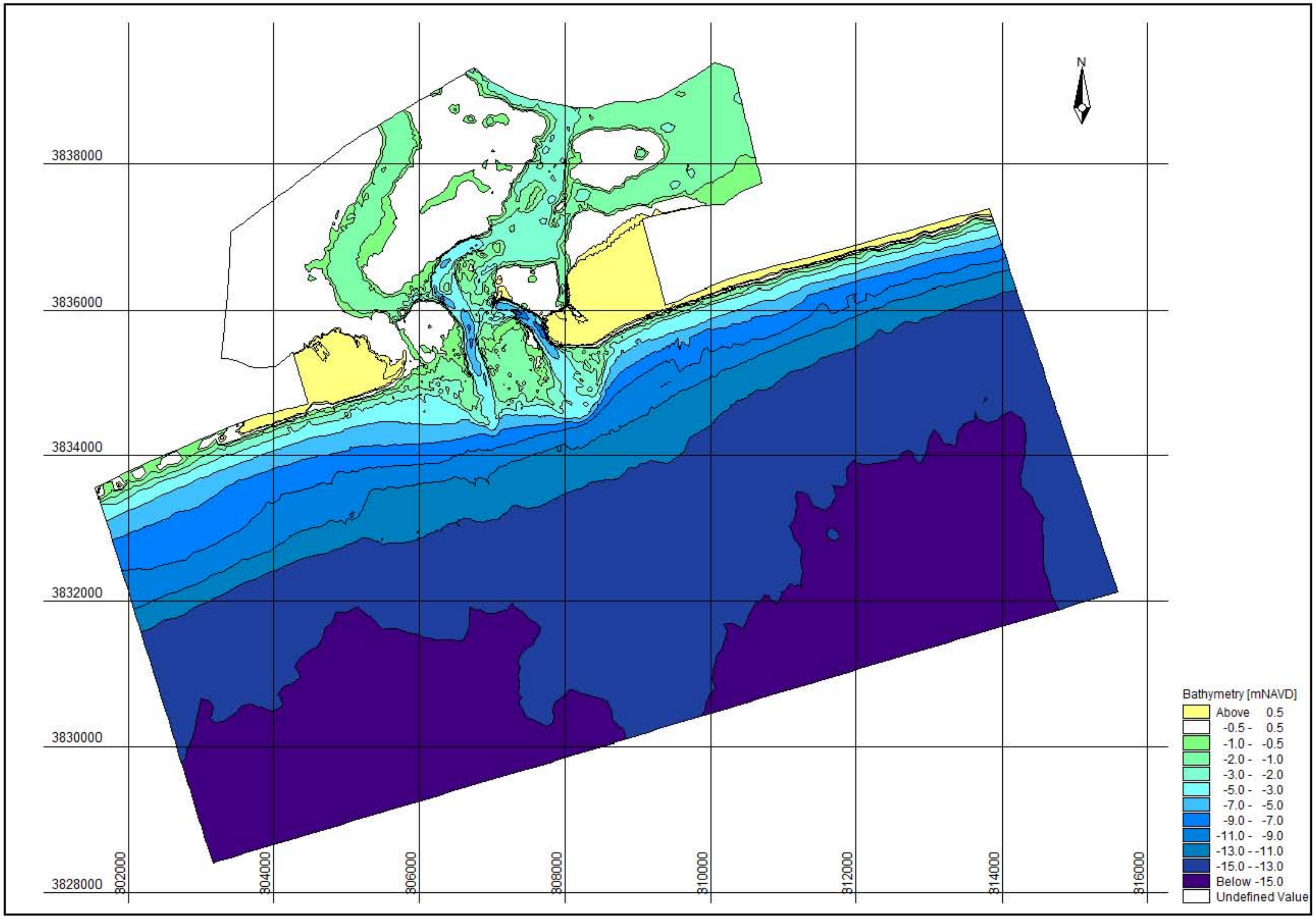


Figure 6-1: Bogue Inlet Local Model Bathymetry

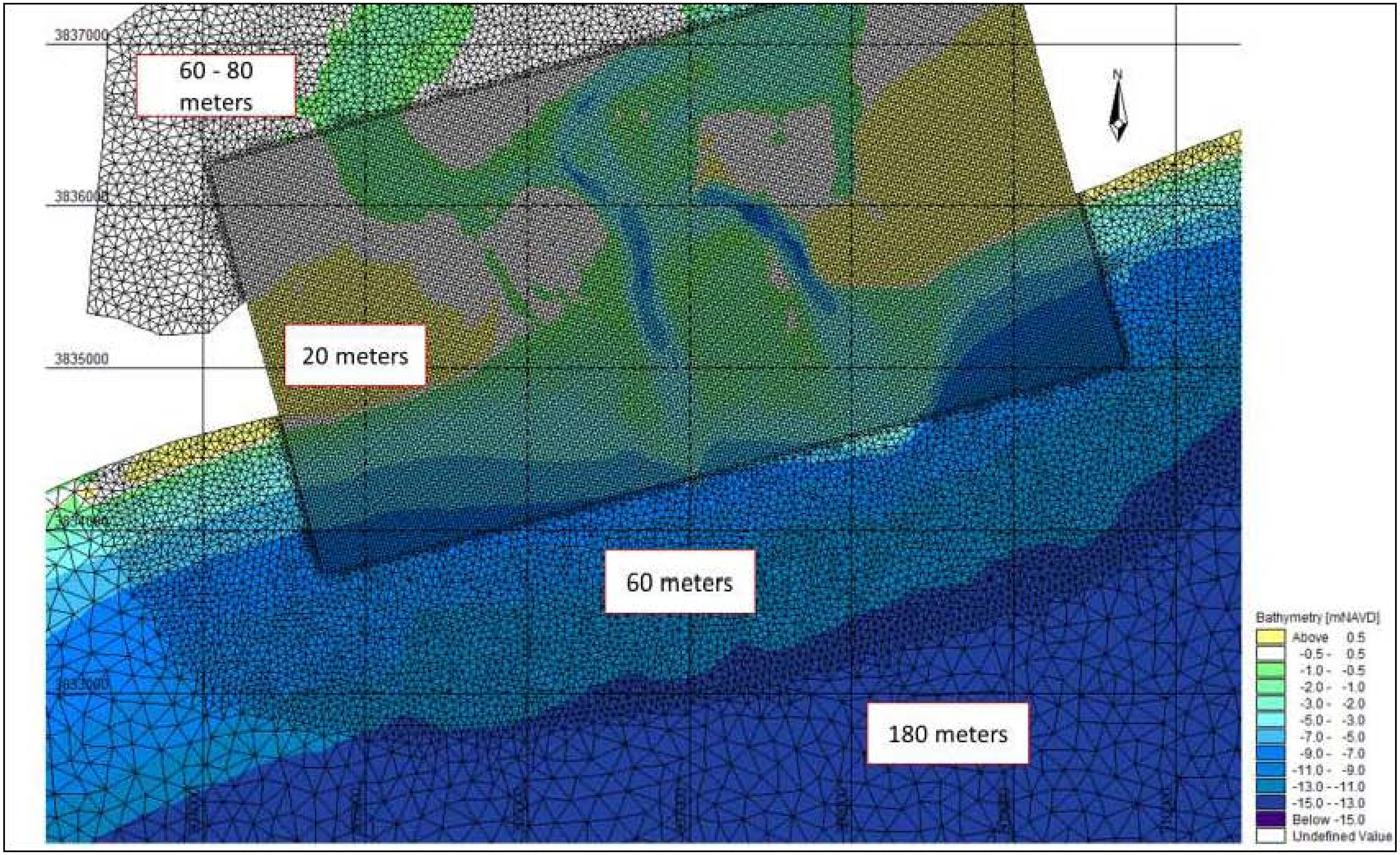


Figure 6-2: Bogue Inlet Local Model Computational Mesh

6.4.2 Hydrodynamic boundary conditions

The Bogue Inlet local model has six open boundaries – three in the nearshore Atlantic Ocean, and three on Bogue Sound and the White Oak channel. Water level and current velocities at these open boundaries were extracted directly from the regional hydrodynamic model results.

6.4.3 Wave boundary conditions

Significant wave height, mean wave direction, and peak wave period results at the three Atlantic Ocean boundaries of the local model were extracted directly from the regional wave transformation model. Wave conditions on the Bogue Sound and White Oak channel boundaries were very minor, and no wave forcing was applied in the local model along those three boundaries.

6.4.4 Sediment transport parameters

Grain size = 0.30mm, based on a review of sediment samples collected in the area by the USACE in 2002.

6.5 Hydrodynamic Model Calibration

The Bogue Inlet local model was calibrated against the June 2005 CS&E measured water level and discharges. Calibration to the measured discharges required changes to both the local and regional models. Final calibrated model results are shown in Figure 6-3 and Figure 6-4, where positive discharges indicate flood tide flow and negative discharges indicate ebb tide flow.

The primary calibration parameters resulting in the best match to the measured discharges and water levels were bed roughness (Manning's M) and model bathymetry in Bogue Sound and the tidal flats inside Bogue Inlet. Bed friction was accounted for using a map of variable roughness, with Manning's *n* values ranging between 0.030 on shoals and flats to 0.017 in open coastal waters.

Changes were required to the regional model bathymetry in Bogue Sound. It was necessary to create deeper, contiguous channels between Beaufort Inlet, Bogue Inlet, and the small inlet immediately west of Bogue Inlet. Measured or charted bathymetry data inside Bogue Inlet, and particularly across the shallow tidal flats, is very sparse. It was therefore necessary to estimate and vary the elevations of connecting channels and shoal areas until an acceptable match was obtained to the measured discharges and water levels at Bogue Inlet.

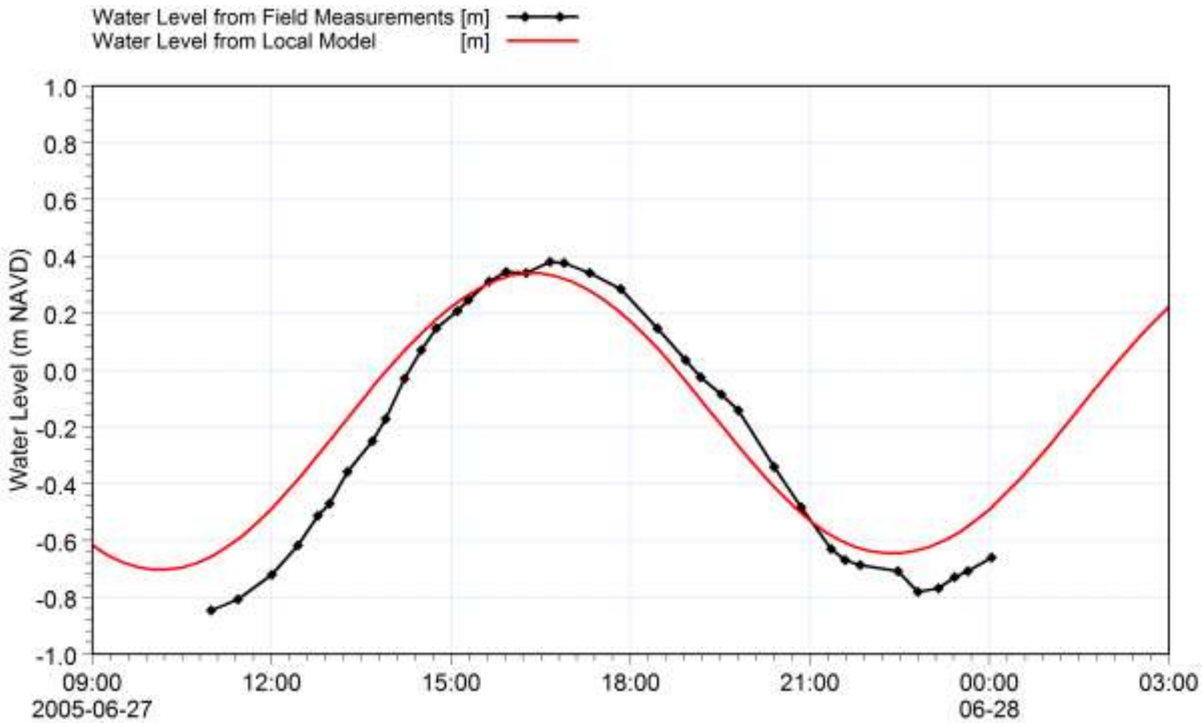


Figure 6-3: Bogue Inlet Model Water Level vs. CS&E Field Measurements

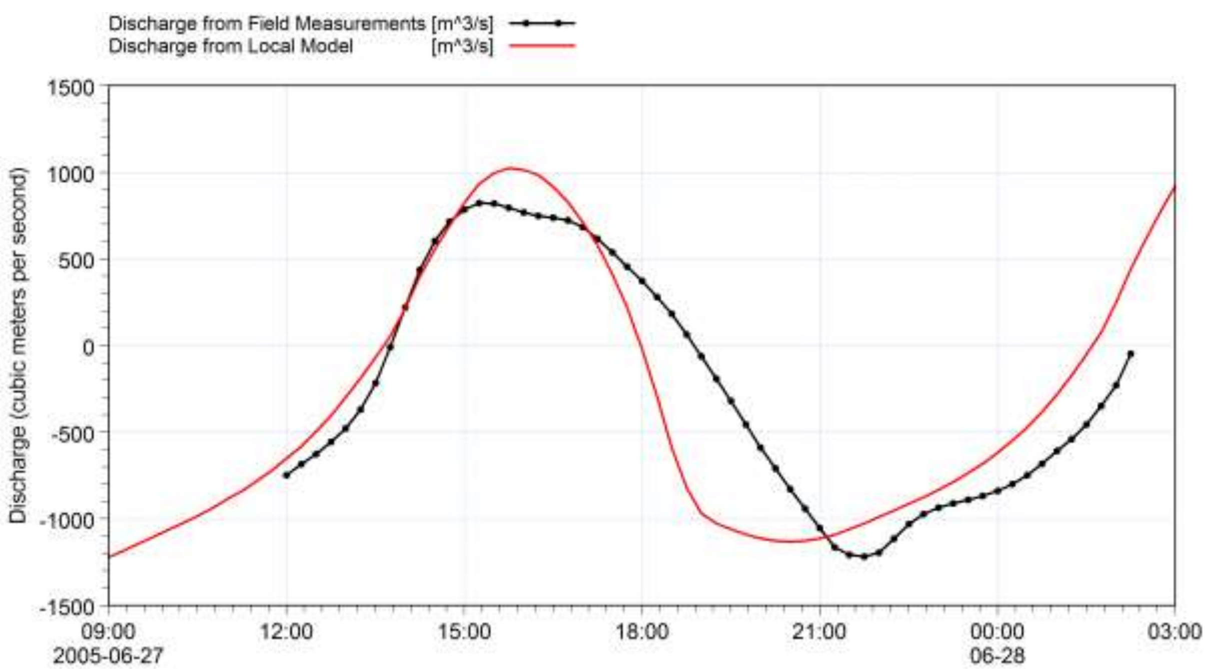


Figure 6-4: Bogue Inlet Model Discharge vs. CS&E Field Measurements

6.6 Schematized Inlet Configuration Scenarios

A simulation period of 1.5 months in the Bogue Inlet local model requires slightly more than 2 days of computational time. Due to the time-consuming nature of this high-resolution local model, it is necessary to limit the number of physical inlet channel configurations simulated. Five separate physical configurations (cases) were developed and are described in Table 6-1. The cases were designed to bracket the range of most relevant channel configurations observed in the GIS-based analytical / empirical analysis of historical Bogue Inlet morphology (representing Type 1, Type 2, and Type 3 categories of ebb channel alignment).

Table 6-1: Bogue Inlet Local Model Channel Configuration Cases

Case (Type)	Description of Schematized Channel Configuration
1 (Type 4)	Authorized ebb channel (baseline), azimuth 168°N
2 (Type 2)	Ebb channel 25 degrees CCW from Authorized
3 (Type 3)	Landward ebb channel 20 degrees CCW from Authorized; Seaward ebb channel 15 degrees CW from Authorized
4 (Type 3)	Landward ebb channel 35 degrees CCW from Authorized; Seaward ebb channel 10 degrees CW from Authorized, centered approximately 1,200 feet west of the 2011 Bogue Banks shoreline
5 (Type 2)	Landward ebb channel 55 degrees CCW from Authorized; Seaward ebb channel 30 degrees CCW from Authorized, centered approximately 1,000 feet west of the 2011 Bogue Banks shoreline
41 (Type 3)	Same as Case 4, with White Oak back channel closed initially
51 (Type 2)	Same as Case 5, with White Oak back channel closed initially
6 (Type 2)	Landward ebb channel 65 degrees CCW from Authorized; Ebb channel 30 degrees CCW from Authorized, centered approximately 650 feet ***east*** of the Bogue Banks shoreline at the Reference Line
7 (Type 2)	Same as Case 6, with White Oak back channel connection rotated CW to test sensitivity
8 (Type 1)	Ebb channel 15 degrees CW from Authorized, centered approximately 1,800 feet west of the 2011 Bogue Banks shoreline
	Total number of morphology simulations = 27

6.6.1 Simulation Packages (repeating time periods)

The morphodynamic model simulations were run as a repeating time series made up of 1.5 months of tidal water levels and currents. Waves were included – dynamically linked to the flow, sediment transport, and morphology calculations – based on the "representative annual" (filtered) wave time series described in Appendix A. Up to four sets of repeating simulations were run for each case, referred to below as "Simulation Packages."

First, each channel configuration case was simulated for a warmup period of 1.5 months. In the morphodynamic (bed update) simulations, an option exists to speed up morphology change by multiplying the change at each time step by a morphodynamic update factor (MORFAC). This allows the model run to produce more bed change in the same amount of time, such that a 1 month simulation with MORFAC = 3 should produce approximately 3 months of bed change. In the warmup simulation period, the bed update calculations were conducted with a MORFAC = 1, indicating no artificial speedup.

At the end of each case's warmup simulation, the ending bathymetry used as the starting bathymetry for a second simulation. The second simulation was conducted using MORFAC = 3, so that the computed bed change was sped up by a factor of three in order to investigate a longer equivalent time period. The warmup plus the second simulation period are grouped together and referred to as Simulation Package A in the discussion below. Simulation Package A is considered to represent approximately 6 months of tides and the equivalent of 4 years of representative waves.

Model results for all channel configuration cases were evaluated after Simulation Package A was finished. Case 4, Case 5, and Case 8 displayed morphology changes that warranted additional simulation periods to be run. Using the ending bathymetries from Simulation Package A as a starting condition, Simulation Package B was run on these cases, consisting of a third 1.5 month simulation period sped up by a factor of three (MORFAC = 3).

To test the effects of a moderate hurricane on channel migration, Case 4, Case 5, and Case 8 ending bathymetries from Simulation Package B were used as starting conditions for a simulation of Hurricane Ophelia's waves, storm surge, and associated flows Hurricane Ophelia comprises Simulation Package C, and morphology was not sped up during this simulation.

Finally, the ending bathymetries from Simulation Package C were run through a final 1.5 month representative tide and wave simulation period sped up by a factor of three (MORFAC = 3), referred to as Simulation Package D.

This last simulation was run to investigate whether the inlet would show "recovery" changes from the hurricane effects. The total effective simulation period for Cases 4, 5, and 8 is considered to represent approximately 15 months of tides and the equivalent of 10 years of representative waves, plus two weeks of waves and hydrodynamics around a significant hurricane event.

6.6.2 Starting bathymetry maps for each case

Model bathymetries for all of the cases were constructed by carving the specified channel geometry into a highly generalized bed elevation model based on the 2005 multi-beam inlet hydrographic survey. First, a 2.5m x 2.5m resolution bathymetry grid was produced from the 2005 multi-beam data. The shoal elevations within the inlet (i.e. between the end point of Bogue Banks and Bear Island) were set to a typical elevation of -0.7m NAVD88, and the inlet channels were filled in to match the adjacent shoal elevations. The seaward slope of the ebb shoal was generalized to provide a smooth and approximately symmetric (west to east) transition from the inlet shoals into deeper Atlantic Ocean waters. This process created the working base bathymetry. Finally, the required ebb channel geometry for each Case was carved into the base bathymetry, and the ebb channel was connected to the Bogue Sound and White Oak River channels remaining from the 2005 multi-beam survey data.

Figure 6-5 through Figure 6-12 below depict the starting model bathymetries for each of the main Cases. Elevations above 0m NAVD88 and below -9.5m NAVD88 exist in each of the model bathymetries, but those contours have been made invisible in the figures so that the aerial image can be seen.

Case 1 (Figure 6-5) represents the Authorized Ebb Channel relocation described in CP&E (2004) and constructed in 2005. The Case 1 ebb channel has an azimuth of approximately 168 ^{O}N and an authorized centerline depth of -5m NAVD88. Case 1 is simulated primarily as a baseline condition for evaluating the inlet morphodynamic behavior observed in the other cases.

Case 2 through Case 8 are shown in Figure 6-6 through Figure 6-12Figure 6-9, respectively.

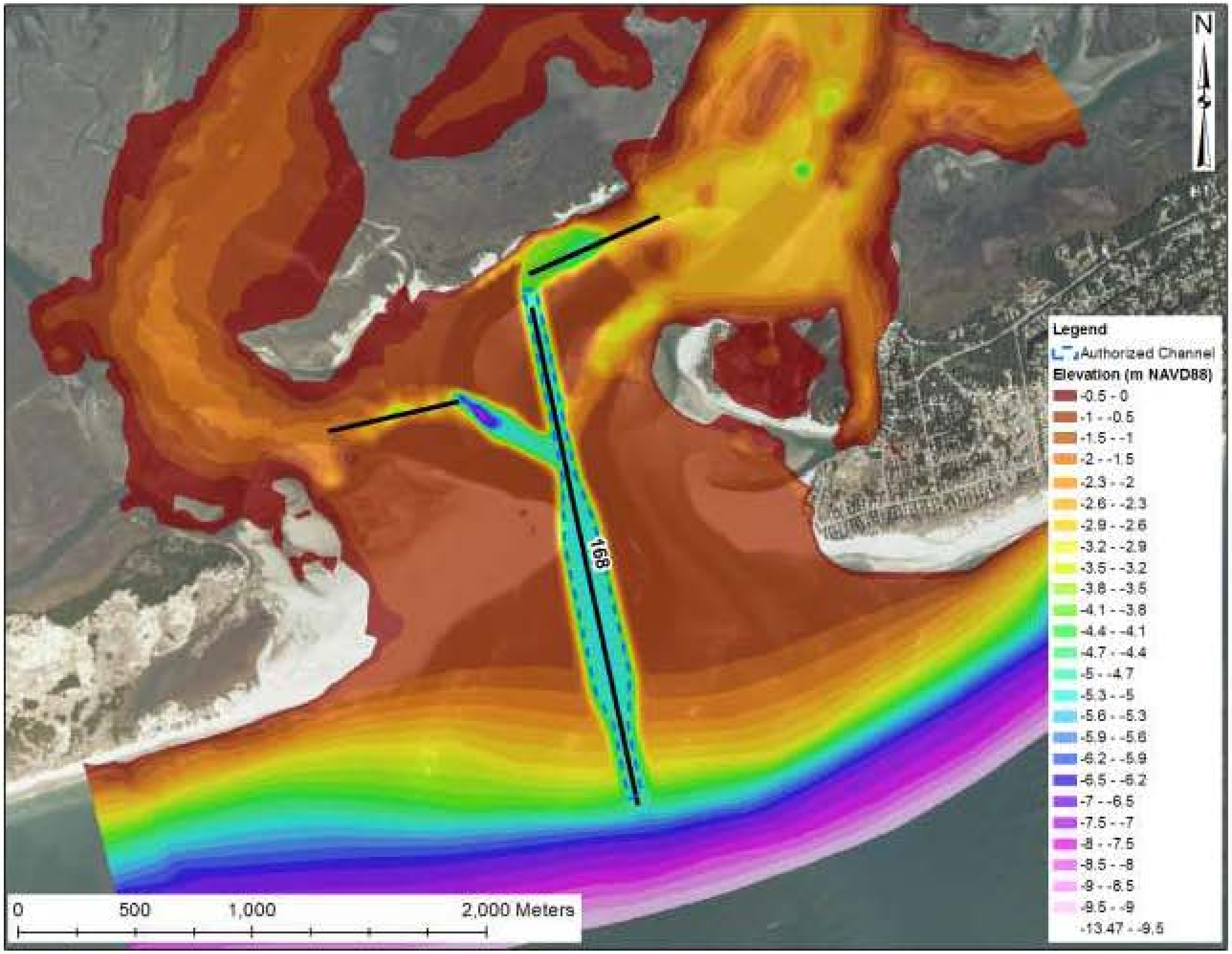


Figure 6-5: Bogue Inlet Local Model – Case 1 Starting Bathymetry

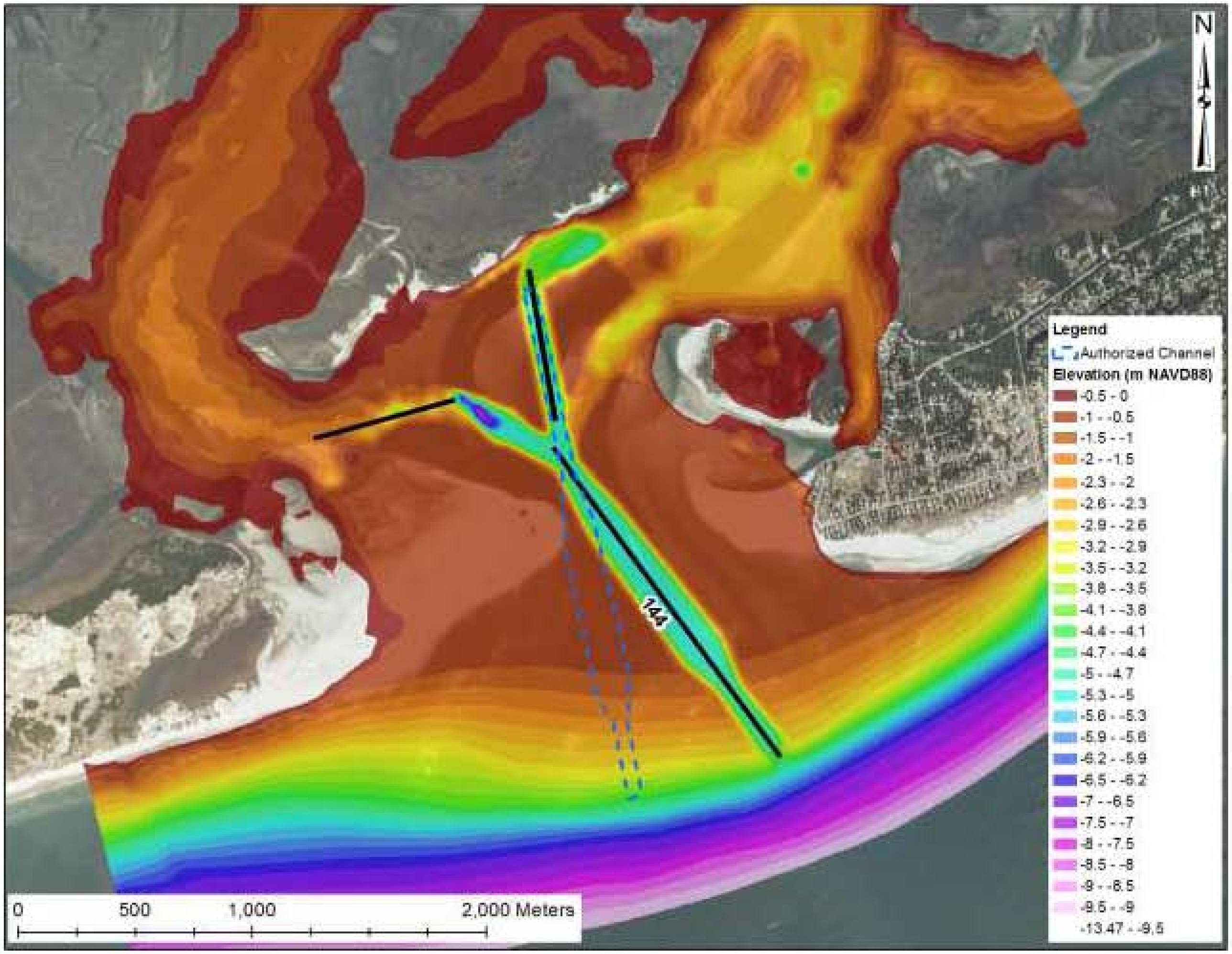


Figure 6-6: Bogue Inlet Local Model – Case 2 Starting Bathymetry

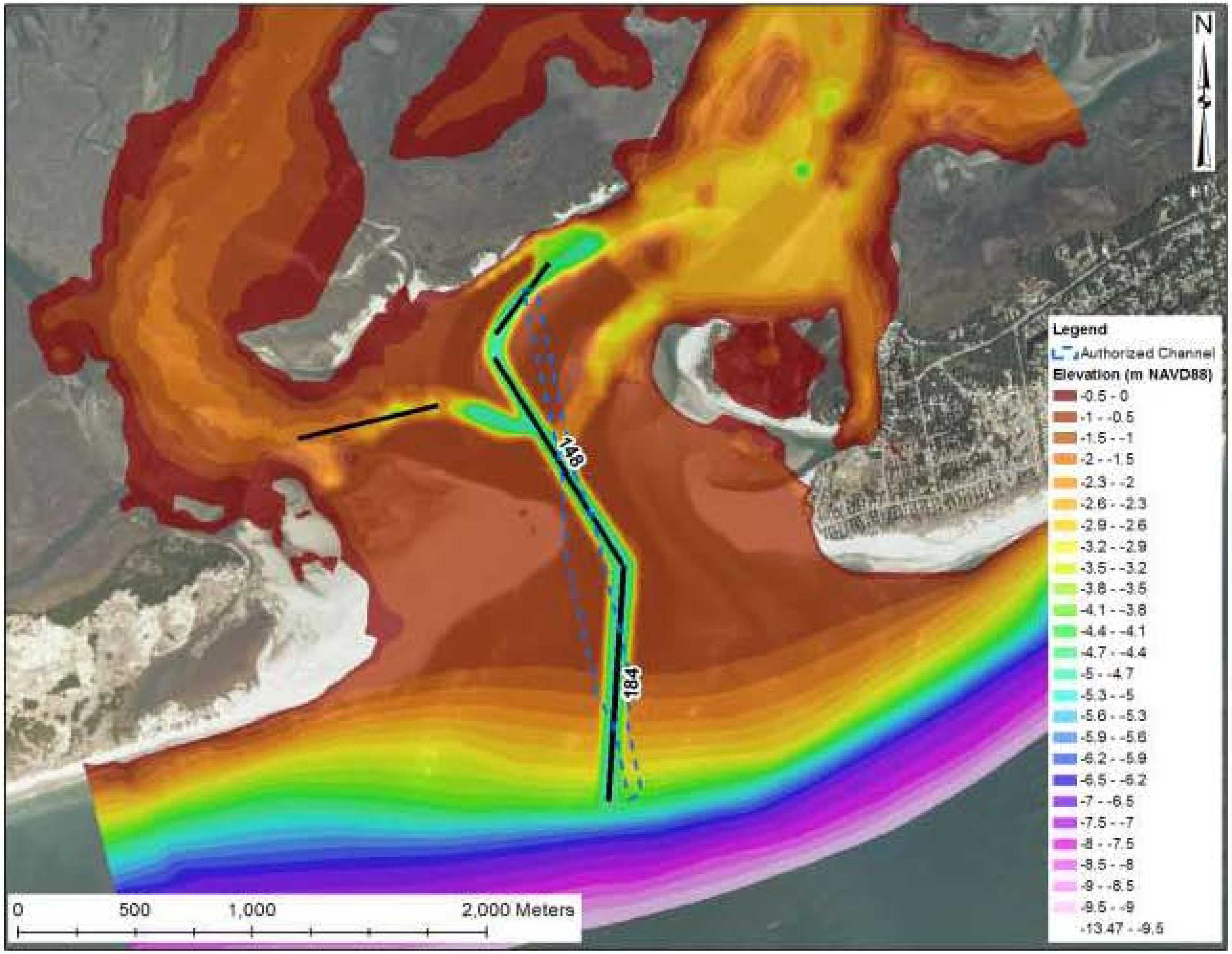


Figure 6-7: Bogue Inlet Local Model – Case 3 Starting Bathymetry

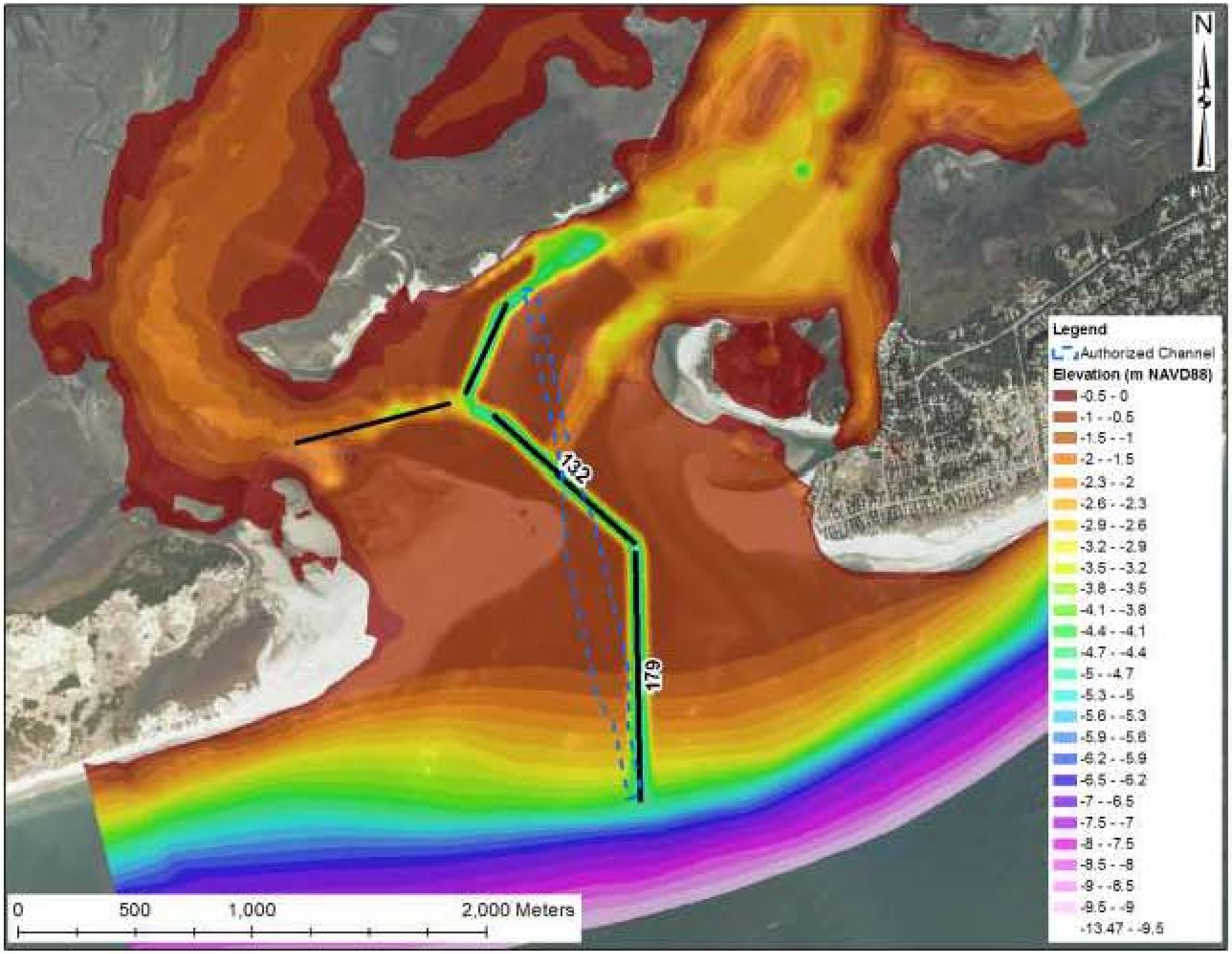


Figure 6-8: Bogue Inlet Local Model – Case 4 Starting Bathymetry

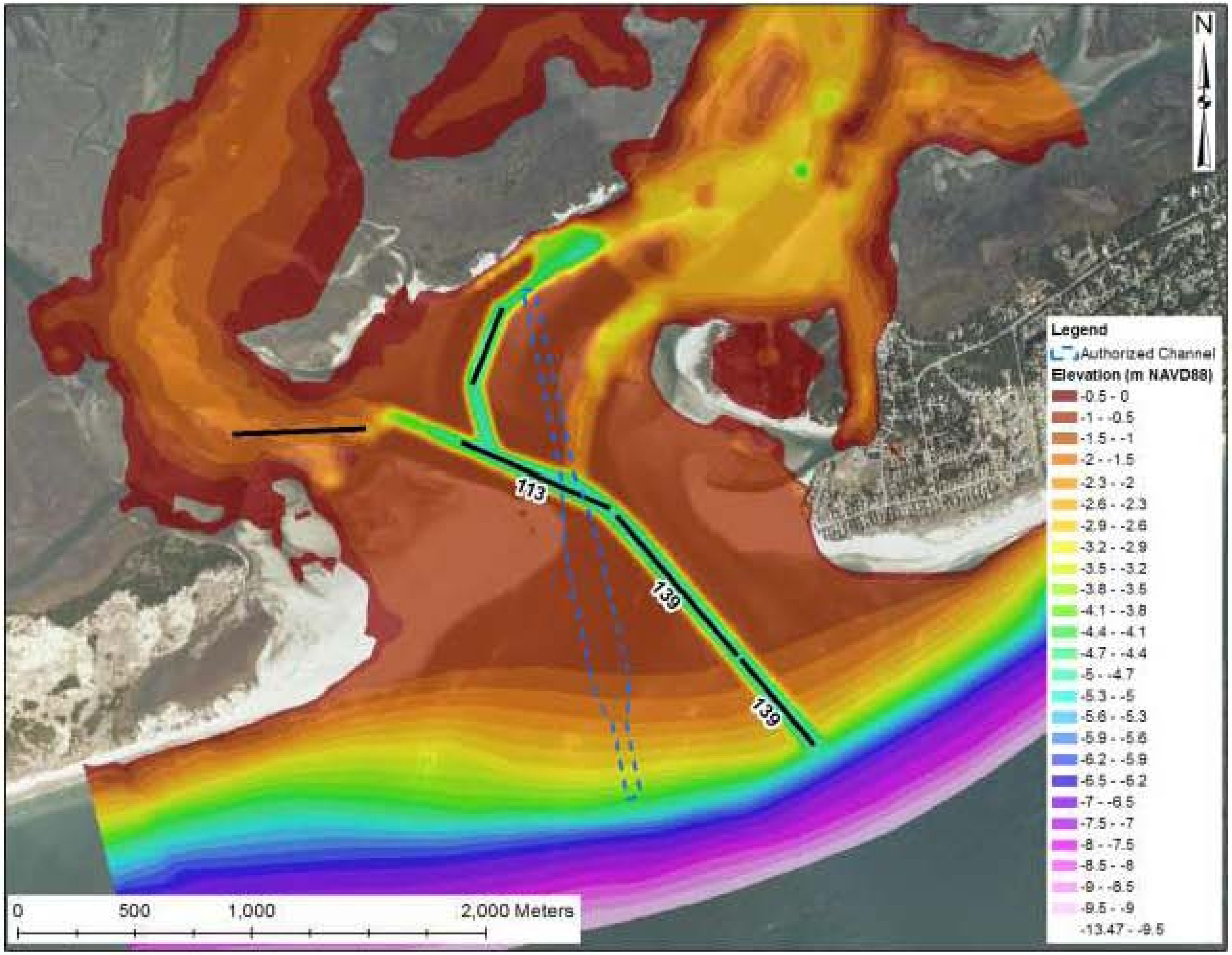


Figure 6-9: Bogue Inlet Local Model – Case 5 Starting Bathymetry

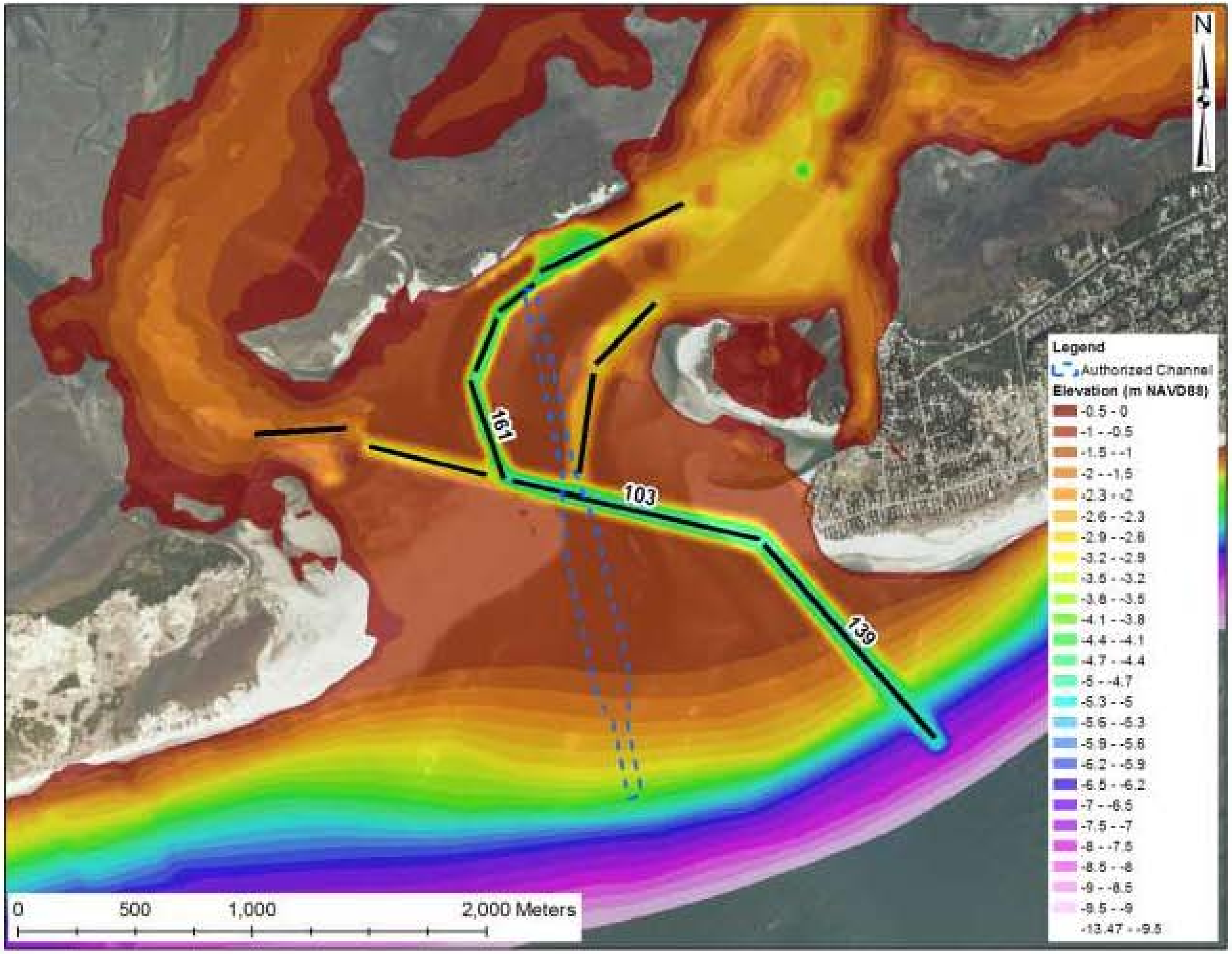


Figure 6-10: Bogue Inlet Local Model – Case 6 Starting Bathymetry

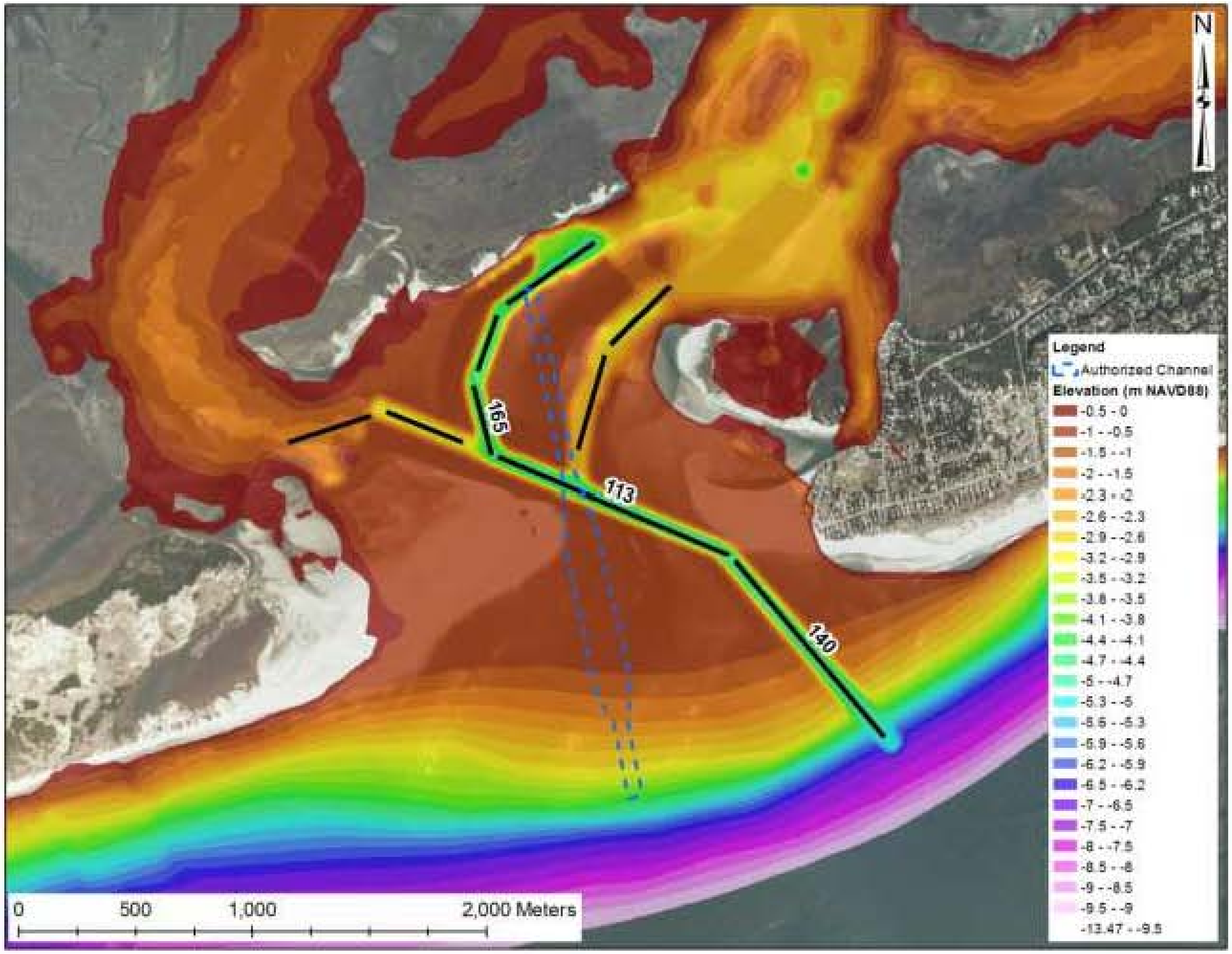


Figure 6-11: Bogue Inlet Local Model – Case 7 Starting Bathymetry

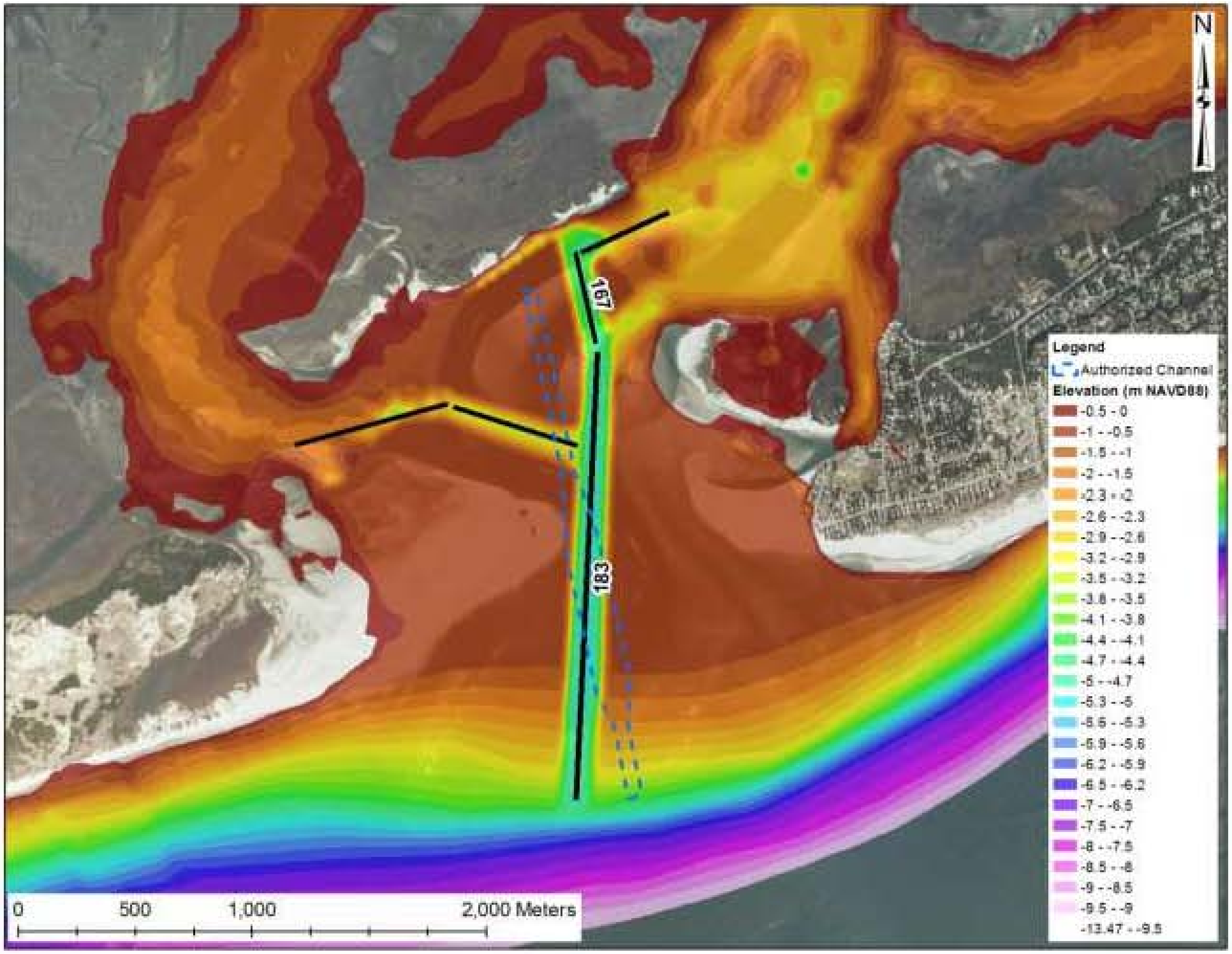


Figure 6-12: Bogue Inlet Local Model – Case 8 Starting Bathymetry

6.7 Model Results for Schematized Channel Configurations

At present, the Bogue Inlet main ebb channel is aligned most closely with a Type 3 channel configuration, approximated by the Case 4 schematic configuration. However, the purpose of the schematized channel case simulations is not specifically to predict future location of the inlet channel from its present-day configuration at a specific time period. The schematic simulations are intended to help understand the trends in behavior that could be expected, starting from a channel configuration like each Case, but the different time scales of tides vs. filtered wave inputs and the use of morphology-accelerating MORFAC values preclude direct estimation of how long it would take in real time for the channel to reach the simulated end configuration. A multi-year continuous simulation was conducted to examine inlet behavior over specific time scales, as discussed in Section 6.7.10 below.

Figure 6-13 through Figure 6-22 show the results of Simulation Package A for all of the channel configuration cases. In the figures, the starting channel configurations (from initial bathymetry) are shown as black lines with black text labels indicating channel azimuth; the red lines and red text describe the model resulting morphology for the simulation indicated in the figure caption. The color contour shading described the inlet and shoal morphology resulting from the numerical model calculations for the simulation indicated (i.e. contour shading goes with the red lines / text indicating the channel centerline alignment).

The background image in each figure is from 2010 (unless otherwise noted in the caption) and is obtained from Google Earth Pro.

The behaviors observed in each model simulation are described below.

6.7.1 Case 1

Case 1 represents Type 4, using the Authorized Channel relocation design as a template. The Base + A simulation package results are shown in Figure 6-13. The ebb channel landward of the reference line rotated slightly CCW, and it rotated CW seaward of the reference line. The overall effect was to take the channel centerline (seaward of the reference line) closer to Bear Island by approximately 500 feet.

Figure 6-14 shows the same Case 1, Simulation Package A model results over a Google Earth Pro aerial image from 2007. Two years post-relocation, the ebb channel (in the image) shows a transition toward a Type 3 configuration. The numerical model results also show movement toward a Type 3 configuration, though not to the same extent as the image. However, the numerical model results cover a shorter period of tidal hydrodynamics influenced morphology (six months).

6.7.2 Case 2

Case 2 represents a very simple kind of Type 2 configuration, with a straight channel rotated CCW from the Authorized Channel design. The Simulation Package A results are shown in Figure 6-15. The ebb channel landward of the reference line rotated very slightly CCW. Seaward of the reference line, it rotated more noticeably in a CW direction, but the seaward exit of the channel deflected CCW again to end in approximately the same position as the starting bathymetry. The channel did not move significantly in a lateral direction between the barrier islands.

6.7.3 Case 3

Case 2 represents a Type 3 configuration. The Simulation Package A results are shown in Figure 6-16. While the most landward reach of the ebb channel rotated CCW, a long reach of the ebb channel rotated CW to be aligned approximately with the Authorized Channel azimuth. Seaward of the reference line, the ebb channel rotated significantly CW. While the channel centerline migrated laterally approximately 350 feet closer to Bear Island in the middle of the inlet, the seaward exit of the channel migrated approximately 1,300 feet closer to Bear Island.

Figure 6-17 shows the Case 3, Simulation Package A model results over the 2007 Google Earth Pro aerial image. As noted above, the ebb channel (in the image) shows a transition toward a Type 3 configuration. This trend is partially echoed by the Case 3 (Type 3) numerical model results at the most landward and seaward reaches, but the numerical model channel is tending to move back toward a more straightly-aligned Type 4 configuration through the middle of the inlet.

The movement of the seaward channel exit significantly toward Bear Island is seen in both the numerical model and the historical aerial imagery from the years following the channel relocation.

6.7.4 Case 4

Case 4 represents a Type 3 configuration with a greater angle between the landward and seaward channel reaches. The Simulation Package A results are shown in Figure 6-18. In contrast to Case 3, the ebb channel landward of the reference line stayed approximately in the same position and orientation. A short reach through the middle of the inlet rotated CW to be aligned approximately with the Authorized Channel azimuth. As in Case 1 and Case 3, seaward of the reference line, the ebb channel rotated significantly CW so that the seaward exist migrated approximately 200 feet closer to Bear Island. In the middle of the inlet, the channel centerline migrated laterally approximately 850 feet closer to Bear Island.

Figure 6-19 shows the Case 4, Simulation Package A model results over the 2010 Google Earth Pro aerial image. The inlet morphology in 2010 is more similar to the Case 4 configuration than seen in the 2007 – 2009 images. The Case 4 Simulation Package A does not show a meaningful transition back toward a straighter channel (Type 4, as in Case 1).

The movement of the seaward channel exit significantly toward Bear Island remains in both the Case 4 model results and in the historical imagery from 2007 – 2010, with some acceleration of this movement seen in the 2010 imagery.

6.7.5 Case 5

Case 5 represents a Type 2 configuration with an angle between the landward and seaward channel reaches (a more realistic case than Case 2 straight-line channel). The Simulation Package A results are shown in Figure 6-20. The ebb channel landward of the reference line migrated slightly toward Bogue Banks but did not show significant rotation. As with Case 2, the seaward channel reach rotated CW, then deflected CCW again to end eastward (toward Bogue Banks) of the starting bathymetry.

6.7.6 Case 6 and Case 7

Case 6 is another Type 2 configuration with a greater angle between the landward and seaward ebb channel sections, and with the seaward ebb channel section located much closer (than Case 5) to the Bogue Banks shoreline. The landward ebb channel segment is oriented to flow smoothing into the White Oak back channel alignment, and the Bogue Sound back channels are tied in to the landward ebb channel at nearly right angles.

In Case 6 the seaward ebb channel reoriented similar to Case 5, and the channel did not move toward Bogue Banks. The ocean end of the seaward channel section rotated to a very oblique eastward opening angle. A wide, shallow incipient channel began to form in the center of the inlet; this development occurred more rapidly in Case 6 than in Case 5, probably reflecting that the Case 6 configuration is less hydraulically efficient than Case 5.

Case 7 is a variant of Case 6 that is discussed in comparison with Case 6 under Section 6.9.

6.7.7 Case 8

Case 8 represents a Type 1 configuration with a non-doglegged main channel rotated CW from the reference line normal. In this configuration, it is likely that flows from the Bogue Sound back channel may dominate migration of the landward to middle portions of the channel. The Simulation Package A results are shown in Figure 6-22. The migration of the ebb channel in Case 8 was very similar to the trends seen for Case 4 and Case 1. The landward portions of the channel did not migrate substantially, and the seaward channel reach rotated CW and migrated 400 to 600 feet toward Bear Island.

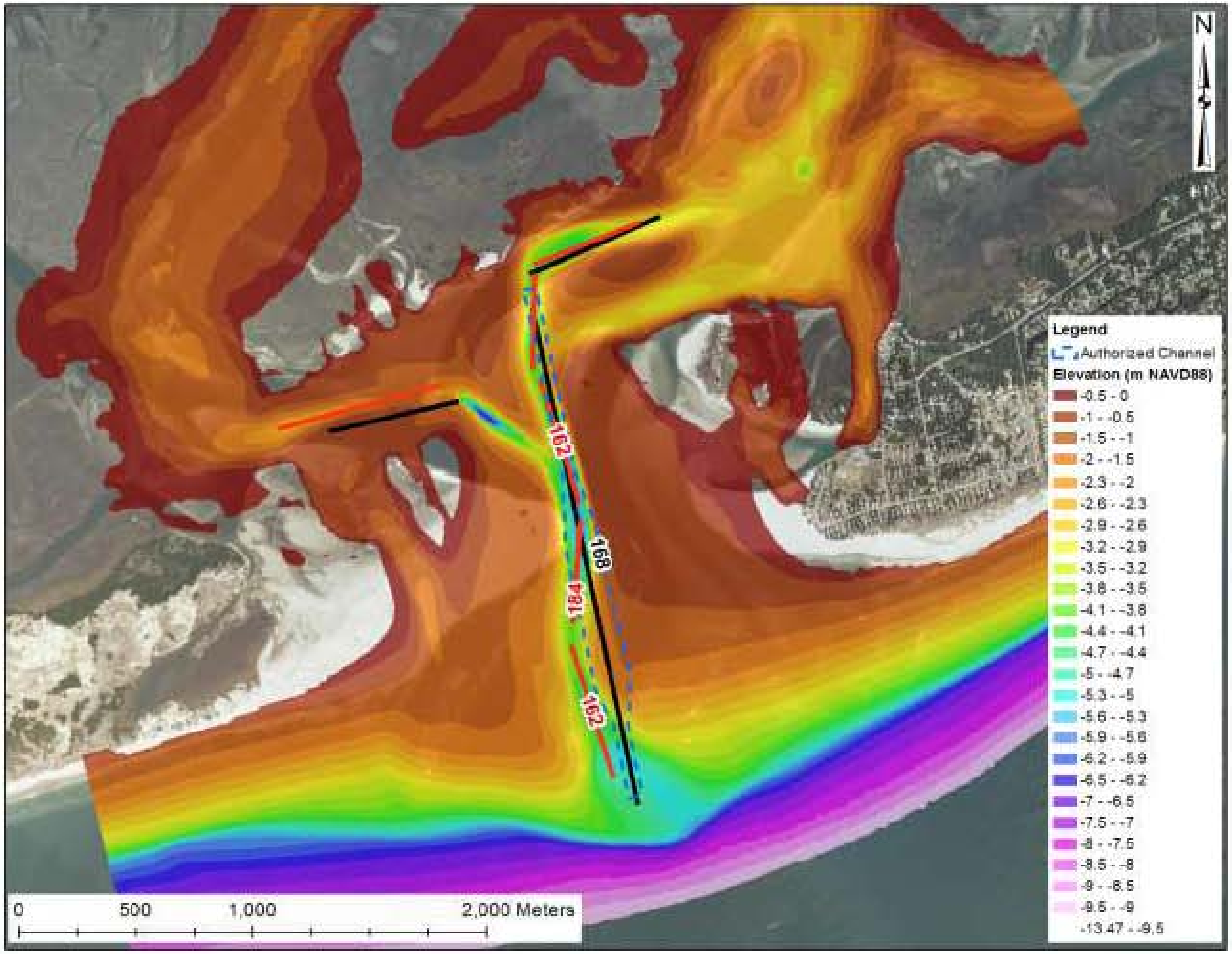


Figure 6-13: Bogue Inlet Local Model – Case 1, Simulation A – Resulting Morphology

Figure 6-14: Bogue Inlet Local Model – Case 1, Simulation A – Resulting Morphology Over 2007 Aerial Image

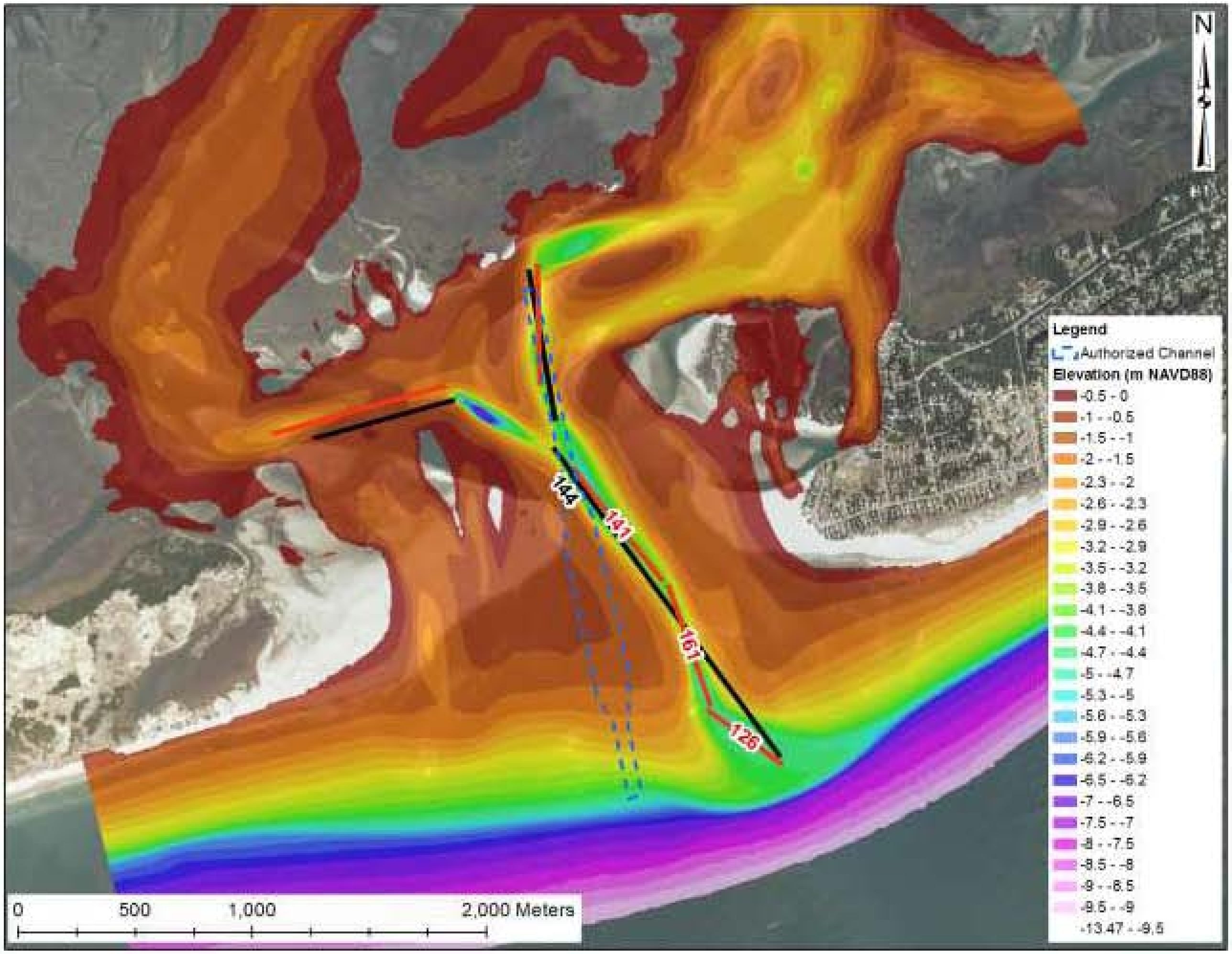


Figure 6-15: Bogue Inlet Local Model – Case 2, Simulation A – Resulting Morphology

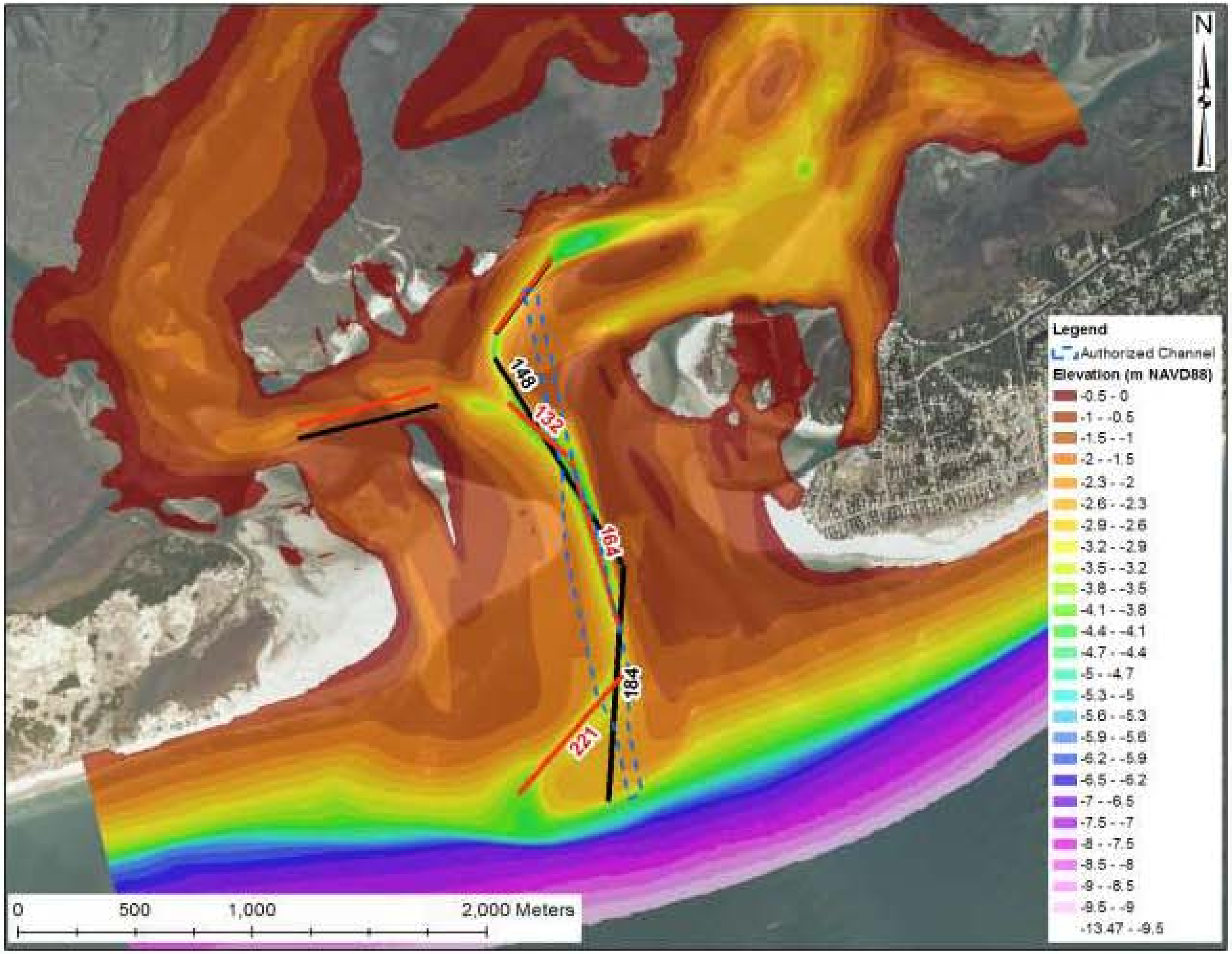


Figure 6-16: Bogue Inlet Local Model – Case 3, Simulation A – Resulting Morphology

Figure 6-17: Bogue Inlet Local Model – Case 3, Simulation A – Resulting Morphology Over 2007 Aerial Image

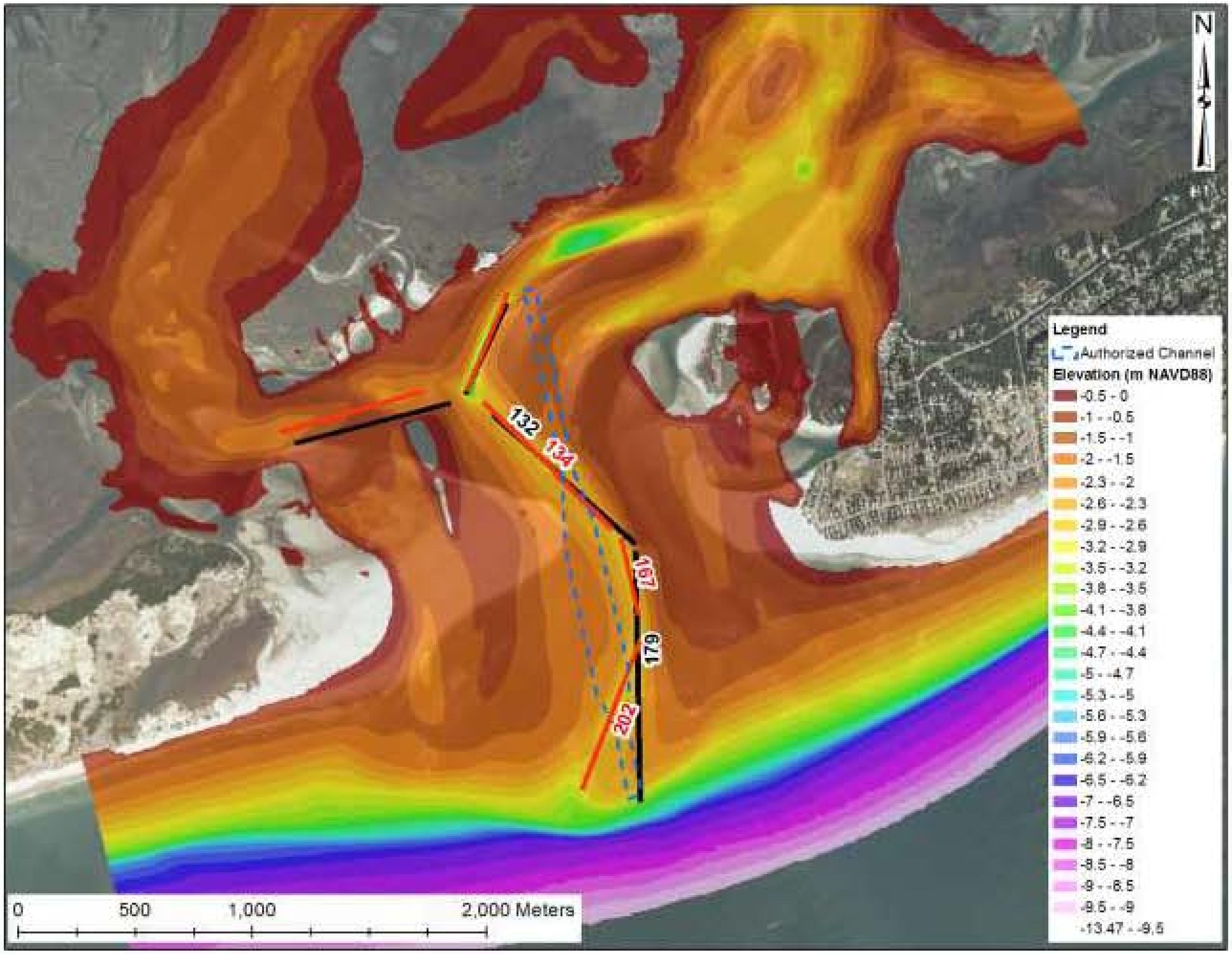


Figure 6-18: Bogue Inlet Local Model – Case 4, Simulation A – Resulting Morphology

Figure 6-19: Bogue Inlet Local Model – Case 4, Simulation A – Resulting Morphology Over 2010 NAIP Image

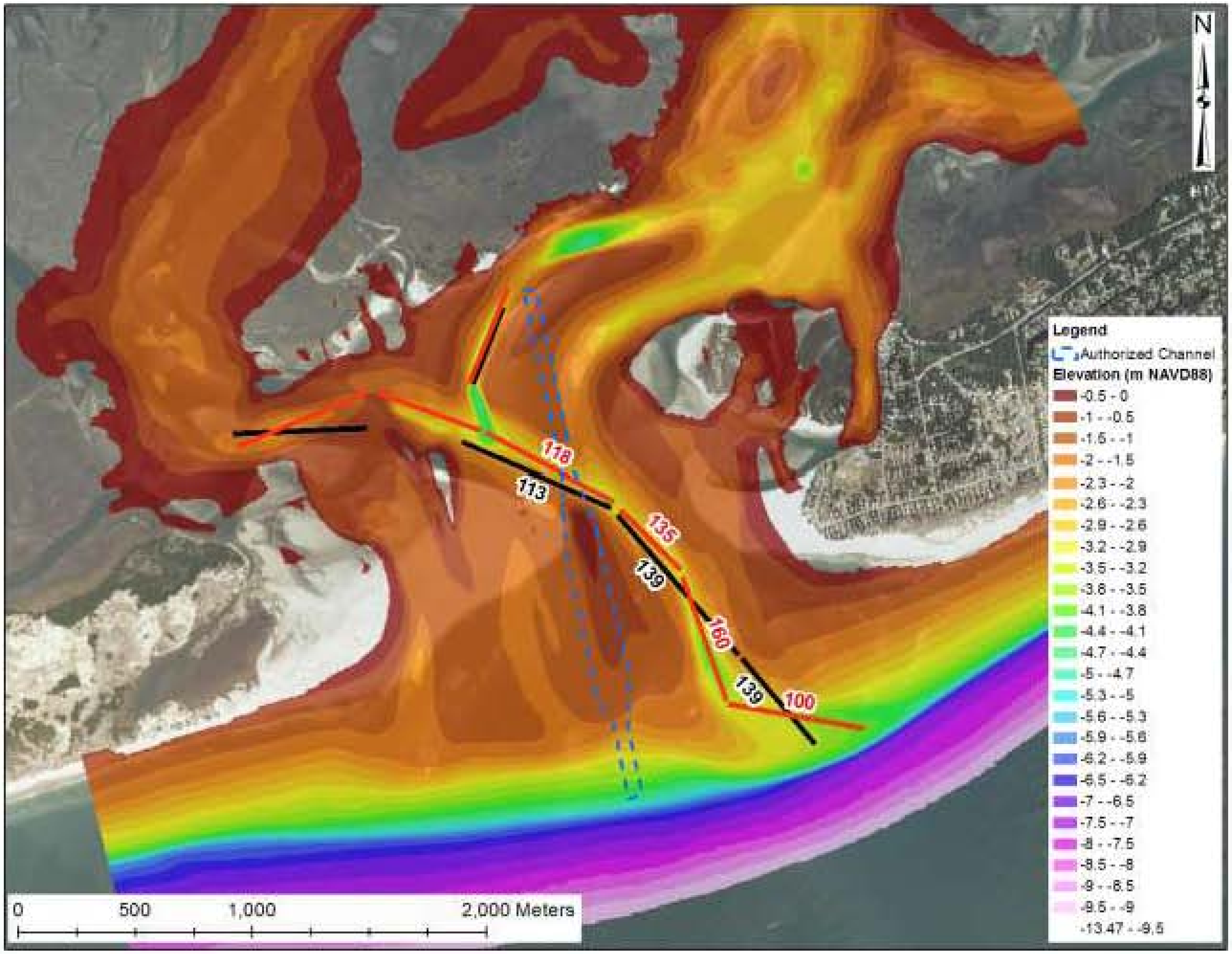


Figure 6-20: Bogue Inlet Local Model – Case 5, Simulation A – Resulting Morphology

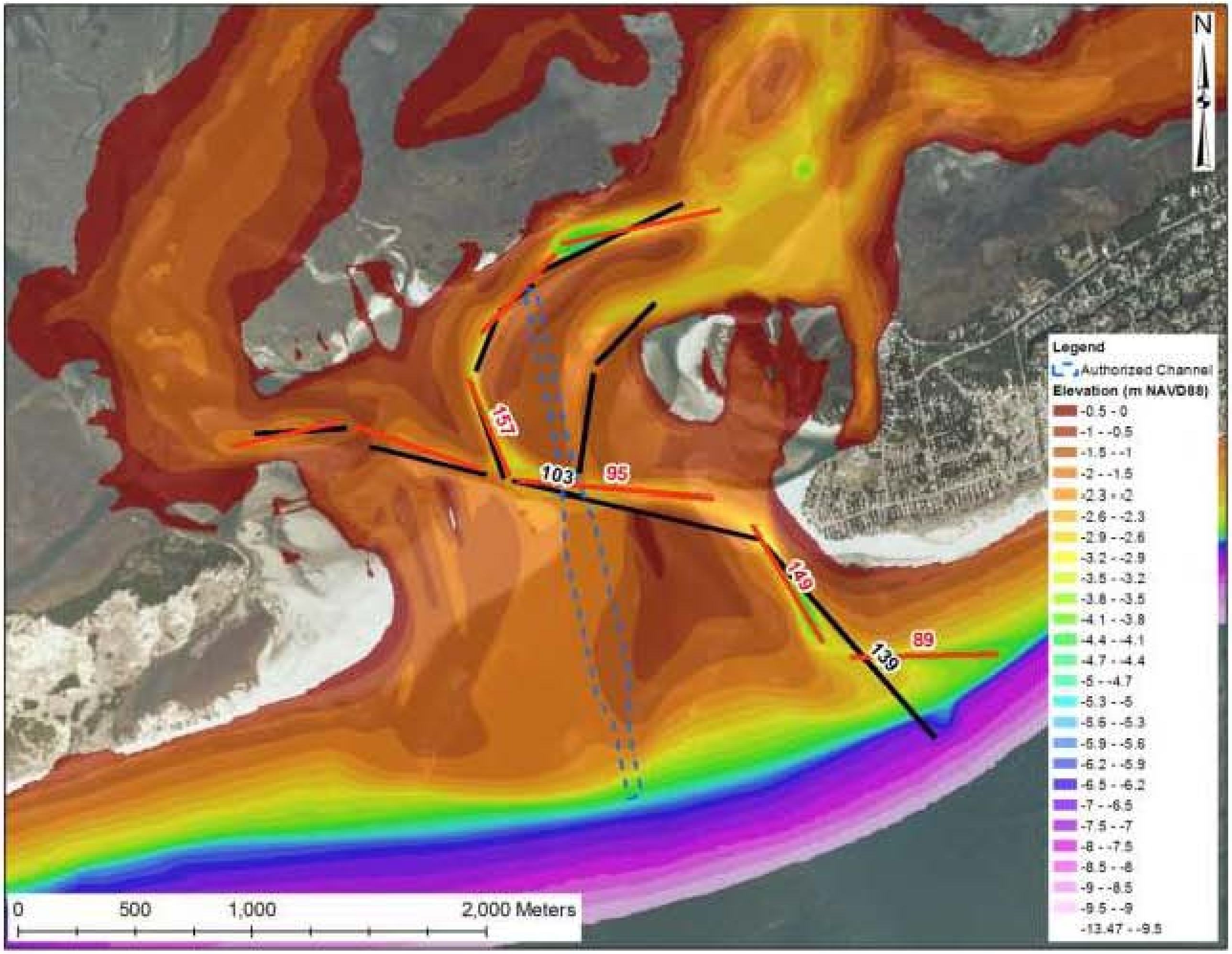


Figure 6-21: Bogue Inlet Local Model – Case 6, Simulation A – Resulting Morphology

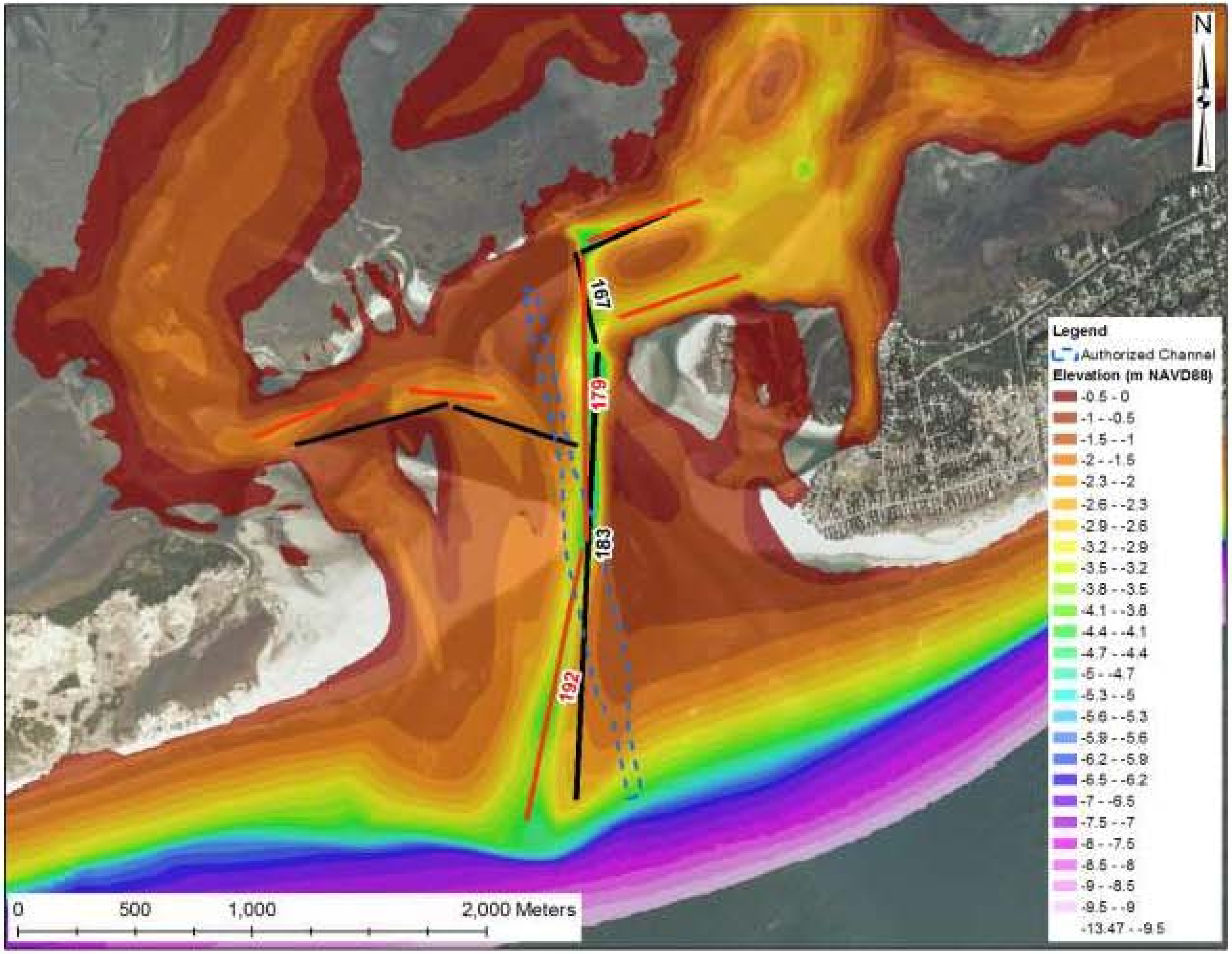


Figure 6-22: Bogue Inlet Local Model – Case 8, Simulation A – Resulting Morphology

Additional simulations (packages B, C, and D) were run as described in Section 6.6.1 for Case 4, Case 5, and Case 8. Simulation Package B was also run for Case 6.

Hurricane Ophelia was included as a as a "moderate" hurricane to see what effects such a storm might have on opening or closing flow ways through the inlet. Measured water levels (including surge) and measured waves were used at the offshore boundary of the regional model to generate local model conditions for Hurricane Ophelia; however, no additional discharges to the White Oak River or Bogue Sound associated with the hurricane were simulated, due to lack of available data.

Each successive simulation used the end bathymetry of the previous simulation as a starting point.

6.7.8 Case 4 – Additional Simulations

Figure 6-23, Figure 6-24, and Figure 6-25 illustrate the progressive changes in channel and shoal configuration for the additional Case 4 simulations. Starting from the end of Simulation Package A (Figure 6-18), the main channel migrated westward toward Bear Island and the width of the channel increased in Simulation Package B. The main channel straightened, the White Oak channel shoaled and rotated toward Dudley Island, as did the Bogue Sound channel. An incipient flood channel near Bear Island increased in width and length.

In simulated Hurricane Ophelia (Simulation Package C), the Case 4 main ebb channel moved further westward toward Bear Island and the depths increased in both the main ebb channel and the incipient flood channel. In Simulation Package D, following on from channel migration in simulation Packages B and C, the main ebb channel continued to straighten, depths continued to increase (becoming closer to the Authorized Channel depth of 5 m NAVD88), and the channel centerline moved slightly westward of the Authorized Channel envelope.

6.7.9 Case 5 – Additional Simulations

Figure 6-26, Figure 6-27, Figure 6-28 illustrate the progressive changes in channel and shoal configuration for the additional Case 5 simulations. The primary trend seen in all three additional simulations is the shoaling of the landward portions of the main ebb channel. The channel did not move consistently eastward or westward – instead the various legs of the channel rotated CW and CCW through the simulations. A second ebb channel appear to have begun to form in Simulation Package B, becoming wider during Hurricane Ophelia (Simulation Package C), and solidifying as a competing discharge path in Simulation Package C. The developing second channel is positioned several hundred feet westward of the centerline of the Authorized Channel.

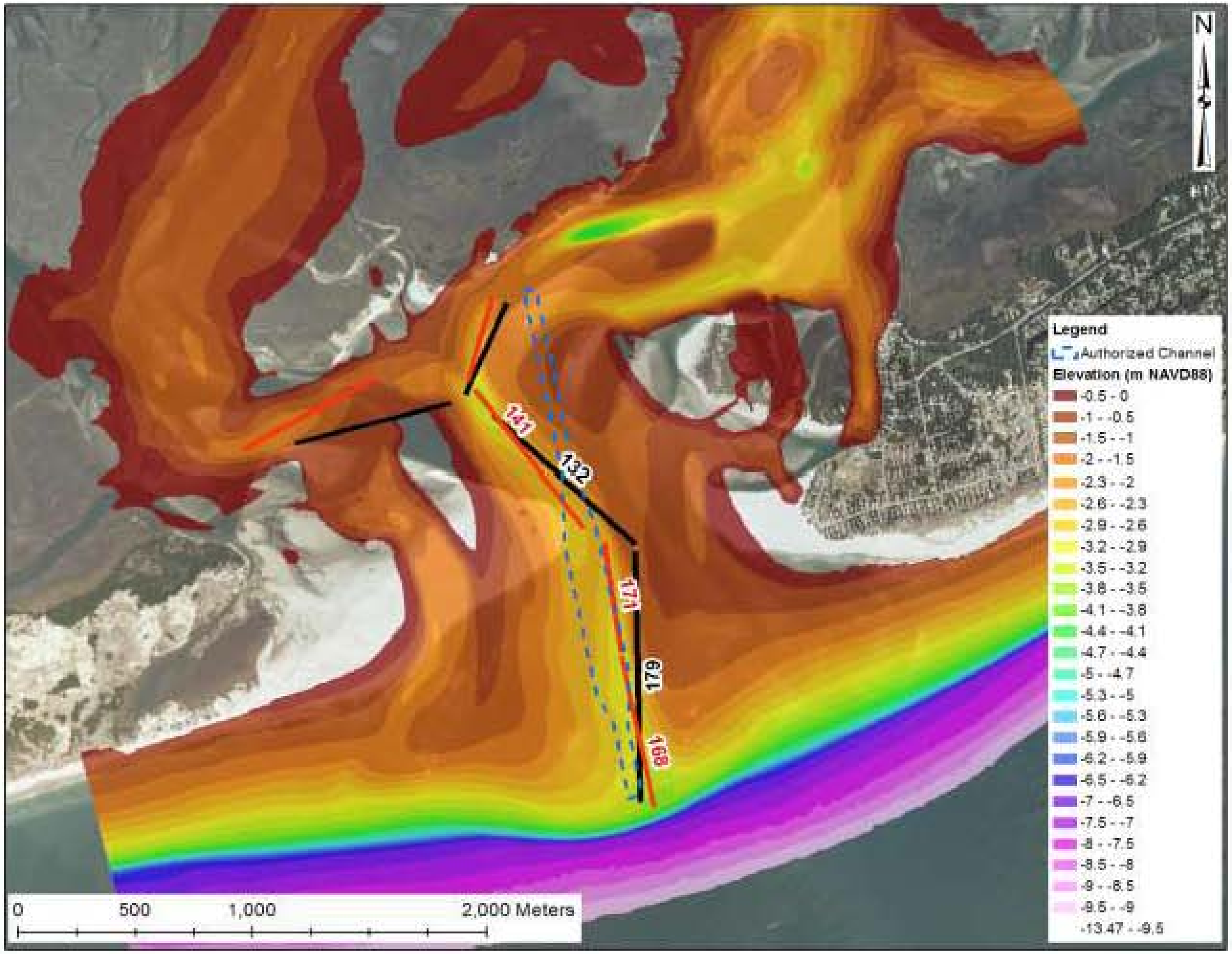


Figure 6-23: Bogue Inlet Local Model – Case 4, Simulation B – Resulting Morphology

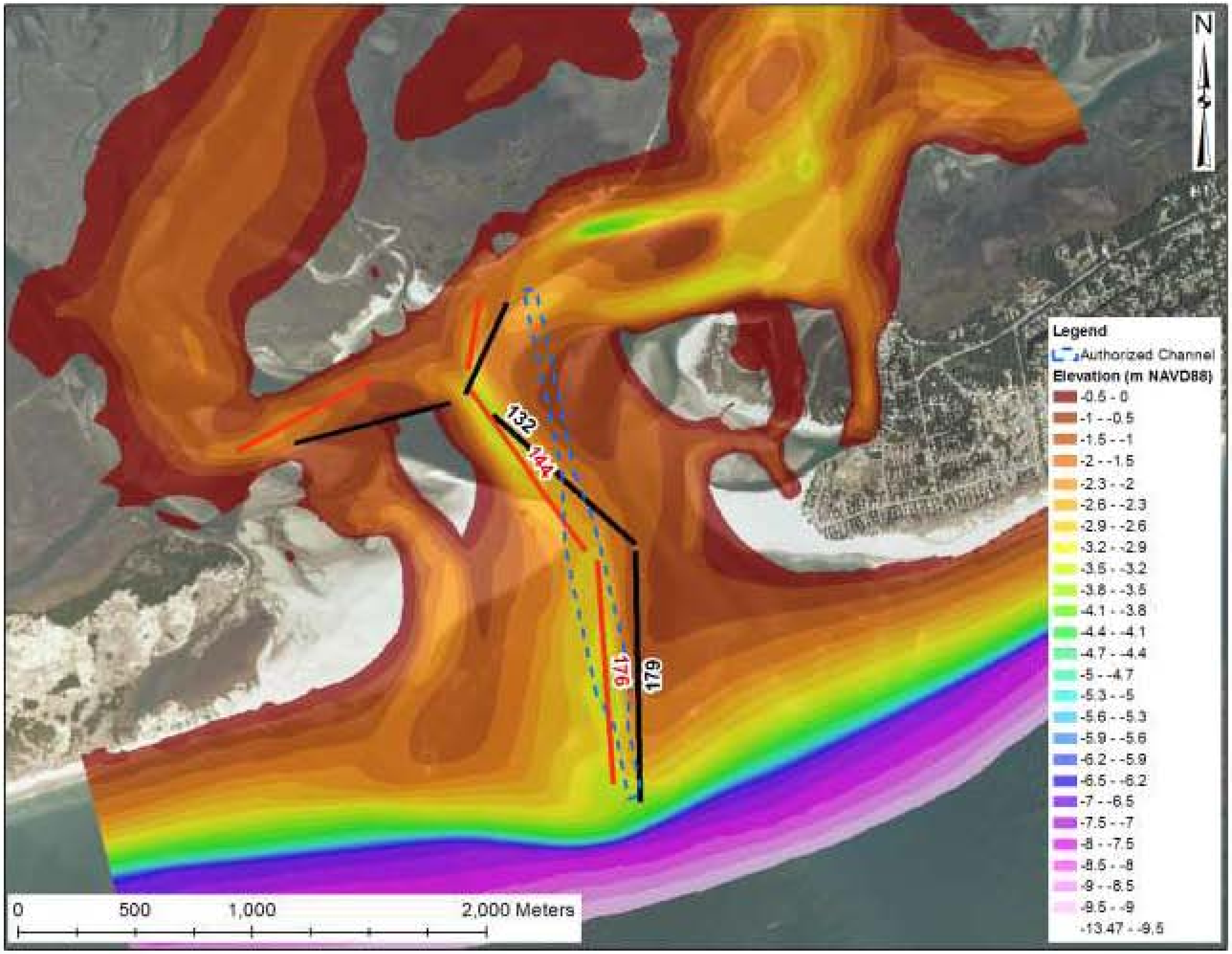


Figure 6-24: Bogue Inlet Local Model – Case 4, Simulation C (Hurricane Ophelia) – Resulting Morphology

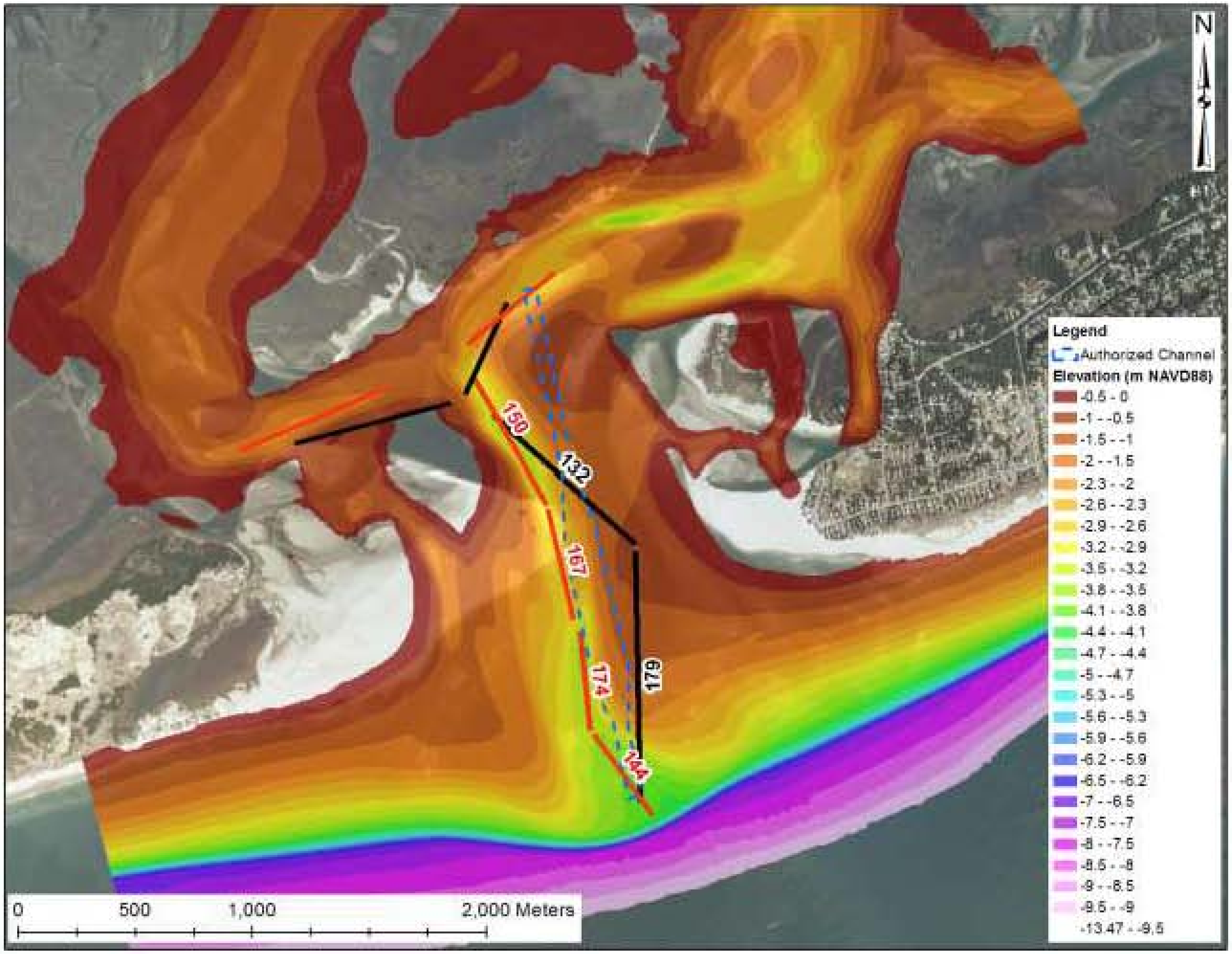


Figure 6-25: Bogue Inlet Local Model – Case 4, Simulation D – Resulting Morphology

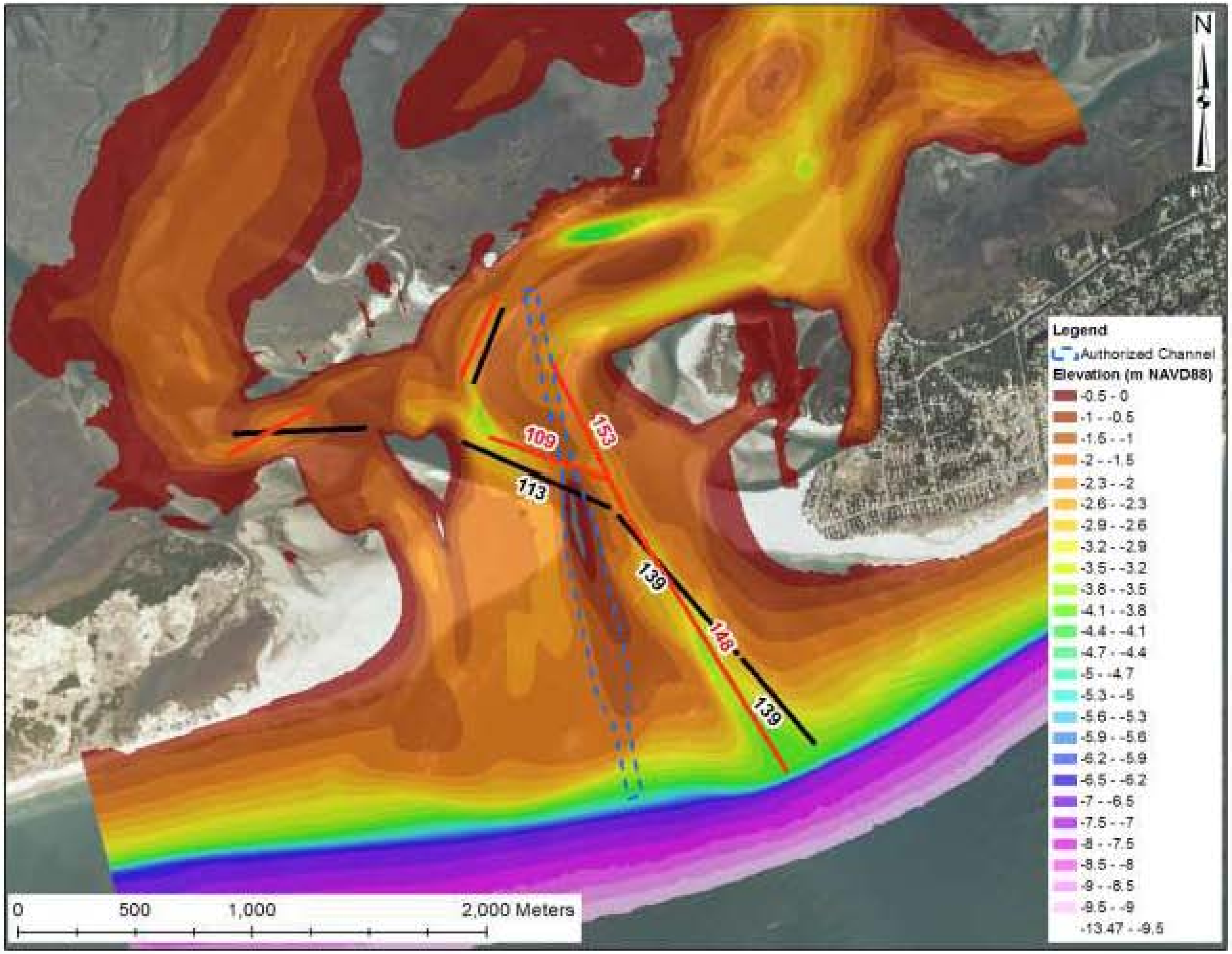


Figure 6-26: Bogue Inlet Local Model – Case 5, Simulation B – Resulting Morphology

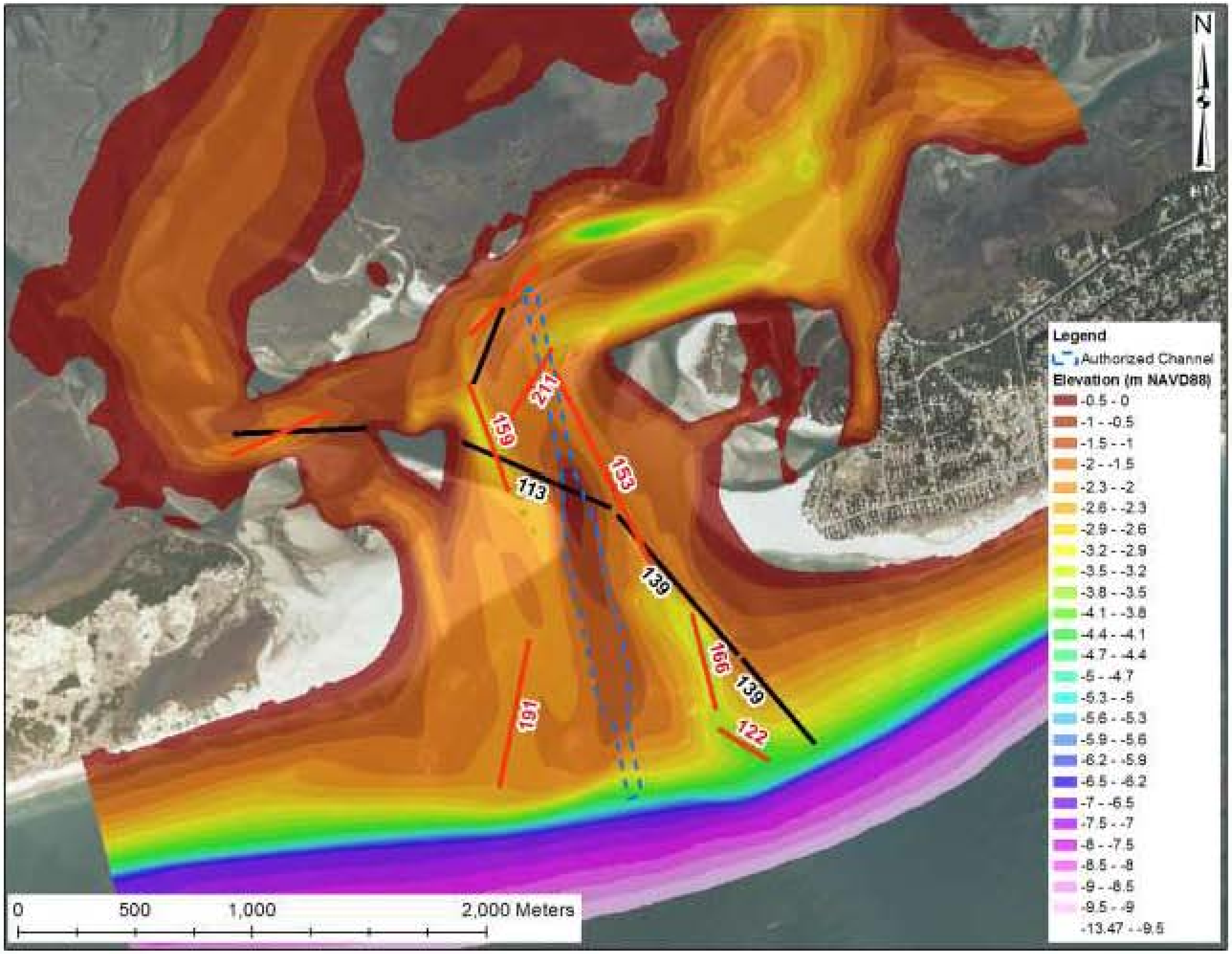


Figure 6-27: Bogue Inlet Local Model – Case 5, Simulation C (Hurricane Ophelia) – Resulting Morphology

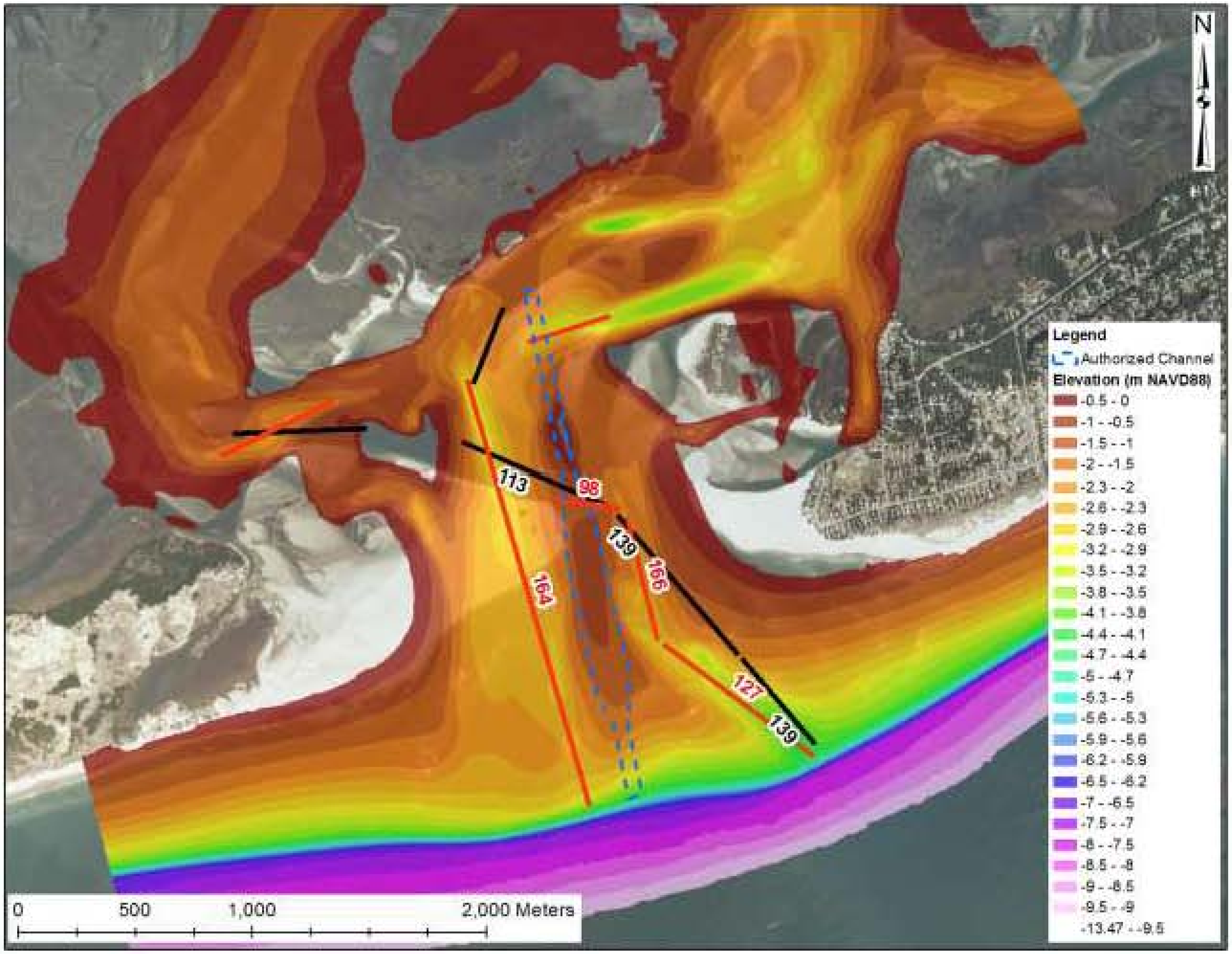


Figure 6-28: Bogue Inlet Local Model – Case 5, Simulation D – Resulting Morphology

6.7.10 Case 8 – Additional Simulations

Figure 6-29 illustrates the results from Case 8 Simulation Package B. The channel migrated slightly westward toward Bear Island without rotating significantly. Channel depths also did not change significantly from Simulation Package A. A shallow incipient channel on the western shoal (between the main channel and the White Oak River back channel) seen in Simulation A was further established. In Simulation Package D (Figure 6-31), the seaward channel reach both rotated CW and widened significantly, while the landward channel reach did not change in position or rotation. The channel depths in the middle reach grew shallower.

In Case 8, the channel reach migrated toward Bear Island and rotated CW. No portion of the channel migrated toward Bogue Banks. This may be due to the more efficient hydraulic connection with the Bogue Sound channel brought about by the CW skew of the main channel. A channel in this configuration appears to be slightly more stable in position than the Case 1 configuration representing the Authorized Channel.

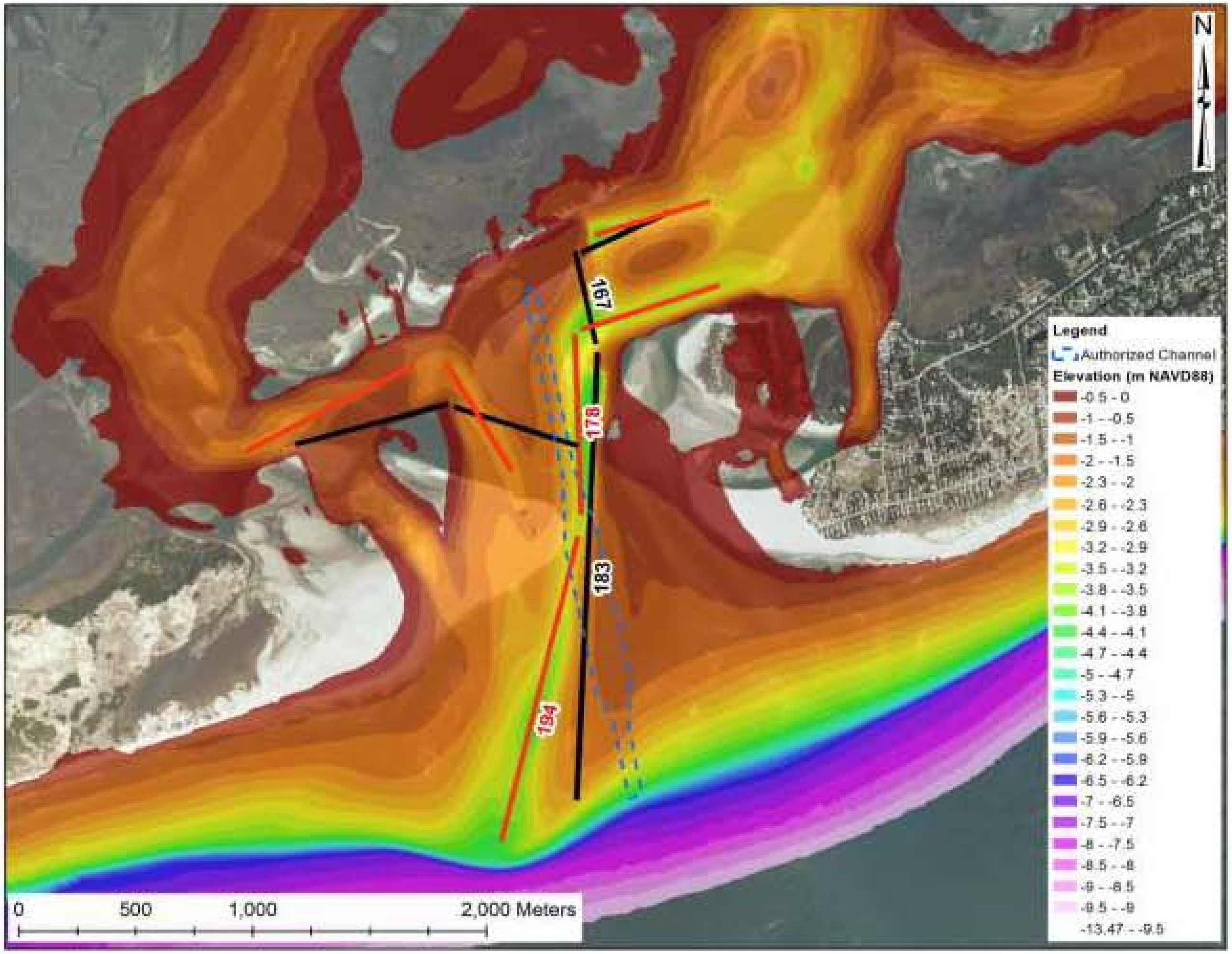


Figure 6-29: Bogue Inlet Local Model – Case 8, Simulation B – Resulting Morphology

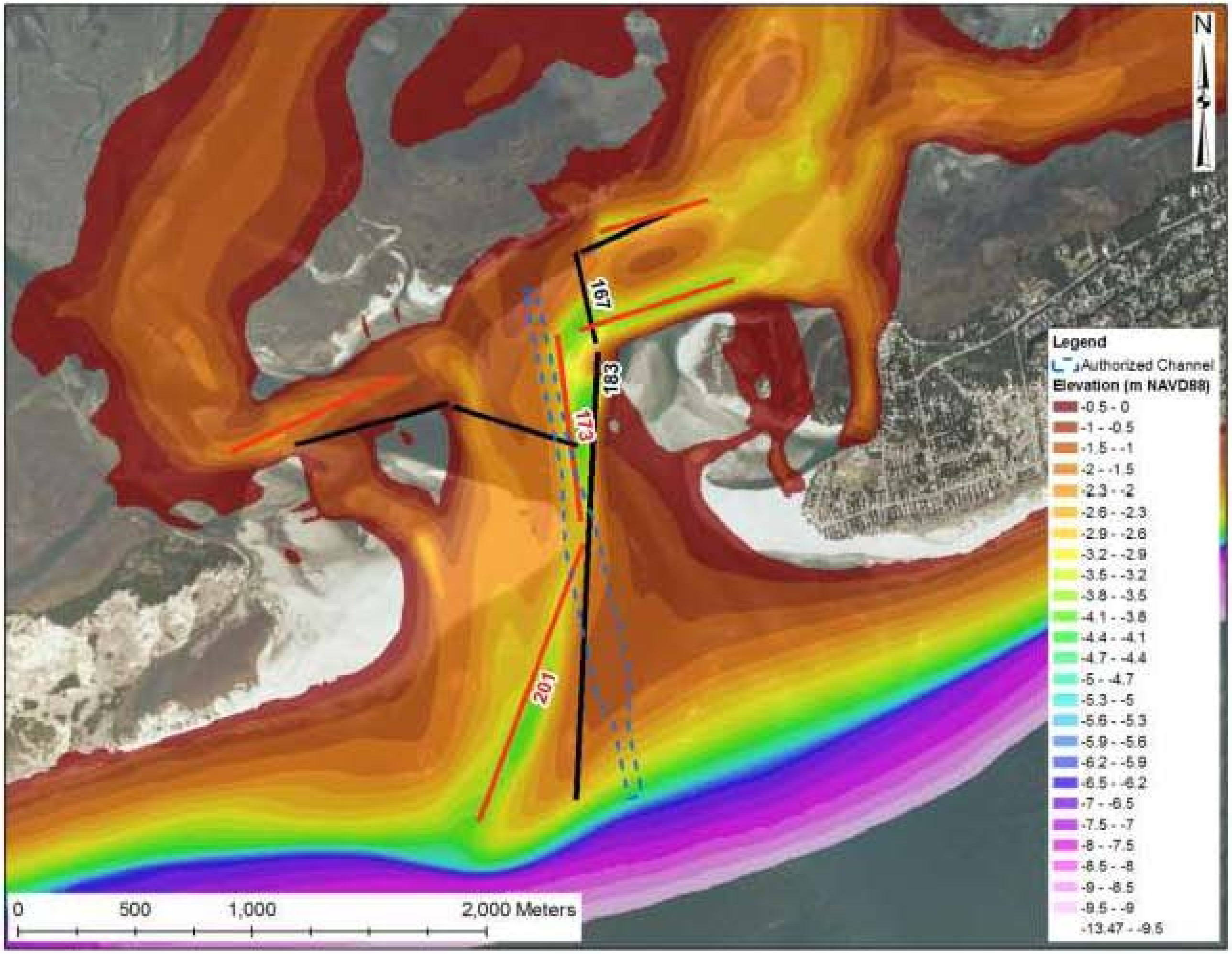


Figure 6-30: Bogue Inlet Local Model – Case 8, Simulation C (Hurricane Ophelia) – Resulting Morphology

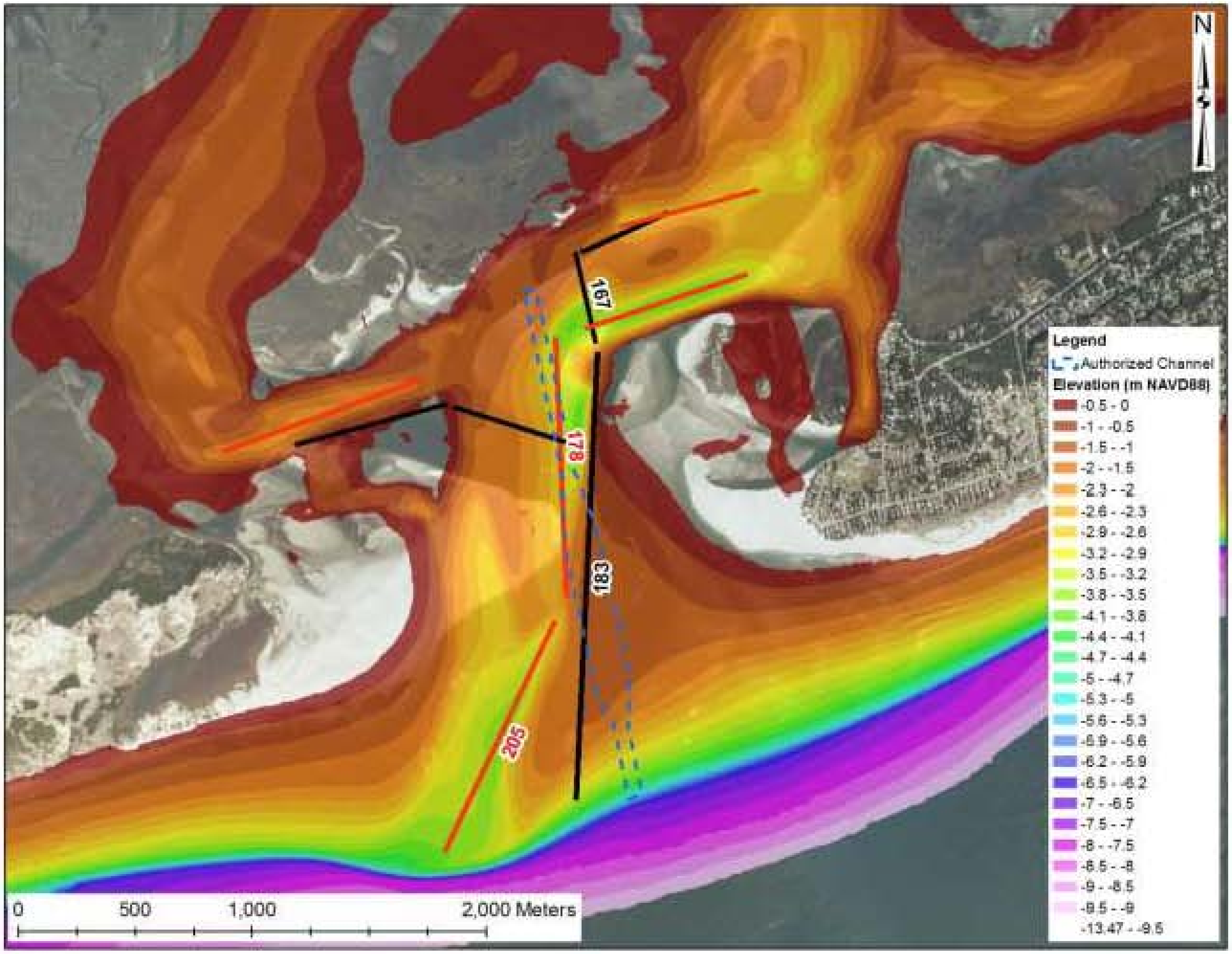


Figure 6-31: Bogue Inlet Local Model – Case 8, Simulation D – Resulting Morphology

6.8 Long-term Continuous Morphodynamic Simulation

The schematized inlet configuration simulations generally indicated that – starting from alignments significantly rotated from the approximately normal Authorized Channel configuration, with associated eastward shifts of the main channel lateral position – the channel would tend to migrate back toward the center of the inlet and rotate to a more normal alignment. Case 5 simulations indicated that, while the originally-specified main ebb channel did not itself migrate significantly westward, it would shoal and begin to lose hydraulic connection with the White Oak and Bogue Sound channels, and a second channel would form near the Authorized Channel.

This behavior appears to be counter to the behavior of the main channel as observed from historical imagery and surveys, in which the channel migrated quickly eastward beginning in 1987, with a significant CCW (Type 2) alignment, and then stayed in that alignment and position well eastward of the Authorized Channel area for more than 15 years. Limitations on the schematized model simulations include the limited real-world time period they cover and the absence of additional hydrodynamic processes such as additional discharges from the White Oak River.

A longer-term continuous simulation was conducted using astronomical tides and synchronous measured offshore waves for the time period August 2005 – August 2006. The model starting bathymetry was based directly on the 2005 multi-beam survey. A MORFAC =2 was applied to extend the effective simulations time to approximately two years, to allow comparison of the results with a 2007 aerial photo of the inlet. This simulation included the effects of H. Ophelia in September 2005.

Figure 6-32 shows the starting bathymetry of the continuous simulation, in the form of color contours over the 2007 aerial image. The Authorized Channel envelope is shown for reference.

Figure 6-33 shows the ending bathymetry from the 2005 – 2006 continuous simulation. Considering the MORFAC = 2 acceleration, it is reasonable to compare the ending bathymetry to the 2007 image. The model bathymetry contours indicate that the channel centerline migrated slightly to the west, and stayed within the bounds of the channel observable from the aerial image. The seaward portion of the channel widened and rotated CW, and the contours align very well with the channel exit seen on the aerial.

The remnant channel along the shoreline of Bogue Banks (left in place during the 2005 relocation) shoaled significantly. This feature is seen in the aerial, and it also echoes the behavior seen in the Case 5 schematic simulation.

This long-term continuous simulation from 2005 – 2006, with accelerated morphology updating, indicated reasonable matching with observed shoals and channels. Thought it is not practical to run the various model Cases for year-long or multi-year continuous simulation periods, the general success of this long-term simulation adds confidence to the use of the schematized model results for the present limited purposes.

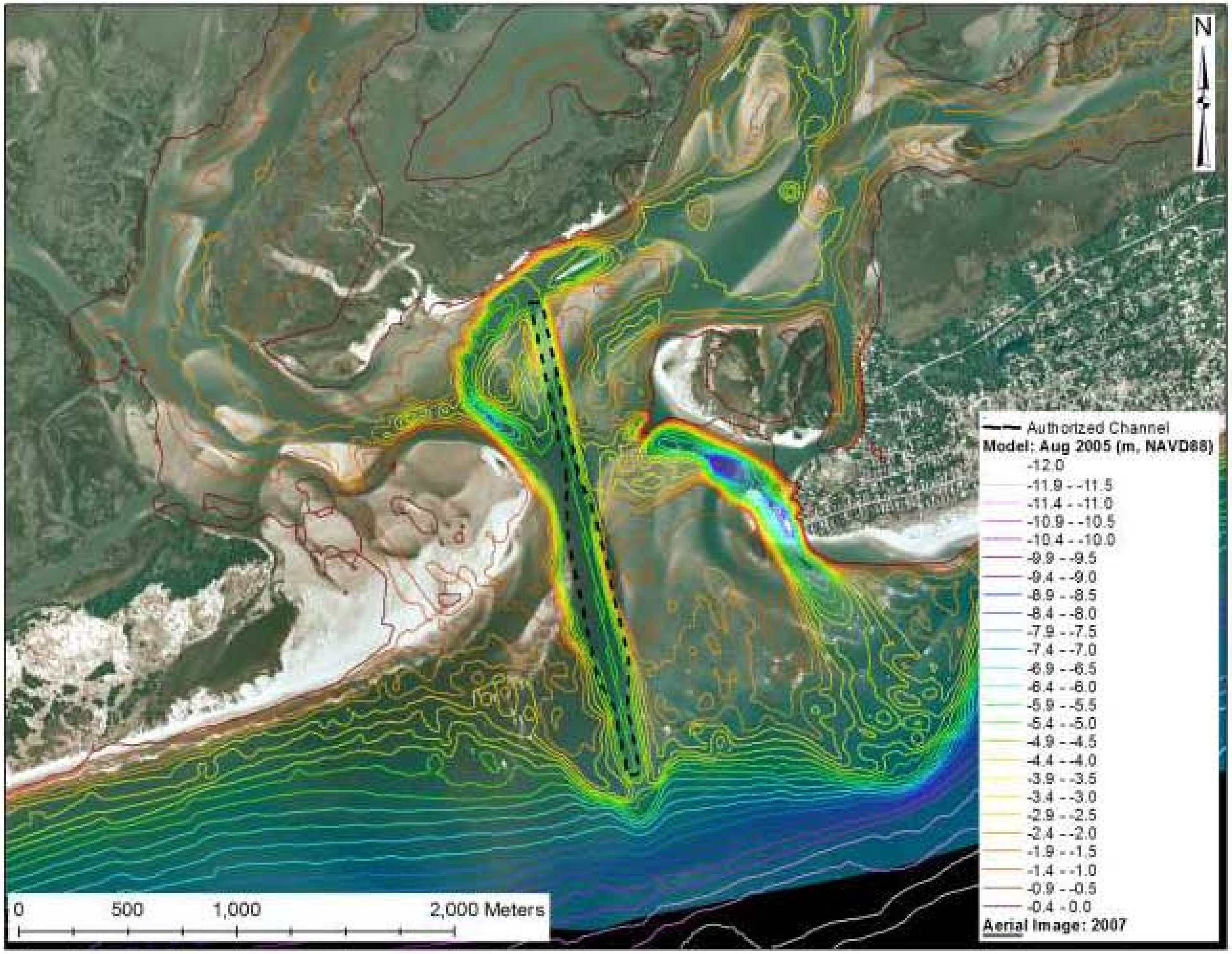


Figure 6-32: Bogue Inlet Local Model 2005-2006 Simulation Starting Bathymetry (Based on 2005 Survey)

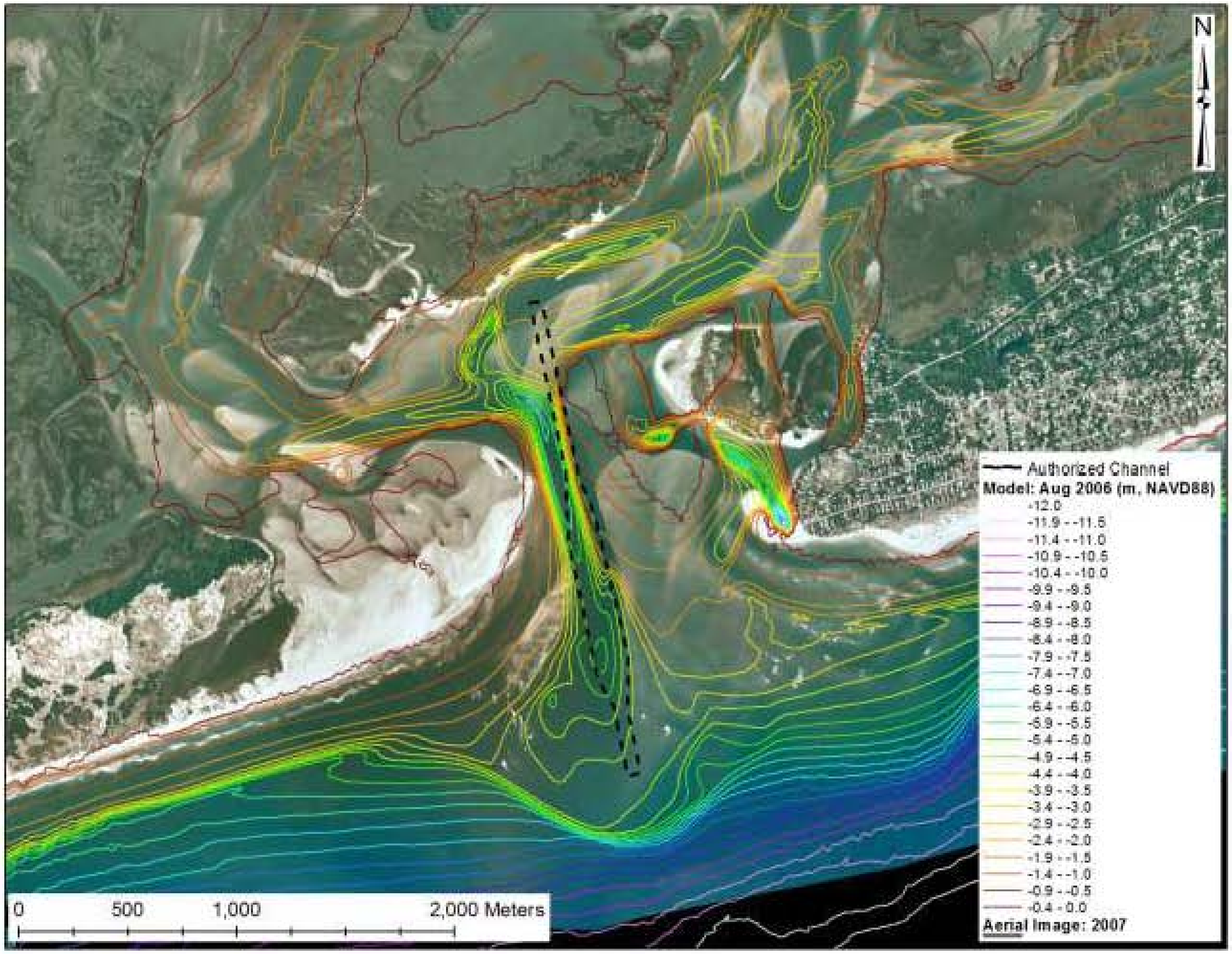


Figure 6-33: Bogue Inlet Local Model 2005-2006 Simulation Morphology Over 2007 Aerial Image

6.9 Additional Test Simulations of River Discharge and Back Channel Connection

The apparent disagreement between recent observed inlet channel migration and the model results for Case 4 indicated that some real-world physical processes are not represented thoroughly in the numerical model simulations. The schematized model configurations are limited in the real-world time period they cover and in the available secondary boundary conditions (such as absence of information on discharges from the White Oak River).

The long-term simulation indicated that the model is able to approximate observed morphology trends when run over a specific historical time period. Additional tests were done with the model by separately:

- adding large discharges into the White Oak River (for starting conditions based on Case 5)
- changing the angle of the connection between the main channel and the White Oak back channel (for starting conditions based on Case 5)
- closing off the connection between the main channel and the White Oak back channel (for Case 4 and Case 5)

None of these incremental changes to Case 4 or Case 5 inlet configurations produced meaningfully different morphology results. The results are presented below as a matter of documentation.

6.9.1 Increased White Oak River discharge

It was speculated that the addition of discharges from the White Oak River (north of Dudley Island) may influence the model to cause the inlet's ebb channel to shift. To that end, a high to extreme river discharge was assumed to have a value of approximately 200 cubic meters per second (7,063 cubic feet per second). This estimate was informed by values published in the July 2, 2004 effective FEMA Flood Insurance Study for Carteret County and Incorporated Areas. Case 6 Simulation Packages A and B were run again with this high discharge from the White Oak river added as a boundary condition. Simulation Packages A and B (Figure 6-35 and Figure 6-36) did not indicate any significant changes in the model resulting morphology with respect to the original Case 6 without river discharges. Very minor variations are noted, mainly that the connection of the White Oak back channel to the main ebb channel is slightly more defined and the incipient center channel forms slightly shallower with the river discharge than without it.

6.9.2 White Oak back channel connection angle with river discharge

Case 7 is the identical to Case 6 with the White Oak River discharge, except that in Case 7 the angle of the White Oak back channel is rotated several degrees CW. Case 7 results for Simulation Package A is presented in Figure 6-37. No significant variations from Case 6, either with or without the river discharge, were noted.

6.9.3 Closing off White Oak back channel connection

It was also speculated that closing the While Oak channel to restrict flow from the western side of Dudley Island, and forcing more flow around the eastern side of Dudley Island through the Bogue Sound channel, may influence the model to cause the inlet's ebb channel orientation or location to shift. Simulation Package A was run on Cases 41 and 51 (based on original Cases 4 and 5, respectively), where the ebb channel was not initially connected to the White Oak (western) back channel. No significant variations from Case 4 and Case 5 were noted.

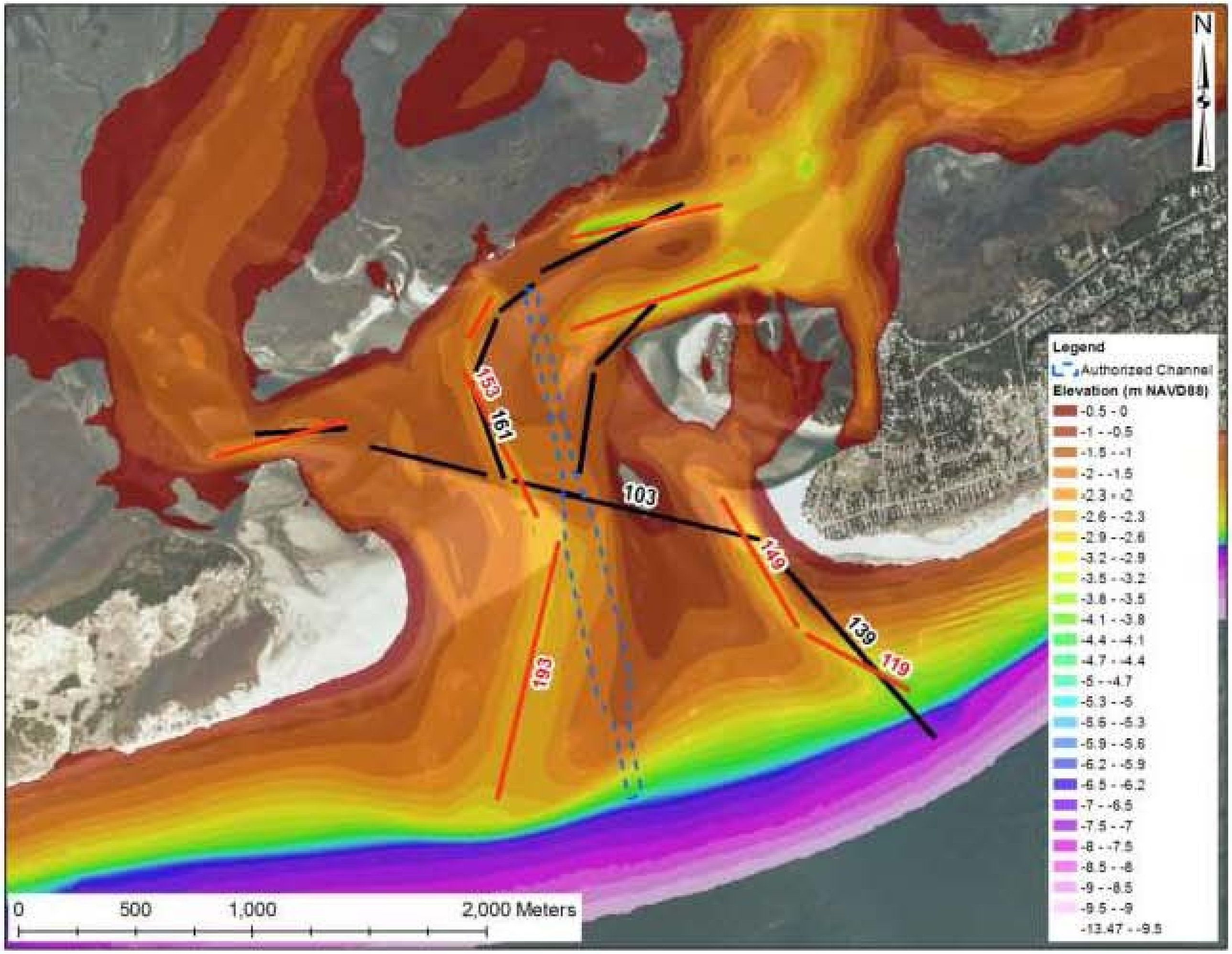


Figure 6-34: Bogue Inlet Local Model – Case 6, Simulation B – Resulting Morphology

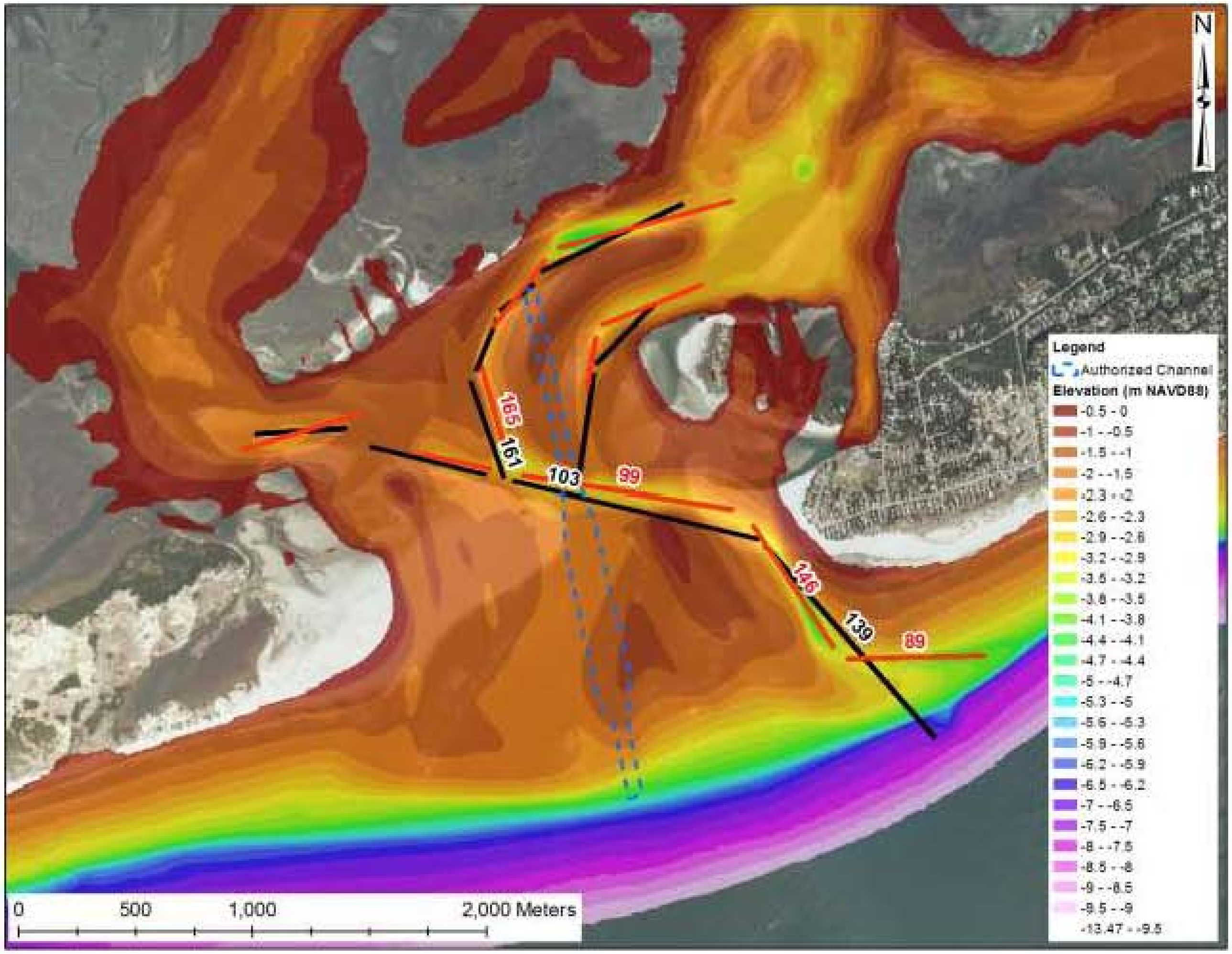


Figure 6-35: Bogue Inlet Local Model – Case 6, Simulation A, with White Oak River Discharge – Resulting Morphology

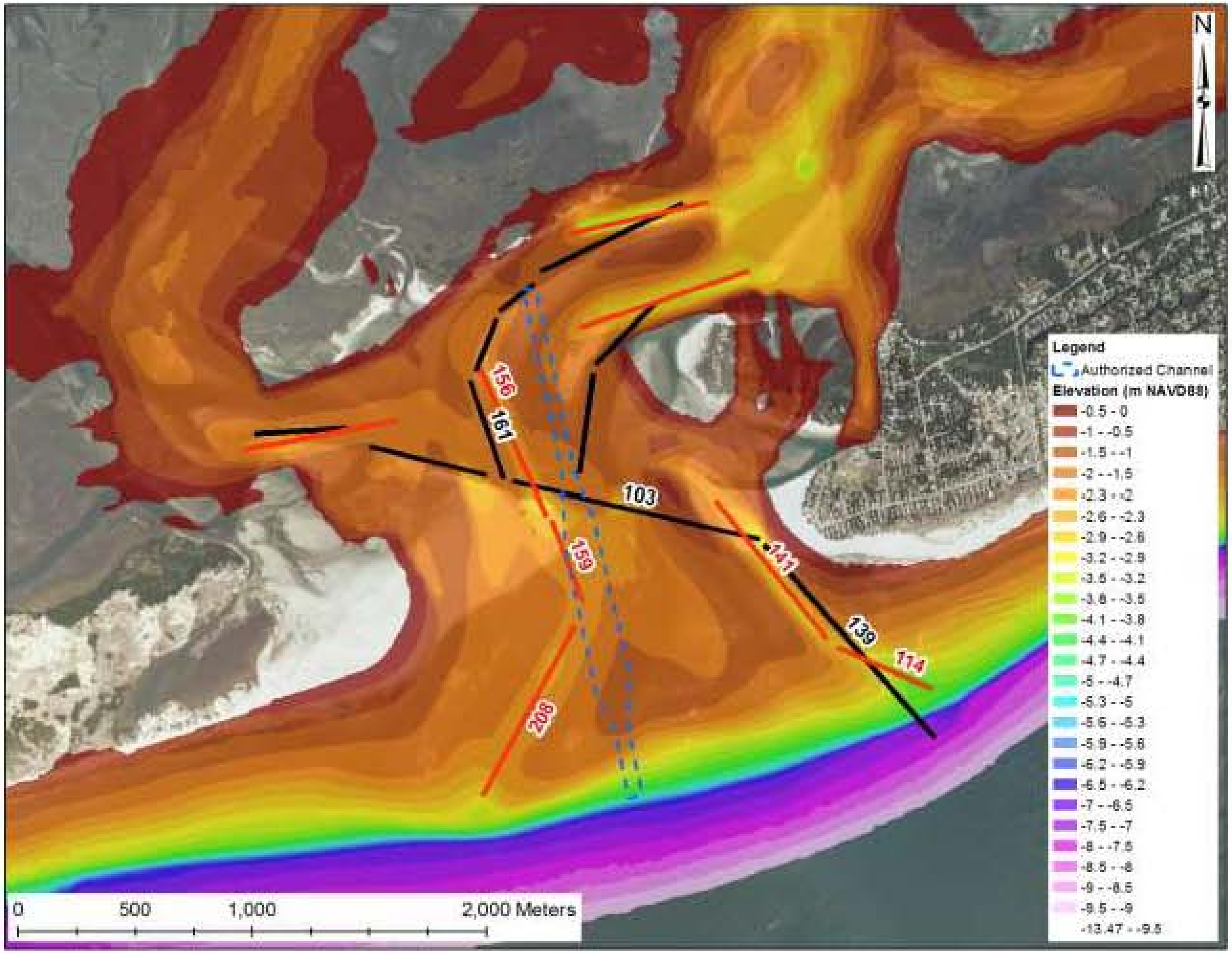


Figure 6-36: Bogue Inlet Local Model – Case 6, Simulation B, with White Oak River Discharge – Resulting Morphology

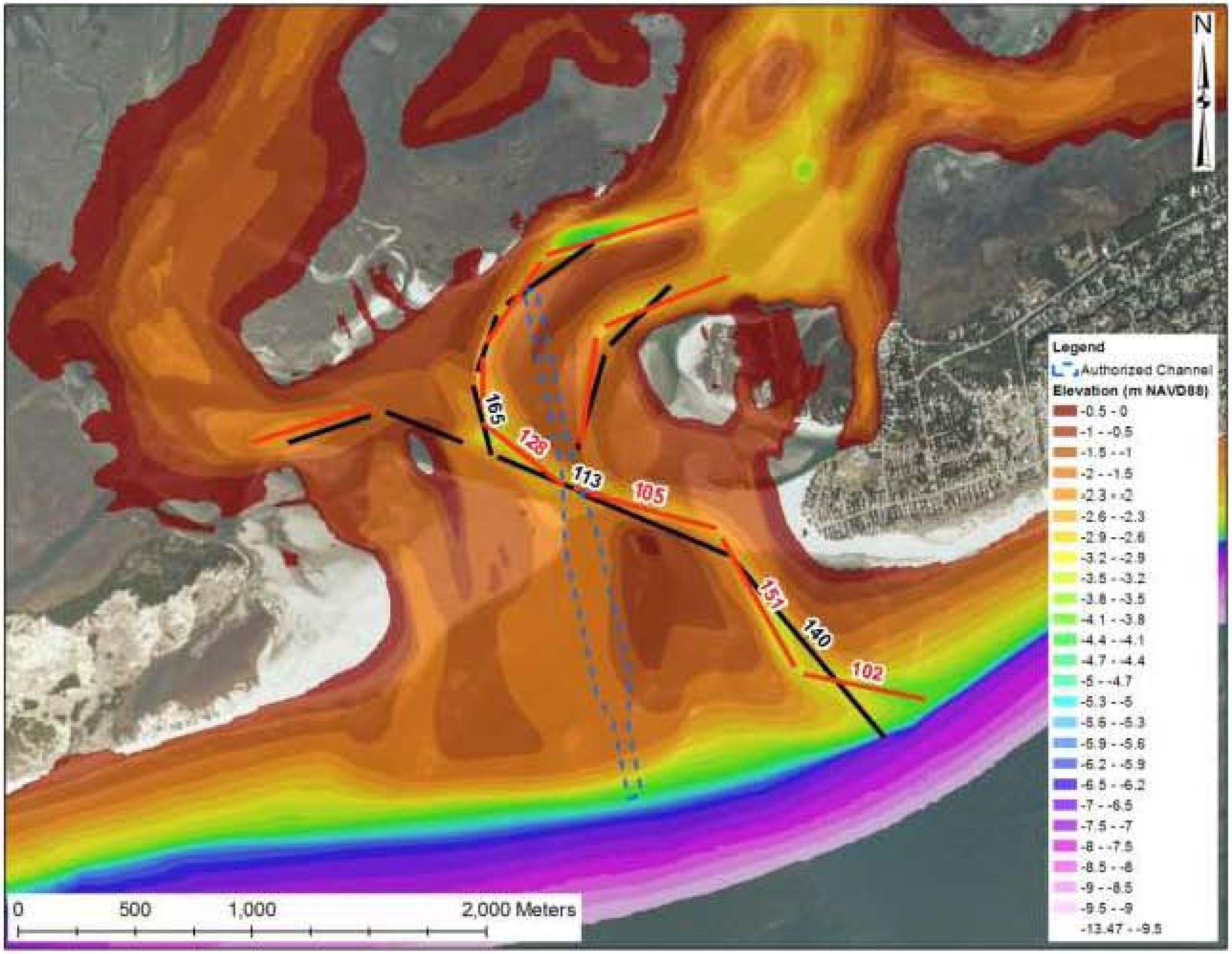


Figure 6-37: Bogue Inlet Local Model – Case 7, Simulation A, with White Oak River Discharge – Resulting Morphology

7.0 STATISTICAL EXTREME STORM WAVES AND WATER LEVELS

A series of six synthetic storm data sets were developed for use in SBEACH simulations. SBEACH requires time-varying total water levels (tide + storm surge), significant wave heights, and wave periods, and an indication of the depth of water in which the wave conditions are specified.

7.1 Extreme Water Levels

Extreme coastal water levels for each of the six “return period” synthetic storms were developed through extreme value analysis (EVA) of historical tide data at the Atlantic Beach Triple-S Pier (NOAA #8656590) and at Beaufort (NOAA #8656483). The available data period at the Atlantic Beach station is relatively short with large gaps, and it was necessary to extend the record of water level data available for analysis by transferring additional years of record from the Beaufort station to an equivalent open coast location. The measured tide data (including surges) was compared for an overlapping time period October 1998 – May 2000 between the Atlantic Beach and Beaufort tide stations. A relationship between peak measured water levels was found such that the peak total water level at Atlantic Beach was, on average, 1.2 times the peak at Beaufort.

Figure 7-1 illustrates the ratio between peak water levels at Atlantic Beach and Beaufort tide stations. The x-axis is the NOAA tide level at Atlantic Beach, and the y-axis is the computed peak ratio (Atlantic Beach level) / (Beaufort level). The red markers are a subset of the full data set, indicating just those data points representing a significant surge peak. While the peak ratios show significant scatter for the full dataset (black markers, standard deviation = 0.13), the surge peaks are more tightly distributed between 1.1 to 1.3 (red markers, standard deviation = 0.06).

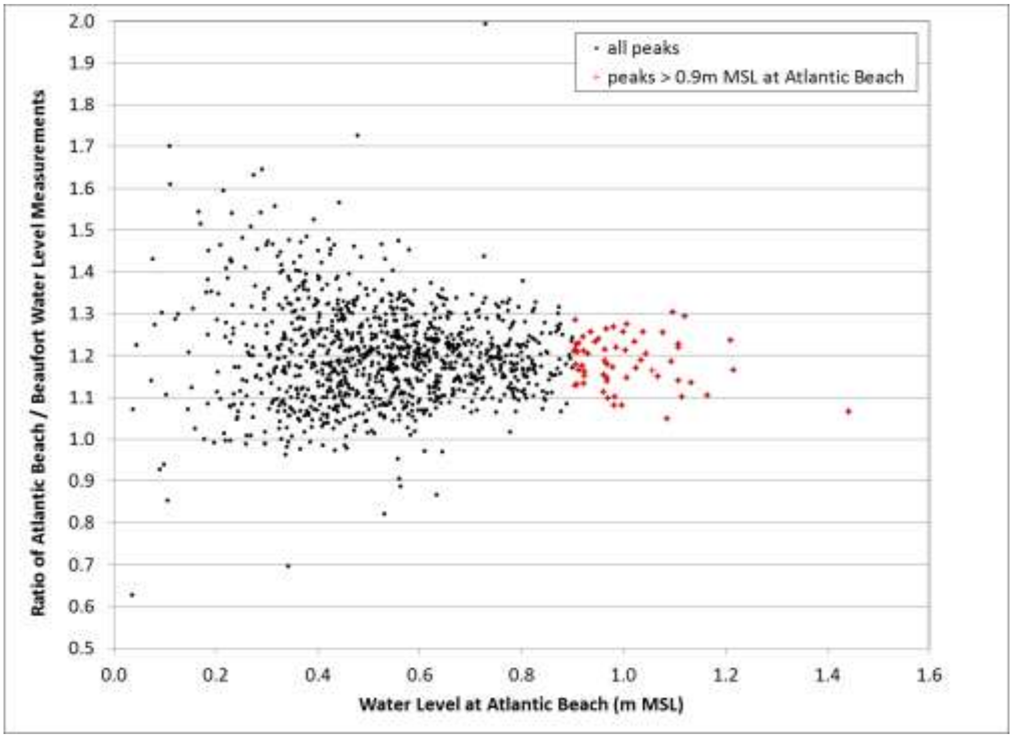


Figure 7-1: Ratio Between Total Water Levels at Atlantic Beach and Beaufort

A total water level EVA was conducted on data at Atlantic Beach, using the Beaufort data scaled up by the ratio of 1.20 to fill gaps in and extend the record. The Atlantic Beach data covered January 1977 – June 2000, with major gaps from December 1983 – October 1998. Scaled Beaufort data were used to fill from December 1995 – October 1998 and to extend from July 2000 – April 2012. A 12-year long gap remained in the combined record from December 1983 – November 1995.

The identified peak water levels (approximately two peaks per day) at Beaufort from years 1977 through 2012 were multiplied by 1.2 to more accurately represent open-coast water levels (based on the computed ratio of the Atlantic Beach tide gage to the Beaufort tide gage), and these peaks were subjected to EVA to estimate peak total water levels at various return periods. The EVA used a peaks-over-threshold approach for peaks above +3.61 ft MSL (+3.13 ft NAVD88) at Atlantic Beach, with a 96 hour (4 day) time window to exclude multiple peaks from the same storm event. The best statistical fit for extreme value estimates was achieved using a Weibull distribution with shape factor k = 0.9 (r^2 = 0.993). Extreme water levels estimated in this way are given in Table 7-1.

Table 7-1: Extreme (High) Total Water Levels for Open Coast Bogue Banks

Return Period	Synthetic Storm Number	EVA on Measured Tide Data (feet NAVD88)	FEMA FIS, Table 13 Summary of Coastal Analyses (feet NAVD88)
100-year	1	6.4	11.6* (9.5 without wave setup)*
50-year	2	6.0	8.0
25-year	3	5.6	-
10-year	4	5.4	4.6
5-year	5	4.8	-
2-year	6	4.4	-

Note: Yellow highlighted values were used in this analysis
The "*" indicates addition of 2.1 ft of wave setup

Extreme water levels for high return periods (50-year and 100-year) were based on values for several locations along the Carteret County Atlantic Ocean oceanfront in Table 13 Summary of Coastal Analyses in the 2004 effective FEMA FIS for Carteret County. All other values used in the SBEACH storm development are based on the EVA described above. Values used for this analysis are highlighted in yellow in Table 7-1. It is important to note that the 100-year return period FEMA stillwater elevations include an allowance for 2.1 feet* of wave setup. Because SBEACH includes its own internal calculations of wave setup, this 2.1 feet of wave setup was removed from the published 100-year return period stillwater elevation before developing SBEACH inputs.

7.2 Extreme Wave Heights

Peak offshore significant wave heights for each of the six synthetic storms were developed through EVA of historical wave data at USACE Wave Information System (WIS) station #63287 (downloaded May 2012 from website http://wis.usace.army.mil/.). This WIS hindcast station is located in the vicinity of NDBC buoy #41036 (Onslow Bay Outer) and in a similar water depth (95 ft), and it covers 20 years from 1980 – 1999. Extreme values were available as calculated by the USACE WIS program, and these are shown in Table 7-2, third column from left. An independent EVA was conducted on the WIS time series data to confirm and/or revise the WIS-estimated values. The EVA was used a peaks-over-threshold approach for peaks above H_{m0} = 4.5 feet, with a 96 hour (4 day) time window to ensure independent storm events were utilized. The best statistical fit for extreme value estimates was achieved using a Weibull distribution with shape factor k = 0.7 (χ^2 = 4.476). Extreme significant wave heights estimated in this way are given in Table 7-2, fourth column from left. Values used for this analysis are highlighted in yellow in Table 7-2.

An EVA was also conducted on the available record of data at NDBC buoy #41036. Because of the relative shortness of the time series at this station, this EVA was conducted only for comparison purposes with the WIS data EVA. EVA values from the buoy #41036 data set are generally lower at each return period than the WIS data set EVA values, as expected due to the limited time period of data at #41036.

Table 7-2: Extreme Wave Heights Offshore of Bogue Banks

Return Period	Synthetic Storm Number	WIS at WIS 63287 (depth=95 ft)	M&N at WIS 63287 (depth=95 ft)	M&N at NDBC 41036 (depth=98 ft)
100-year	1	50.4	51.0	41.3
50-year	2	45.3	44.6	37.1
25-year	3	40.1	38.6	33.1
10-year	4	33.3	31.2	28.2
5-year	5	28.1	26.2	24.8
2-year	6	21.3	20.5	20.9

Note: Yellow highlighted values were used in this analysis

7.3 Historical Storms Time Series Analysis

Simple extreme peak water levels and peak wave heights are not sufficient for providing input to SBEACH simulations. To simulate the effects on beach profile evolution occurring at different points in a "typical" hurricane or similar storm, a time series of rising and falling water levels and wave heights is needed. The following approach was taken to develop the necessary storm wave height, period, direction, and water level time series for SBEACH.

Water levels (from NOAA Atlantic Beach and NOAA Beaufort, scaled) and wave heights (from NDBC buoy #41036 Onslow Bay Outer and Atlantic WIS #63287) were extracted for a set of 11 historical hurricanes, tropical storms, and nor'easters that affected the project area. Hurricane Isabel (2003) and Hurricane Ophelia (2005) were excluded due to lack of available wave data of sufficient quality to support the analysis. The following storms were included in the analysis:

- Josephine (1996)
- Bertha (1996)
- Fran (1996)
- Earl (1996)
- Bonnie (1998)
- Floyd (1998)
- Irene (1999)
- Dennis (1999)
- Gabrielle (2007)
- Irene (2011)
- Nor'easter (2009)

The storm wave heights, wave periods, and water levels were plotted on a single chart by computing a new time axis for each storm based on hours before/after the storm's peak wave height – such that the storm peaks were aligned on the plot. The combined plots were then evaluated to assess a representative "shape" of the rising and falling waves and water levels and to develop a relationship between storm duration and storm intensity. Observations from this assessment include:

- Hurricane Fran (1996) had the highest peak H_s = 10.8 meters (35.4 ft), with Hurricane Bonnie (1996) very close at peak H_s = 10.5 meters (34.4 ft). Hurricane Fran's peak significant wave height falls between the wave heights estimated in the EVA for 10-year and 25-year return periods in Table 7-2.

- Hurricane Irene (2011) had the highest peak water level (+1.645 mMSL or +5.4 ftMSL), and Hurricane Fran had the next highest at +1.562 mMSL (+5.1 ftMSL) These values also fall between the total water levels estimated in the EVA for 10-year and 25-year return periods in Table 7-1.

- Hurricane Bonnie had a much longer time distribution (hours above a given wave height) than all of the other storms. Hurricane Fran's duration and its rising and falling leg "shapes" were more representative of the majority of the storms.

Storm rising and falling leg (wave height) durations and peak wave periods occurring during storms were found to be loosely correlated with storm peak significant wave height.

The duration of the storm was found to be related to the magnitude of the peak wave height. Linear best-fit regression equations were fit to the data in order to find a convenient relationship for specifying duration and "shape" of the synthetic design storms for SBEACH.

The relationship between peak wave period (T_p) and significant wave height (H_s) was investigated at both NDBC 41036 and WIS 63287. For the larger wave heights (H_s > 4m), the following power curve best-fit relationships were found:

NDBC 41036: $T_p = 3.2308\, H_s^{0.7203}$ ($r^2 = 0.2584$)

WIS 63287: $T_p = 5.3327\, H_s^{0.4318}$ ($r^2 = 0.2428$)

The extreme peak water levels, extreme peak significant wave heights, and relationships between peak wave height to storm rising / falling legs and peak wave periods were used together to synthesize design storm time series. Hurricane Fran was determined to be the most representative historical storm for use as a pattern to create the synthetic design storms. From comparison of the Hurricane Fran peak significant wave heights with the extreme wave height analysis, Hurricane Fran was between a 10-year and 25-year return period wave event at this location.

7.4 Wave Transformation to SBEACH Boundary Condition

The MIKE 21 SW model discussed in Chapter 5.0 was used to transform the synthetic design storms' time series of waves from the relatively deep water Atlantic WIS station #63287 to a nearshore position at Bogue Banks with a depth of approximately –40 ft NAVD88. The time series of storm waves and water levels for several of the synthetic design storms as input to SBEACH are shown in Figure 7-2 through Figure 7-5. Peak values of waves and water levels input to SBEACH are given in Table 7-3.

Table 7-3: Wave Height, Wave Period, and Total Water Level Input to SBEACH at Peak of Design Storm Simulations

Return Period	Synthetic Storm Number	Offshore H_{m0} feet (depth=95 ft)	Nearshore H_{m0} feet (depth=40 ft)	Nearshore T_P seconds (depth=40 ft)	Water Level feet NAVD88
100-year	1	51.0	21.0	12.8	9.5
50-year	2	44.6	19.5	12.0	8.0
25-year	3	38.6	18.5	11.4	5.6
10-year	4	31.2	17.8	10.9	5.4
5-year	5	26.2	16.6	10.4	4.8
2-year	6	20.5	14.2	9.8	4.4

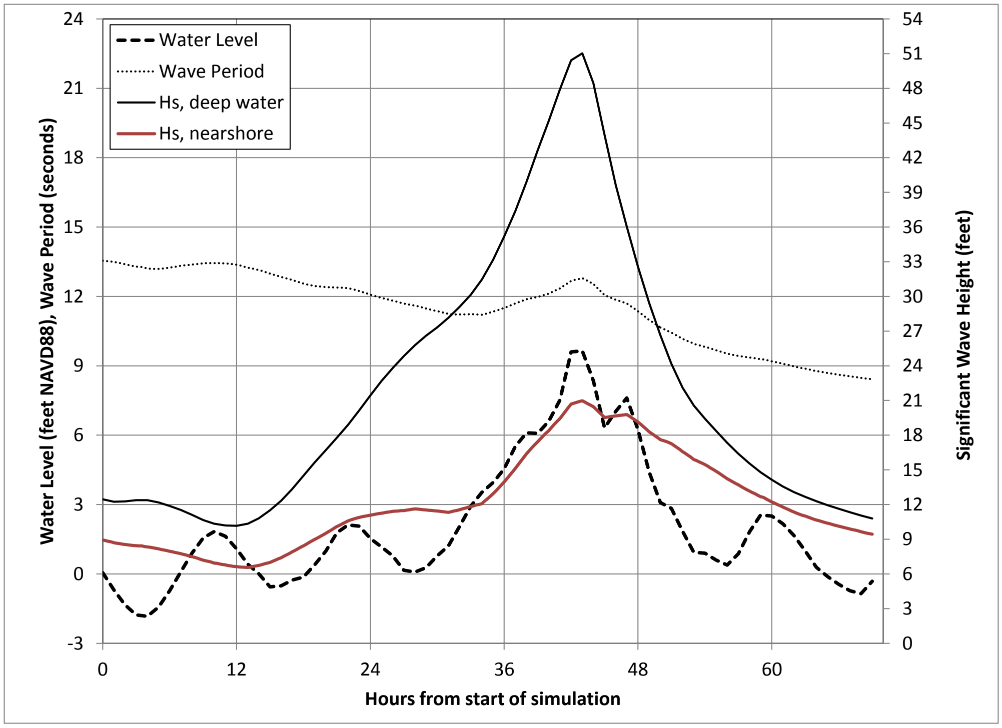


Figure 7-2: SBEACH Input Waves and Water Level, 100-yr RP

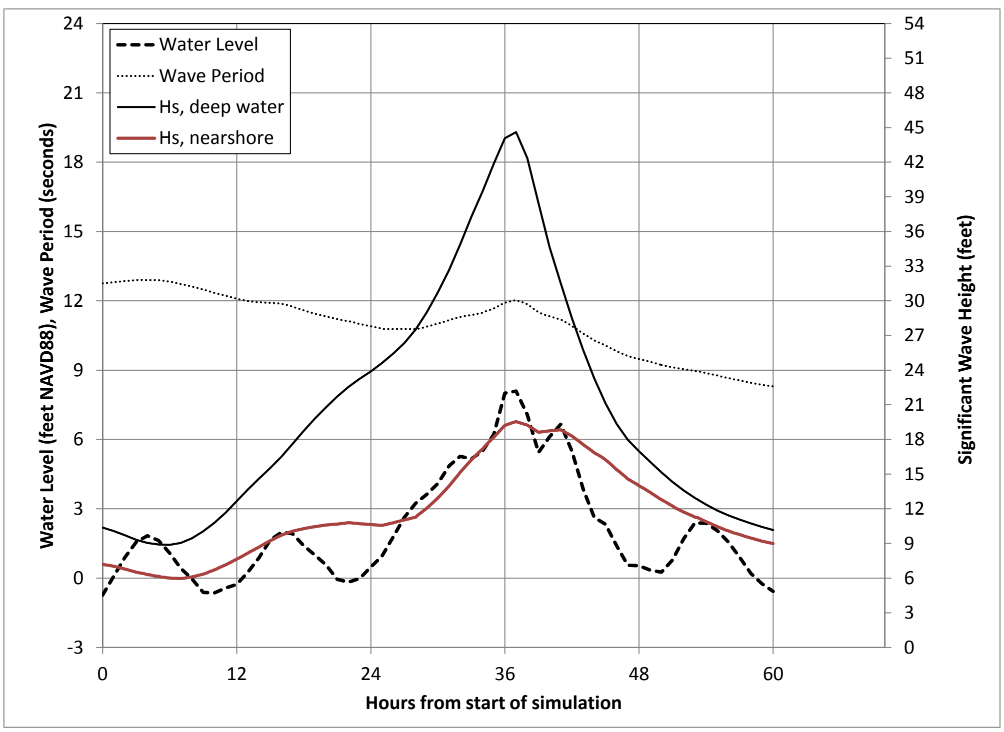


Figure 7-3: SBEACH Input Waves and Water Level, 50-year RP

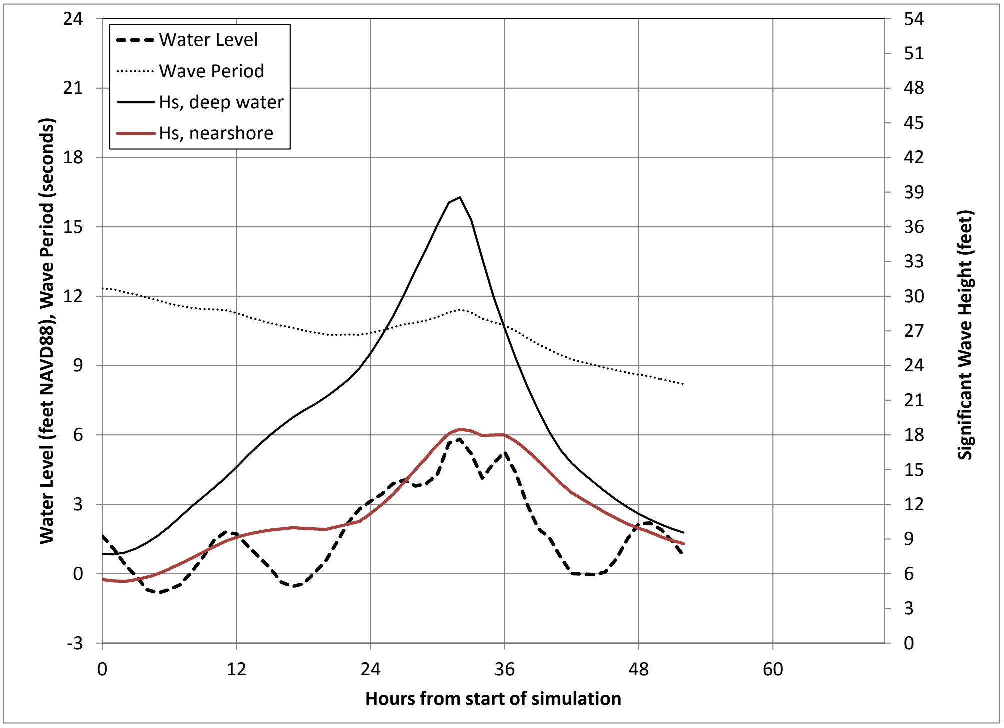


Figure 7-4: SBEACH Input Waves and Water Level, 25-year RP

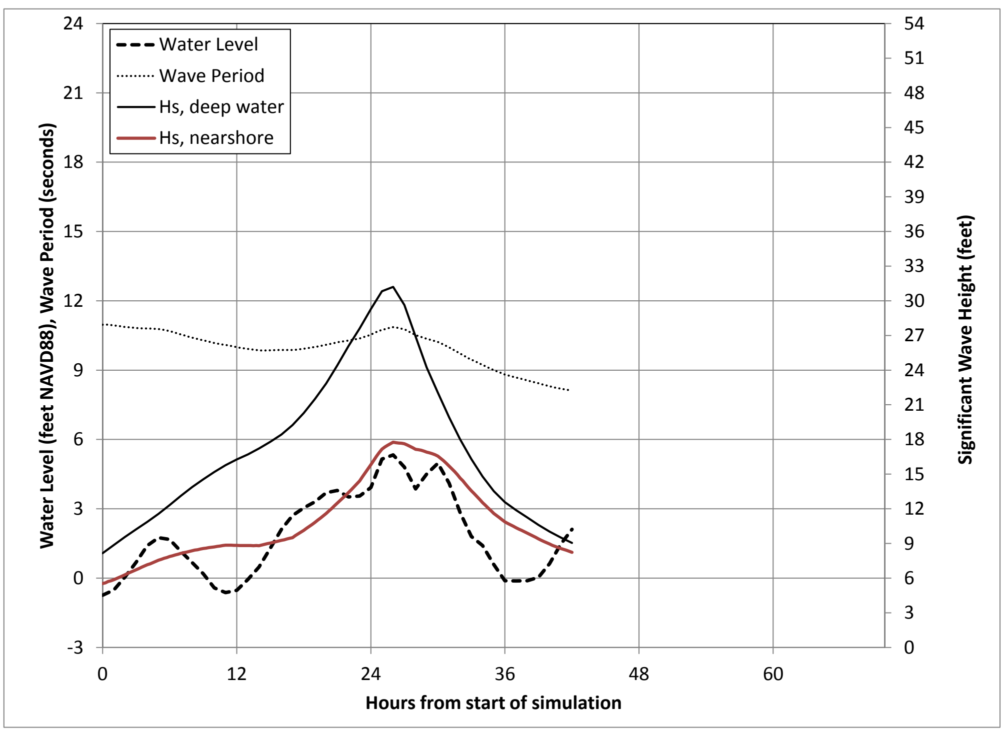


Figure 7-5: SBEACH Input Waves and Water Level, 10-year RP

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 General

This document is a first interim report of a study expected to progress over the coming months. The conclusions and recommendations presented here are intended to provide an update on the study progress and to fuel discussion regarding next steps that may be taken to utilize the models in developing or refining shoreline management planning.

8.2 Bogue Inlet

An analytical study of Bogue Inlet channel morphology was conducted using historical aerial imagery from 1938 – 2011. The study was conducted by defining and then measuring a small set of geometric parameters such as the position and alignment of the main ebb channel and the two landward channels connecting Bogue Inlet with Bogue Sound and the White Oak River. The analytical study component indicated extreme variability in the ebb channel position and alignment from 1938 to approximately 1987, while from 1987 – 2004 the channel moved consistently eastward and maintained a counterclockwise (CCW) alignment relative to a hypothetical "straight line" through the middle of the inlet. Since the ebb channel was relocated in 2005 to an approximate straight alignment at a mid-inlet lateral position, the ebb channel has again migrated eastward, though at a lesser rate than seen in the 1987 – 1992 migration. The post-relocation channel also has not yet realigned to a consistent CCW orientation, but currently has a CCW alignment landward and CW alignment seaward of the defined Reference Line. The analytical study component appears to indicate that the ebb channel will eventually migrate further east and that the ebb channel may need to be relocated again at some future date.

A product of the initial analytical study is a proposed area, or "safe box," within which the main channel of Bogue Inlet would be allowed move, without triggering engineering intervention. This "safe box" was developed as described in the main Engineering Report body.

A program of numerical model simulations was then envisioned to confirm or revise (i.e. potentially narrow) the limits of the proposed "safe box". The dynamically coupled wave, flow, sediment transport, and bathymetry change (morphodynamic) model simulations were run for several idealized (schematized) inlet channel configurations. The model simulations were intended to provide an indication of whether there is a certain (approximate) lateral position, channel orientation, or combinations of both which, once reached, may speed up (or inhibit recovery from) migration of the channel to unacceptable positions near Bogue Banks or Bear Island.

A series of five schematized (simplified) inlet configuration Cases were simulated under the forcing of representative tidal hydrodynamics and wave conditions. A morphological acceleration factor was applied to amplify the change in bed elevations seen during a given simulation period, to make greater use of computational resources during the processor-intensives simulations.

The schematized inlet configuration simulations generally indicated that – from most of the starting inlet geometries – the main channel would tend to migrate back toward the center of the inlet and rotate to a more normal alignment similar to the Authorized Channel. The Case 5 simulations indicated that, while the originally-specified main ebb channel did not itself migrate significantly westward, it would shoal and begin to lose hydraulic connection with the White Oak and Bogue Sound channels, and a second channel would form near the Authorized Channel.

The numerical model results do not indicate a channel position, rotation, or combination of parameters that suggest that proposed "safe box" should be refined.

The schematized Case model simulations provided results that are in some ways counter to what has been observed with respect to inlet migration post-2005 relocation. Particularly, the Case 4 starting condition generally reflects the main ebb channel shape and position relative to the Authorized Channel observed in 2009 – 2010, but the model results behaved differently than expected from recent observed channel positions.

Tests were conducted on the numerical model to investigate the potential source(s) of this disagreement. A long-term continuous simulation from 2005 – 2006, with accelerated morphology updating, indicated reasonable matching with shoals and channels observed from a 2007 aerial photo. The general success of this long-term simulation adds confidence to the use of the schematized model results for the present limited purposes.

Additional tests of incremental changes to Case 4 or Case 5 inlet configurations – such as changes to the White Oak River back channel and its connection to the main channel; high discharges in the White Oak River – did not produce meaningfully different morphology results from the original Case 4 and Case 5 simulations.

Therefore, it appears that the use of the "safe box" determined from the analytical analysis (Section 8.3) is a prudent approach to provide infrastructure protection for adjacent inlet shorelines. It also appears that the 2005 Authorized Channel dimension and location are valid. A slight improvement that may provide longer timeframes for stability appears to be to rotate the 2005 Authorized Channel by 15 clockwise (CW) as shown in Figure 8 27 below. Additional information and studies outlining the design of the 2005 Authorized Channel can be found in the 2004 CP&E report (CP&E, 2004).

Figure 8-1: Example 2005 Authorized Channel Rotated 15 Degrees

9.0 REFERENCES

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