APPENDIX Q

WAVE CLIMATE ANALYSIS AND SUPPLEMENTS

SUB-APPENDIX Q1

WAVE CLIMATE ANALYSIS

St. Lucie County

Offshore Borrow Area & Wave Climate Analysis

prepared for

St. Lucie County Florida

by

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1.0 Introduction

In general, the purpose of this document is to address public comments and Florida Department of Environmental Protection (FDEP) staff concerns regarding the potential changes in wave climate landward of the proposed offshore borrow area for the proposed *South County Beach and Dune Restoration Project* (*Project*) in St. Lucie County, Florida. This analysis:

- applies the Steady-state Spectral Wave Transformation model STWAVE to the Project area under two bathymetric conditions:
    (1) the pre-dredged, existing condition, and
    (2) fully-excavated borrow sites as estimated to be potentially needed to provide fill over the *Project* life.
- follows and makes use of portions of the analysis conducted by the U.S. Army Corps of Engineers (USACE) Jacksonville District in 2008 (Hadley, 2008) to model wave climate changes associated with the proposed dredging of the Capron Shoal as a borrow area for the *Ft. Pierce Shore Protection Project*.

St. Lucie County is located along the southeastern Atlantic Coast of the Florida peninsula, as shown in Figure 1. This region, like all coastal regions, experiences wave conditions that significantly drive coastal processes and impact the shoreline. The result is a coastline that experiences both areas of erosion and areas of accretion during storms. One factor that contributes to the formation of erosional and accretional zones is the local shoreline planar geometry. Another factor is the complex offshore bathymetry in the region.

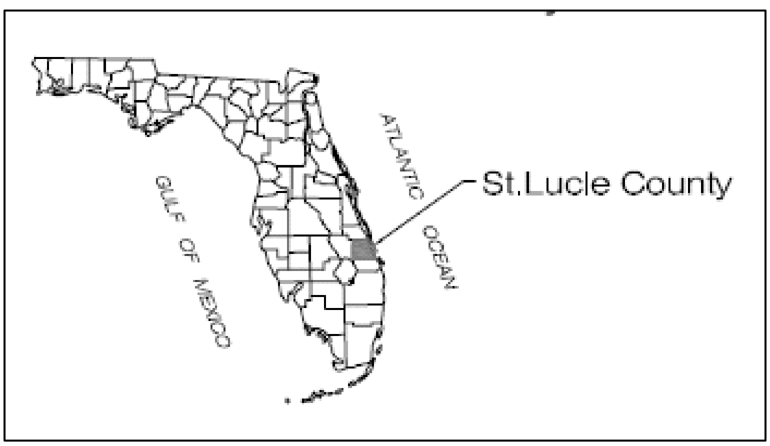


Figure 1: Location Map

Offshore of St. Lucie County, the bathymetry is complex due to the presence of several shoals, as shown in Figure 2. Although offshore bathymetry tends to remain stable over the long term if left undisturbed, the presence of beach quality sands in the nearby shoals makes them an excellent source of beach fill material (Hadley, 2008). While borrow sites are a valuable component of maintaining healthy beaches, altering the bathymetry of the shoals might change the nearshore wave characteristics enough to alter the position or long term stability of the shoreline.

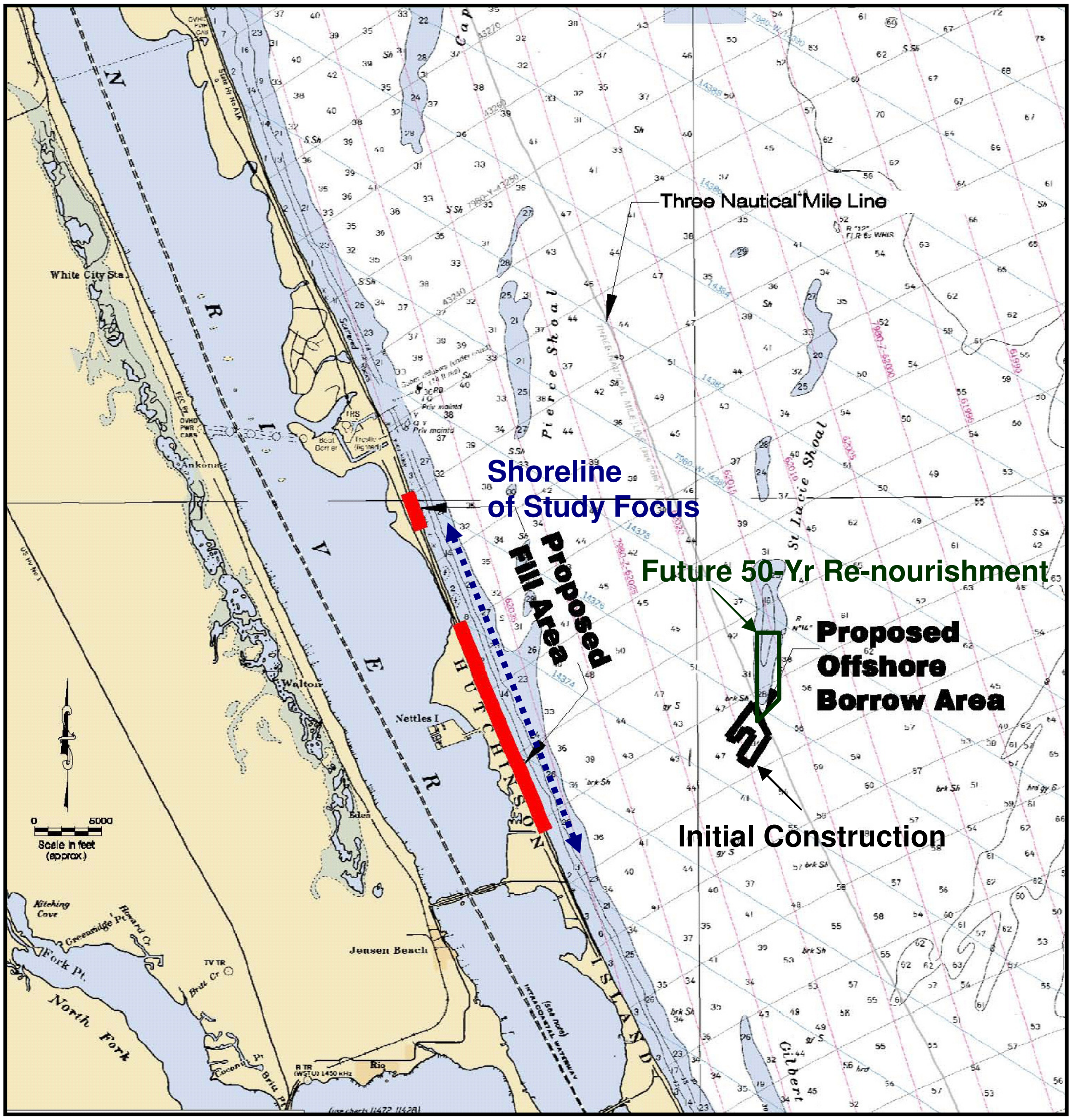


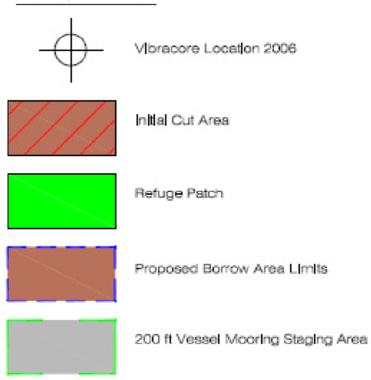
Figure 2: Project Area - Borrow Area & Fill Area

This study evaluates changes to the wave climate as a result of the proposed dredging and also assesses if further analysis is required to quantify sediment transport changes resulting from the excavation the proposed borrow area in the vicinity of the adjacent shoreline of St. Lucie County. To evaluate potential changes to wave climate, the Steady-state Spectral Wave model STWAVE was applied. Wave heights, wave directions, and wave periods for each potential borrow site change were then compared and a determination of the potential for significant sediment transport changes was made. The configuration of the proposed borrow area is illustrated for the initial construction in Figure 3a, and for future re-nourishment over the 50-year life of the Project in Figure 3b; the relative location of these borrow areas is illustrated in Figure 2.

NOTES:

1. Contours prepared by Coastal Tech from bathymetric survey conducted by Coastal Planning & Engineering, April 2006.
2. Core locations from data in report: South St.Lucie County Hurricane & Storm Damage Reduction Project 2006 Geotechnical Investigations to identify sand sources by Coastal Planning & Engineering.
3. Coordinates are in feet based on Florida State Plane Coordinate System, East Zone, North American Datum of 1983 (NAD83).
4. Elevations are referenced to the North American Vertical Datum 1988 (NAVD88).
5. The 3 nautical mile line is the inner boundary of the Federal fisheries jurisdiction and the limit of the states' jurisdiction under the Submerged Lands Act (P.L. 83-31; 67 Stat. 29, March 22, 1953).
6. Refuge Patch region along shoal crest shall remain undisturbed to minimize impacts to benthic organisms and related fisheries.
7. The Contractor shall excavate material from the "Initial Cut Area" for transport and placement on the beach to construct the Project. If undesirable material is encountered in the "Initial Cut Area", the Contractor shall move dredging operations within the borrow area to locate desirable material.
8. The Contractor shall not moor vessels or stage equipment on the ocean bottom outside the "Vessel Mooring/Staging Area."
9. The Contractor shall not (a) moor vessels or stage equipment on the ocean bottom - unless "diver assisted".

LEGEND:



Coordinates of Borrow Area Corners		
Corners	Northing	Easting
1	1076058	931072
2	1073627	932227
3	1071394	930842
4	1071996	929986
5	1073752	931117
6	1074185	930479
7	1073227	929774
8	1073516	929185

Figure 3a: Initial Construction - Borrow Area

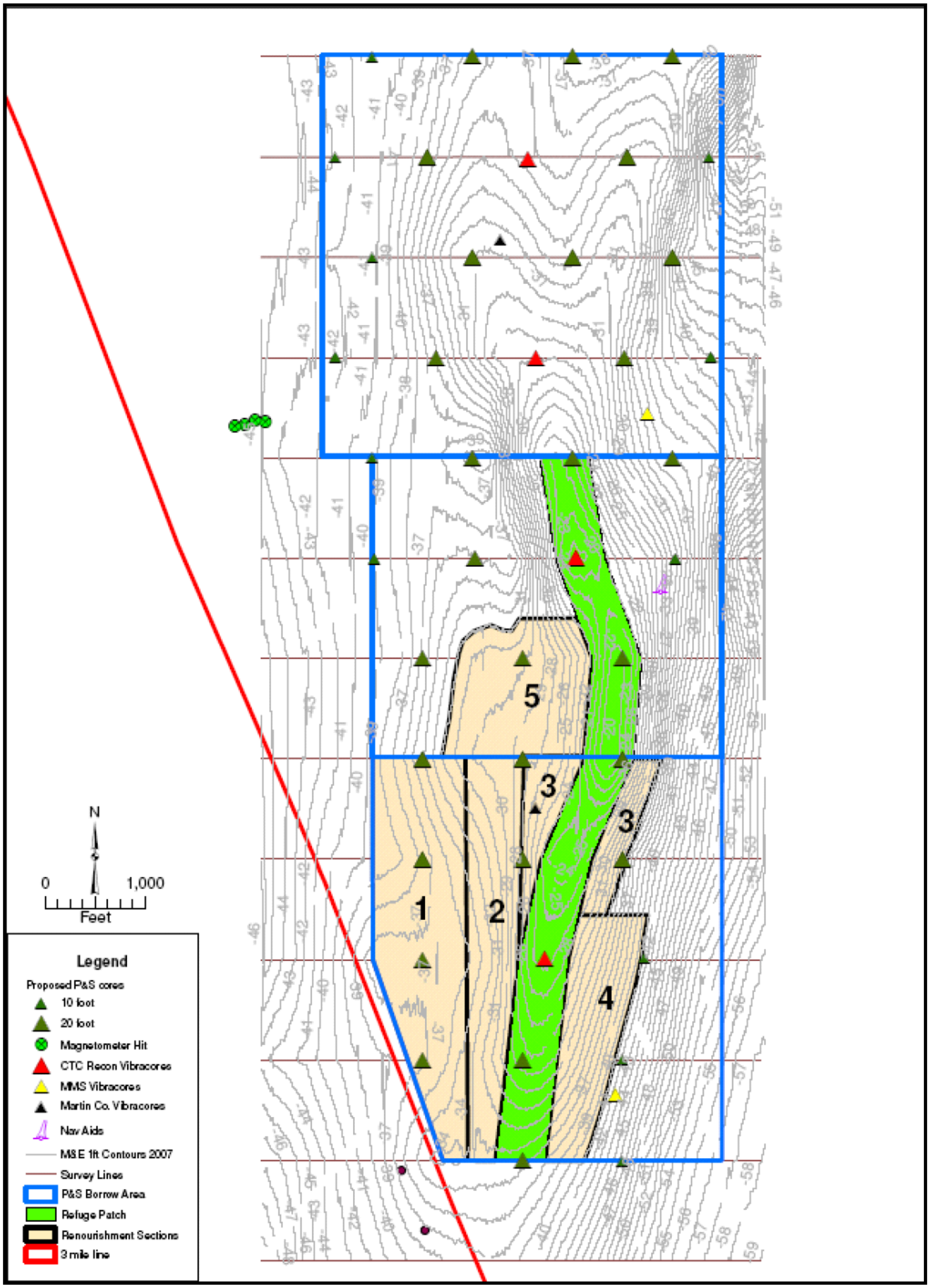


Figure 3b: Future Construction Borrow Area –Re-nourishment over 50-year Project Life

2.0 Project Site

The St. Lucie County shoreline extends along approximately 21.5 miles of Atlantic Ocean coast between Indian River County to the north and Martin County to the south. The focus of this study is on the southern portion (≈5 miles) of the St. Lucie County shoreline as illustrated in Figure 2. This portion of the County shoreline is considered most likely to be impacted by the excavation of the potential borrow site.

3.0 Study Overview

In order to evaluate the wave climate in the study area and determine any significant changes to sediment transport patterns caused by removal of material from the borrow site, model grids representing both the existing bathymetry and the potential fully excavated bathymetry are created. The relative difference with and without borrow site excavation is determined for an array of incident offshore wind and wave conditions. The incident wave fields for the existing and for the dredged bathymetry are analyzed and compared. From this analysis, it is determined whether significant changes to the incident wave energy are induced by dredging the shoal.

The offshore borrow area for initial construction is located along the southern limits of the St. Lucie Shoal, denoted in the permit sketches as 'Area 5' for use in the renourishment of the South County beaches and dunes – as depicted in Figure 3a. Sand for future re-nourishment is proposed to be obtained from the sub-areas 1 through 5 – as depicted in Figure 3b. Neither borrow area has been previously excavated. This analysis accounts for all material to be potentially excavated, either on this project or multiple future projects, should they be permitted. The impacts of excavating to the projected dredge limits of this site were investigated to the depths reflected in Table 1.

4.0 STWAVE Model

As identified by Hadley (Hadley, 2008):

"The STWAVE model is a two-dimensional spectral wave transformation model for the simulation of wave propagation over complex bathymetry. STWAVE accepts arbitrary directional wave spectra specified at an offshore boundary and propagates the spectral energy in the onshore direction. It is a finite difference model, which calculates wave spectra on a Cartesian grid using a backward ray-tracing scheme (Smith, et al, 1999). Model results, including spectral output, significant wave height, mean wave period, and wave direction are obtained by numerically solving the steady-state spectral energy balance equation. This equation is given as:

$$\frac{\partial cc_g E(f,\theta)}{\partial x} + \frac{\partial cc_g E(f,\theta)}{\partial y} = S_{at} + S_{nl} + S_{ds} + S_{br}$$

The left hand side of the equation represents wave propagation refracting and shoaling, where

E = spectral energy density
f = frequency of spectral component
θ = propagation direction of spectral component
c = phase speed of spectral component
c_g = group velocity of spectral component
x,y = plan-view spatial coordinates

The terms making up the right hand side of the equation, known as source terms, represent distribution and dissipation of energy based on principals of linear theory. These terms are defined as:

S_{at} = wind input
S_{nl} = nonlinear wave-wave interactions
S_{ds} = dissipation within wave field
S_{br} = depth-induced wave breaking

… these source terms … are solved via conservation of momentum flux to the forward and rear face of the spectrum where the energy is redistributed. S_{br} dissipates energy based on water depth and wave steepness.

STWAVE has several inherent limitations. For the best application of the model to wave transformation problems, the following assumptions must be made:

a. Mild bottom slopes
b. Negligible wave reflection
c. Spatially homogeneous offshore waves
d. Steady state waves, winds, and currents
e. Linear refraction and shoaling with negligible bottom friction effects
f. Linear wave-current interaction

Due to the nature of the solution scheme, spectral energy is limited to propagation in a half-plane directed toward shore. All energy propagated offshore is neglected."

5.0 Wave Model Input

Existing Bathymetry

Digital bathymetry for the St. Lucie County coastal zone was obtained from the National Oceanic and Atmospheric Administration (NOAA). This data was compiled by the USACE (Hadley, 2008) from seven digital surveys available through NOAA database; the existing NOAA bathymetry data files are used herein to define the pre-dredged, existing condition. These surveys provide extensive offshore coverage. Although these surveys are greater than 10 years old, the general stability of the offshore bathymetry, showing little long-term change, makes them excellent sources for detailed coverage of the complex offshore characteristics.

Borrow Site Bathymetry

The maximum dredge-cut depths are assumed to represent the fully-excavated borrow sites; this includes areas seaward of the 3 mile marker into Federal waters. The maximum dredge-cut depths are described as follows:

Table 1: Borrow Area Design Dredge Depths

Borrow Area	Depth (ft-NAVD)	Depth (m-NAVD)
Initial Construction - Area 5	-49.0	-14.9
Future Construction - Sub Area 1 - 4	-39.9	-12.2
Future Construction - Sub Area 5	-33.0	-10.1

The wave transformation analysis was performed in two separate phases. Phase 1 encompassed the smaller 'Initial Construction Borrow Area 5', for which all wave cases were modeled. Phase 2 consisted of the larger 'Future Construction 50-Year Borrow Area' and the 'Initial Construction Borrow Area 5', for which only the most energetic wave cases were modeled.

STWAVE Grids

As identified by Hadley (2008): "In order to analyze wind-wave transformation within the project area, a series of bathymetric grids, representing the existing condition and the fully excavated borrow site were required. The STWAVE computational grids were generated using the SMS (Surface-water Modeling System) software package developed by Brigham Young University (Brigham Young, 1997)."

The computation grid domain extends from approximately R-90 to R-115 (approximately 5 miles) within St. Lucie County in the North-South direction and from 0.5 to 14 miles offshore from the shoreline in the East-West direction. The boundaries of the grid domain are established based upon the expected cone of influence associated with predominant wave angle approaches used for this analysis. The shoreline is assumed to have a shore normal azimuth of 70 degrees magnetic North – based upon an average for the FDEP profiles in the model domain – per FDEP website data. Wave rays are assumed in 22.5 degree increments – as identified by Hadley (2008). The "cone" of potential wave influence on the shoreline is assumed to be 2 times the wave ray increments or 45 degrees – about the shoreline azimuth of 70 degrees. Therefore, the cone of influence represented is between 25 degrees and 115 degrees (45 degrees north and south of shore normal). The seaward boundary of the computation grid extends approximately 14 miles offshore and corresponds to the location of the Wave Information Study (WIS) station #450 which provided the wind and wave data for model input. The grid has a resolution of 300 feet. The model domain encompasses both the initial and subsequent 50-year borrow areas.

Wave, Wind, and Current Input

For purposes of this analysis, the wave input file used to drive the STWAVE model is based upon the wave data statistics employed by the USACE in 2008 (Hadley, 2008) to model wave climate changes associated with dredging of by Capron Shoal – as originally derived by the USACE from WIS data. Currents are comparably "not included in this study." WIS hindcast data are generated using the numerical hindcast model WISWAVE (Hadley, 2008). WISWAVE is driven by wind fields overlaying a bathymetric grid. The model output includes the significant wave height, peak and mean wave period, peak and mean wave direction, wind speed, and wind direction (Hadley, 2008). The WIS hindcast for the Atlantic Ocean covers a 20-year period from 1980 to 1999 and includes both tropical storms and hurricanes during that time frame. WIS station #450 is used herein; this station is located at Latitude 27.5N and Longitude 80.08W, 14 miles east of the Fort Pierce Inlet. The water depth at this location is 75.5 feet (23 meters).

Figures 4 and 5 below summarize all WIS wave and wind conditions at the station (from Hadley, 2008). As identified by (Hadley, 2008):

"Approximately 175,000 wind and wave conditions are included. Given the extent and resolution of the STWAVE input grid, such a large number of conditions is prohibitive as model input. In order to summarize and consolidate the information into a manageable number of representative model runs, 12 representative deepwater wave conditions were developed based on monthly weighted averages weighted according to frequency of occurrence … An average wave height, wave period, wave direction, wind speed, and wind direction were determined for each month over the entire 20-year record."

The maximum monthly wave conditions were used to generate an extreme condition over the 20-year hindcast record. The most significant of these events (August through November) reflect hurricane conditions, while December through March reflect slightly less powerful northeasters, followed by milder summer storm events between April and July (Hadley, 2008). Average and Maximum monthly deepwater wave and wind conditions are given in Tables 2 and 3, respectively. These 24 monthly wave cases were modeled for the smaller 'Initial Construction Borrow Area 5'. Of those model runs, the three most significant wave events were applied to the larger subsequent Future Construction 50-year Borrow Area.

From: (Hadley, 2008)

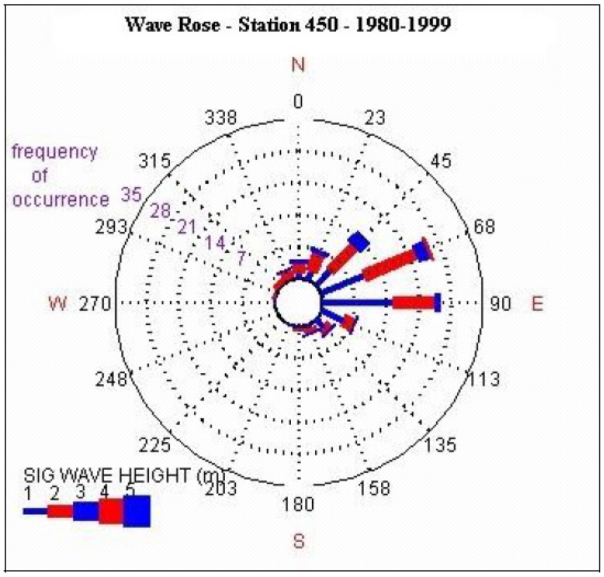


Figure 4: WIS Station 450 - Wave Rose

From: (Hadley, 2008)

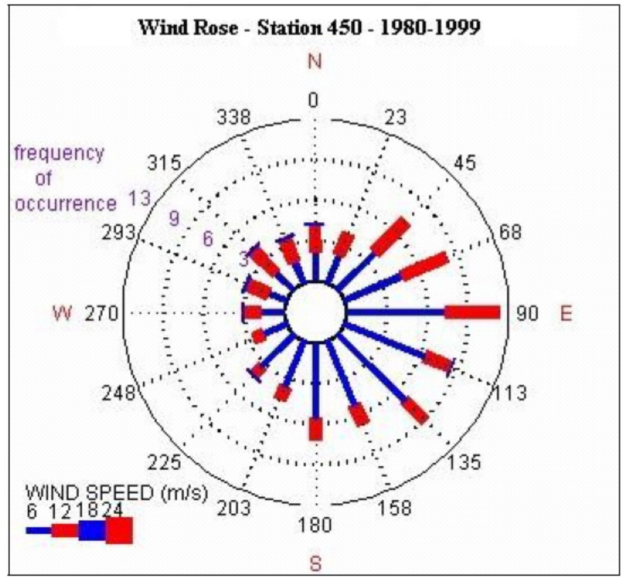


Figure 5: WIS Station 450 - Wind Rose

Table 2: Average Monthly Wave Conditions from 1980 to 1999 (From: Hadley, 2008)

Month	Wave Height (ft)	(m)	Peak Period (sec)	Wave Direction (deg*)	Wind Speed (mph)	(m/sec)	Wind Direction (deg)
January	5.0	1.5	5.9	59	13.7	6.1	67
February	5.1	1.6	6.0	60	14.2	6.4	69
March	4.9	1.5	5.8	66	14.2	6.3	77
April	4.3	1.3	5.5	70	12.8	5.7	83
May	3.6	1.1	5.2	73	11.3	5.0	90
June	2.9	0.9	4.8	80	10.2	4.5	100
July	2.3	0.7	4.4	93	9.7	4.3	112
August	2.9	0.8	5.0	82	9.9	4.4	101
September	3.9	1.2	5.9	68	10.7	4.8	80
October	5.1	1.6	6.0	60	13.7	6.1	63
November	5.5	1.7	6.1	61	14.9	6.7	63
December	4.9	1.5	6.0	57	13.4	6.0	62
* Wave and wind directions are given in degrees true north							

Table 3: Maximum Monthly Wave Conditions from 1980 to 1999 **(From: Hadley, 2008)**

Month	Wave Height (ft)	(m)	Peak Period (sec)	Wave Direction (deg*)	Wind Speed (mph)	(m/sec)	Wind Direction (deg)
January	12.4	3.8	8.3	62	31.5	14.1	75
February	17.1	5.2	12.5	72	28.9	12.9	65
March	23.8	7.3	14.3	49	33.1	14.8	10
April	10.3	3.1	10.0	39	21.5	9.6	30
May	9.2	2.8	5.6	20	22.2	9.9	-20
June	8.5	2.6	8.3	58	21.9	9.8	60
July	12.0	3.7	8.3	133	34.0	15.2	142
August	22.1	6.7	11.1	80	22.8	10.2	156
September	22.8	7.0	12.5	44	44.7	20.0	-20
October	26.7	8.2	12.5	80	63.1	28.2	70
November	19.3	5.9	12.5	58	40.3	18.0	45
December	14.2	4.3	10.0	52	34.5	15.4	11
* Wave and wind directions are given in degrees true north							

The input spectra used for this analysis is identical to that used in the Capron Shoal analysis conducted by the USACE. As identified Hadley (Hadley, 2008):

- "The spectra were generated from WIS wave and wind conditions using a JONSWAP spectral form with a spectral peakness parameter, γ, ranging from 3.3 to 5.0 depending on the peak frequency".
- "A $\cos^n$ directional distribution was then applied to address directional spreading. The exponent n … ranged from 4 to 10 based on the peak wave period".
- "The final spectra were comprised on 35 direction bands covering a half-plane in 5-deg increments and 30 frequencies ranging from 0.04 Hz to 0.33 Hz with a frequency increment of 0.01 Hz."

7.0 Results

Twenty-four individual model runs, representing twelve monthly average wave conditions and twelve monthly maximum wave conditions, were applied to each of the bathymetric grids: existing 'pre-dredged' condition and the condition with a fully excavated Borrow Area 5 for initial Project construction. The output for each case was obtained globally (i.e. at every cell of the output grid). Because the purpose of this study was to determine the effect of the borrow area excavation on the nearshore wave climate, the results in this section are presented only as differences (+ or -) in wave parameter relative to the existing condition. The model results for the initial borrow area indicated that the maximum wave conditions for the months of October, September, and February most significantly affected waves. Therefore, these three wave cases (only) were applied to the conditions associated with complete excavation of the initial and 50-year borrow areas required for future Project maintenance. The results are summarized below:

Borrow Area 5:

Figures 6 through 17 indicate the differences in wave height over the entire model domain, corresponding to the average monthly wave conditions with complete excavation of Borrow Area 5 for initial Project construction. Figures 18 through 29 indicate the differences in wave height over the entire model domain corresponding to the maximum monthly wave conditions with complete excavation of Borrow Area 5 for initial construction.

These figures depict the differences in wave height associated with complete excavation of Borrow Area 5, which would somewhat impact the ambient wave climate, most notably in the immediate vicinity of the borrow site itself; it should be noted that Hadley (2008) reached the same conclusion for the Capron Shoal analysis. As was the case for Capron Shoal, this analysis reveals that increases and decreases in wave height can be seen in a concentrated pattern around the excavation site. The changes in wave height appear to propagate from the borrow site shoreward in a fan-like pattern, as might be expected.

Qualitatively trends can be seen in these results - comparable to the conclusions reached by USACE for the Capron Shoal analysis, for which Hadley (2008) states:

- "…while the overall impact of the borrow site excavation is an increase in wave energy, a close look at the results indicates that the magnitude of the change in energy deceases as the waves propagate toward shore",
- "Fundamentals of coastal engineering suggest that bottom topography, water depth, and incident wind have a significant influence on the development of waves",
- "Just as changes to the borrow site will alter the magnitude and direction of waves, the unchanged bottom topography between the shoal, the shoreline, and the steady incident wind will stabilize both the magnitude and direction of the waves back to a condition that reflects the environmental conditions",
- "As the deep water waves propagate over the shoal and move shoreward, they grow steadily steeper until breaking in the shallower near-shore waters. When this occurs the waves become depth-limited".

The kinetic energy resulting from waves is proportional to the wave height squared. Therefore, to the extent that alteration of the bathymetry would slightly increase the transmitted wave heights, it is qualitatively expected that the transmitted energy may increase as well, at least within the zone of the increased wave heights. The model results in the Figures 6 to 29 also indicate zones within which there was a decrease in wave heights and comparably a lessening of transmitted energy. The overall magnitude of increased energy where wave heights increase and the net amount of transmitted energy for all incident waves in total is unknown. As noted for the Capron Shoal analysis, bathymetry in the form of bottom friction continues to affect waves even after they have passed beyond the borrow area and before reaching the shoreline. Average monthly wave heights are lower than the maximum monthly wave heights, and therefore, would have less energy and be less influenced by the altered bottom topography. Differences in wave heights for average monthly conditions ranged from -0.02m to

0.03m compared to -0.28m to -0.34m for maximum monthly wave conditions – essentially an order of magnitude difference between typical average conditions and less frequent extremal maximum conditions. The results indicate that the maximum change in wave height would likely occur in the month of October and was 0.34 meters (1.11 feet) immediately landward of the excavated borrow site. The maximum input wave for this monthly was 8.2 meters (26.7 feet); the predicted change in wave height therefore, represents an approximate 4% increase, a relatively insignificant change in wave height.

Although wave height is a key component to shoreline response, wave direction also plays a significant role in the movement of sediment in the littoral zone (Hadley, 2008). An evaluation of wave direction over the entire project domain yielded differences similar to those for wave heights with the greatest change occurring directly in the vicinity of the borrow site. No changes to the wave period occurred within the grid domain.

<u>50-Year Borrow Areas</u>:
The results of above analysis of Borrow Area 5 indicated three most significant wave cases, which were chosen for model application for the condition associated with complete excavation of Borrow Area 5 (for initial Project construction) and complete excavation of the "50-Year Borrow Areas" (for future Project maintenance). The three wave cases include:

1. October – the most significant of all the wave events,
2. September – slightly less significant in magnitude but waves approach the borrow area north of shore-normal, and
3. February – is approximately 10% less in magnitude that September, however waves approach the borrow area from the shore-normal direction.

The wave height difference plots for each of these three wave cases – for the condition associated with complete excavation of all potential Project borrow areas - are given in Figures 30 thru 32.

A plotting scale of +/- 0.05 meters was used for all the wave height difference plot figures for consistency with the USACE methodology. However, increasing the plot scale to +/- 6 reveals finer, more detailed, contours of the wave height differences, as shown in Figure 33 for the maximum October conditions. This Figure clearly depicts:

- significant wave height dissipation as the waves translate shoreward, and
- relatively insignificant wave height differences along the nearshore regime.

8.0 Conclusions

In summary, the model results indicate that dredging of the St. Lucie Shoal would affect the transmitted wave heights and therefore, the amount of wave energy on the shoreward side of the borrow area from a given wave. In both wave cases (average and maximum), in the vicinity of the borrow site, the changes were more pronounced, although wave effects appear to be minimal and insignificant in terms of the ultimate effect on the shoreline because of wave height/energy dispersion between the dredged site and the shoreline.

Taking energy as a function of the wave height squared (H^2), and using the maximum increase in wave height from all 24 modeled cases would suggest an increase in kinetic energy in the shadow of the Borrow Area 5 (for initial construction condition) of approximately 8%. This maximum energy increase subsequently would be reduced by the continued frictional effects of the unaltered bathymetry shoreward of the borrow areas. Similarly for the conditions associated with the 50-Year borrow areas, examination of the wave height difference results indicate only a small zone in the north-west corner of sub-area 1 and 2 of the 50-Year borrow area, where the transmitted waves were 7% larger as a result of the borrow area modifications. Therefore, the maximum predicted increase in kinetic energy is approximately 14% in this location. However, this effect was very limited in extent and at all other areas of the grid the height differences were typically only 1% or less.

Based upon the above:

- It is unlikely that full-excavation of the proposed St. Lucie Shoal borrow areas would have a significant impact on sediment transport rates along the shoreline in the lee of the shoal.
- No further analysis appears warranted to quantify sediment transport changes resulting from the excavation of the proposed borrow areas.

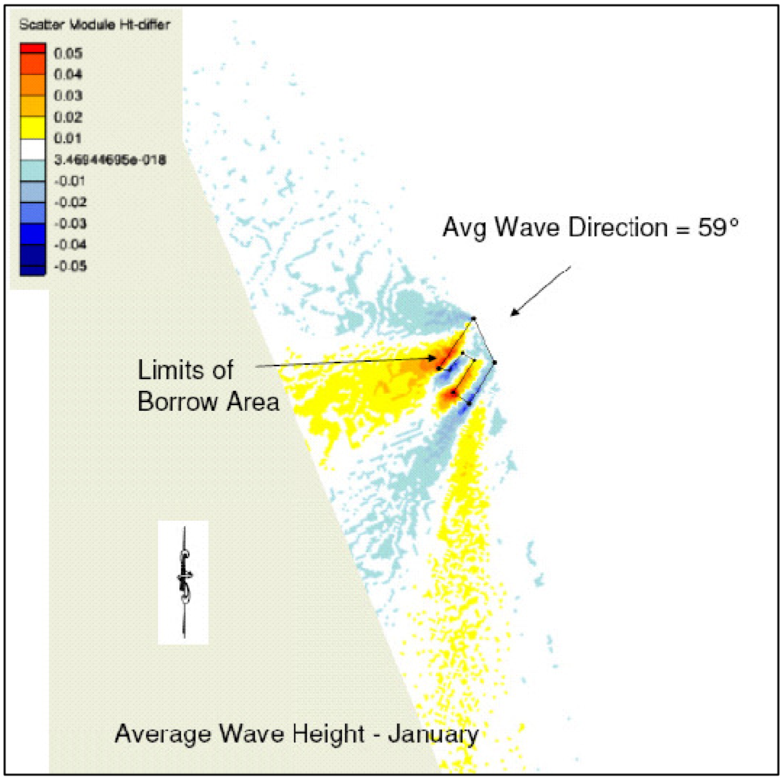


Figure 6: Wave Height Difference in Meters – Average Wave (1.5m at 5.9sec)

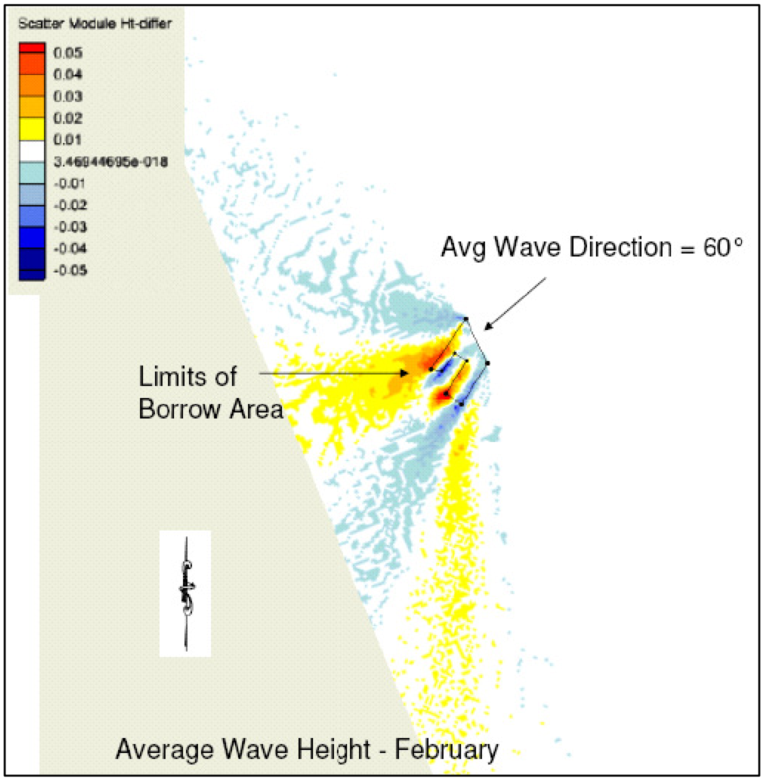


Figure 7: Wave Height Difference in Meters –Average Wave (1.6m at 6.0sec)

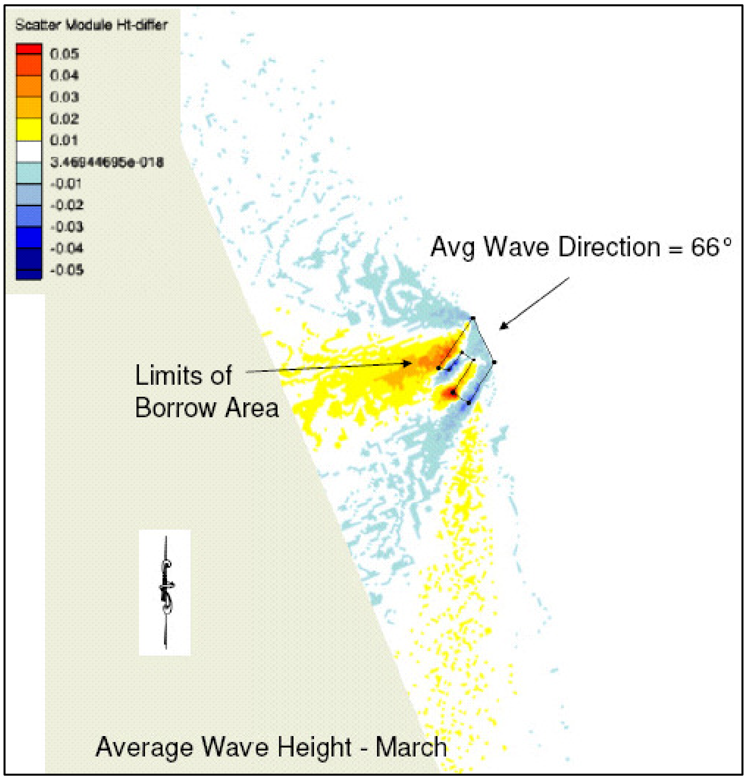


Figure 8: Wave Height Difference in Meters –Average Wave (1.5m at 5.8sec)

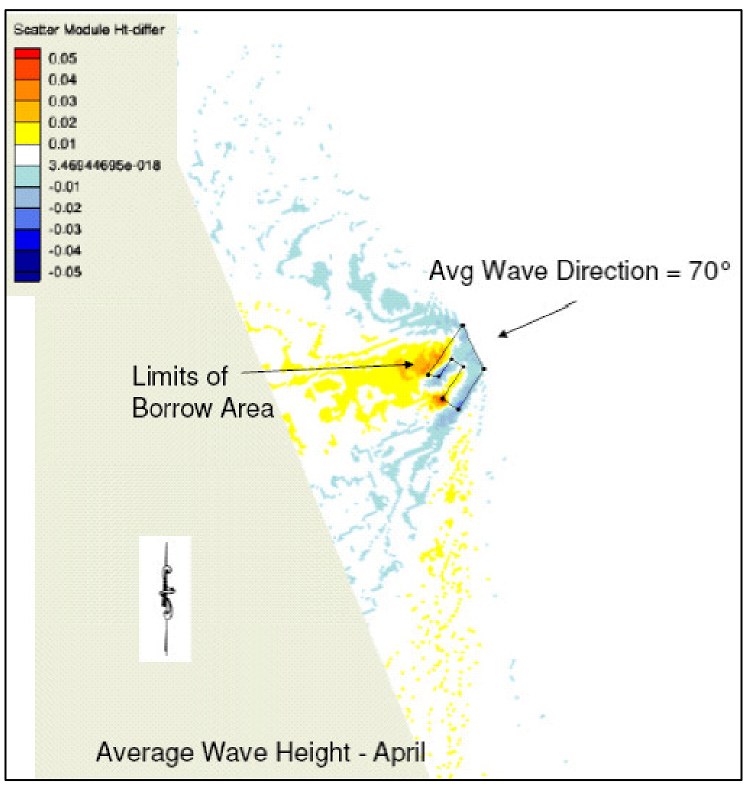


Figure 9: Wave Height Difference in Meters –Average Wave (1.3m at 5.5sec)

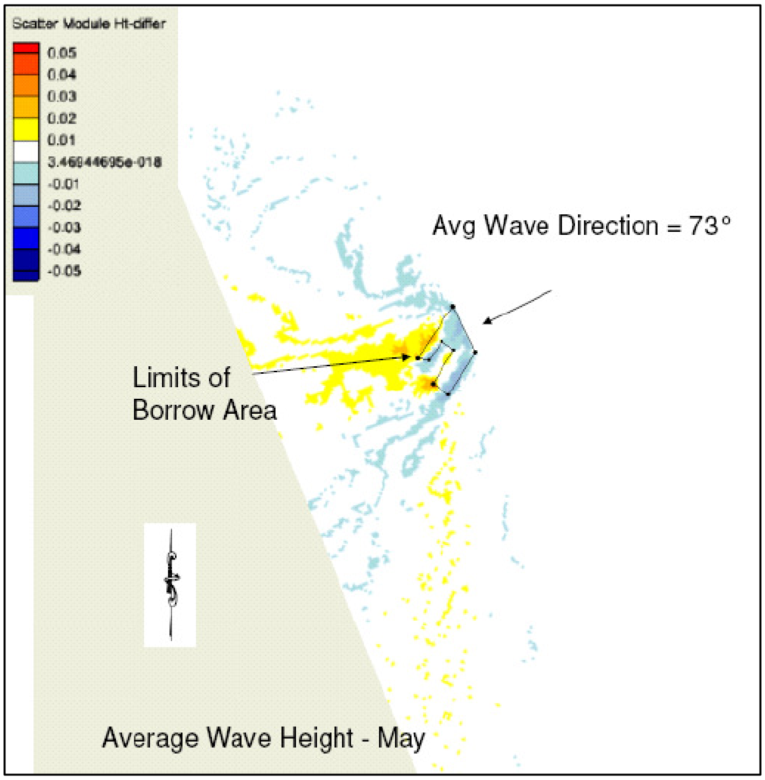


Figure 10: Wave Height Difference in Meters –Average Wave (1.1m at 5.2sec)

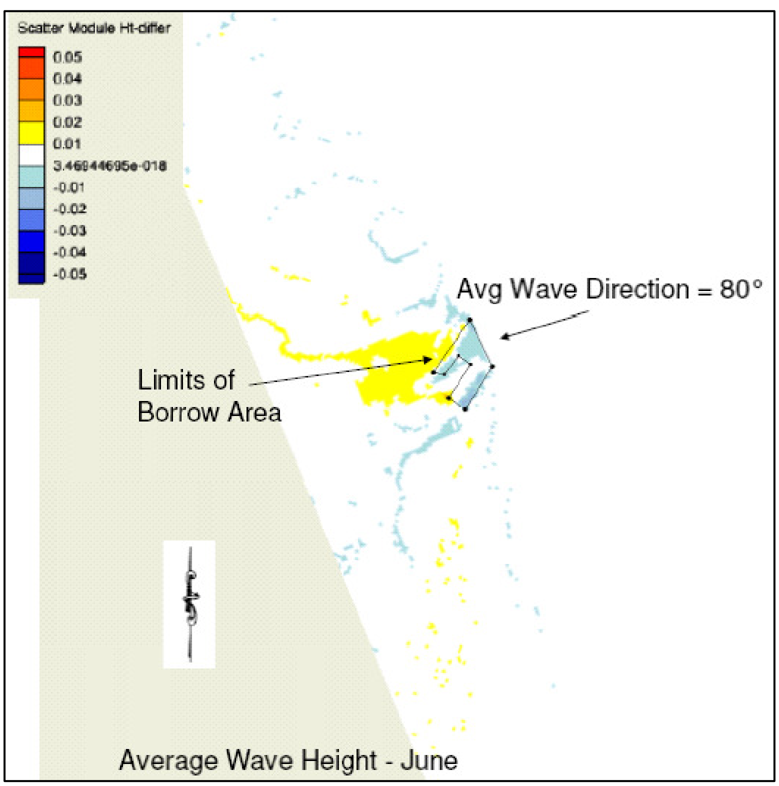


Figure 11: Wave Height Difference in Meters –Average Wave (0.9m at 4.8sec)

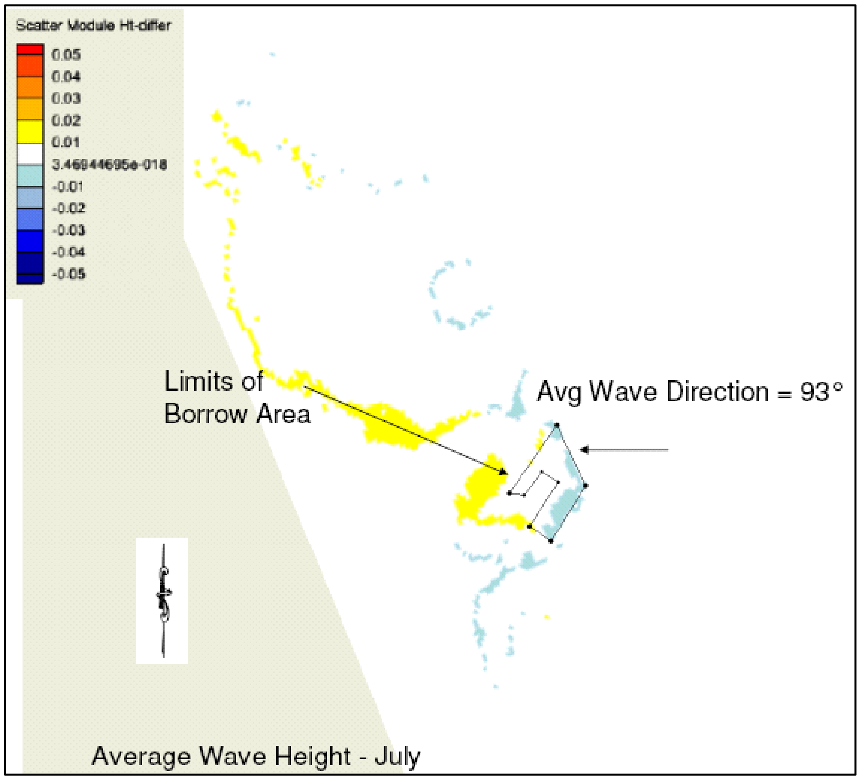


Figure 12: Wave Height Difference in Meters –Average Wave **(0.7m at 4.4sec)**

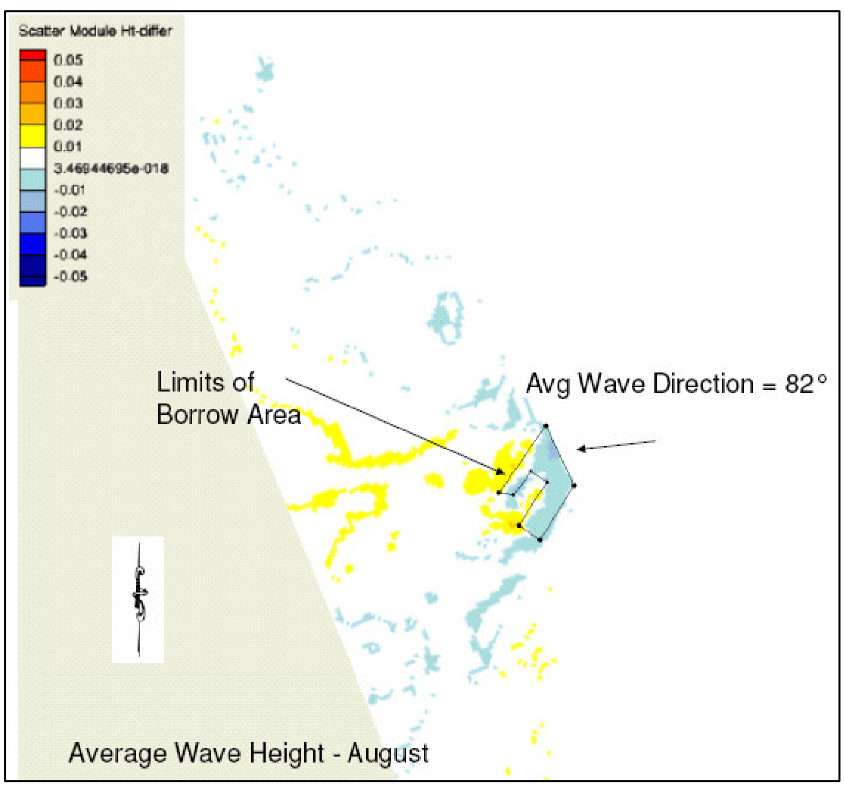


Figure 13: Wave Height Difference in Meters –Average Wave **(0.8m at 5.0sec)**

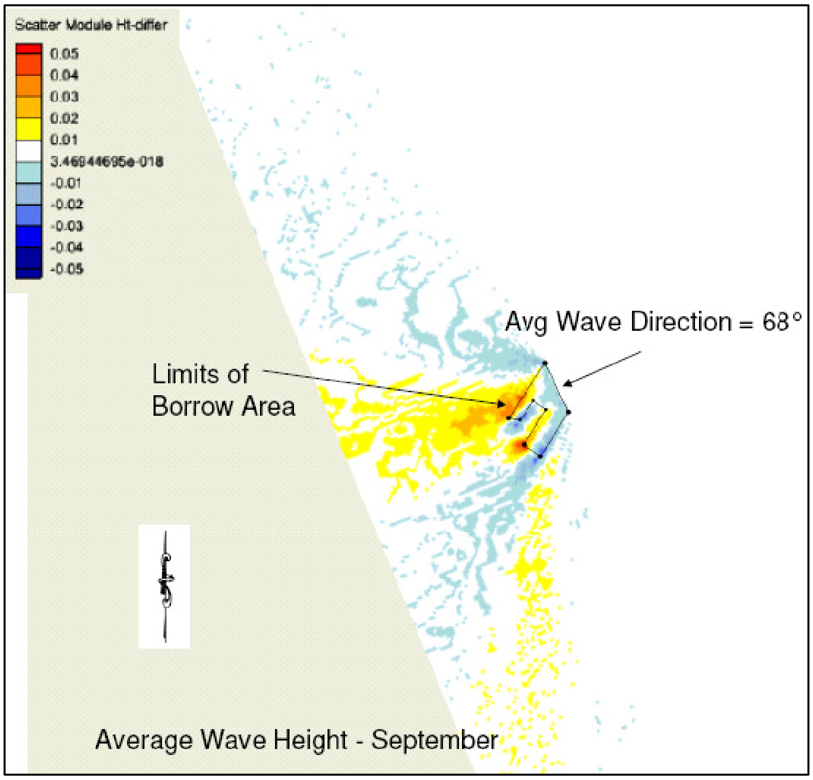


Figure 14: Wave Height Difference in Meters –Average Wave (1.2m at 5.9sec)

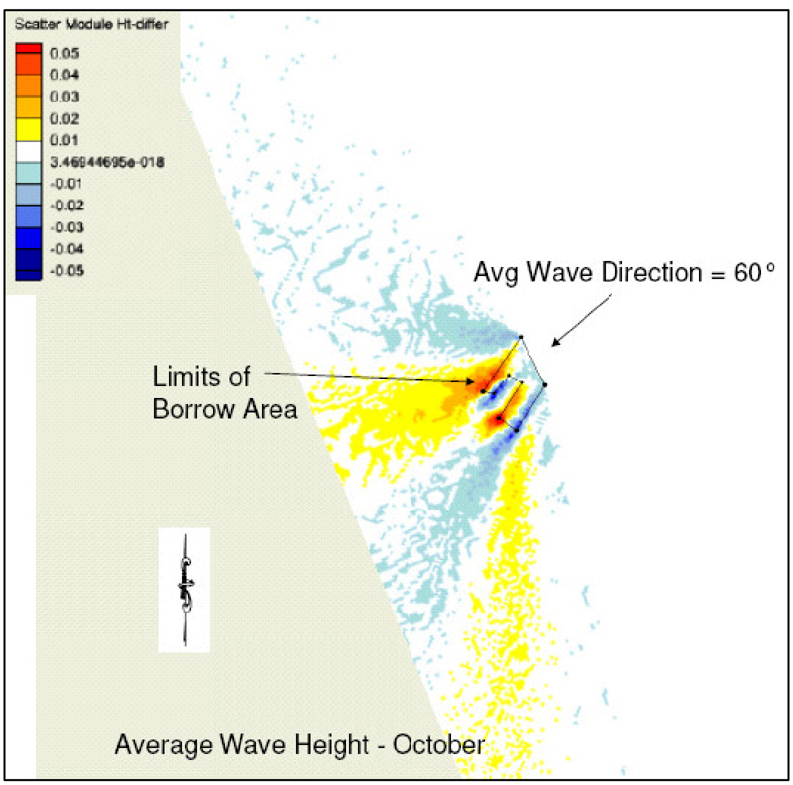


Figure 15: Wave Height Difference in Meters –Average Wave (1.6m at 6.0sec)

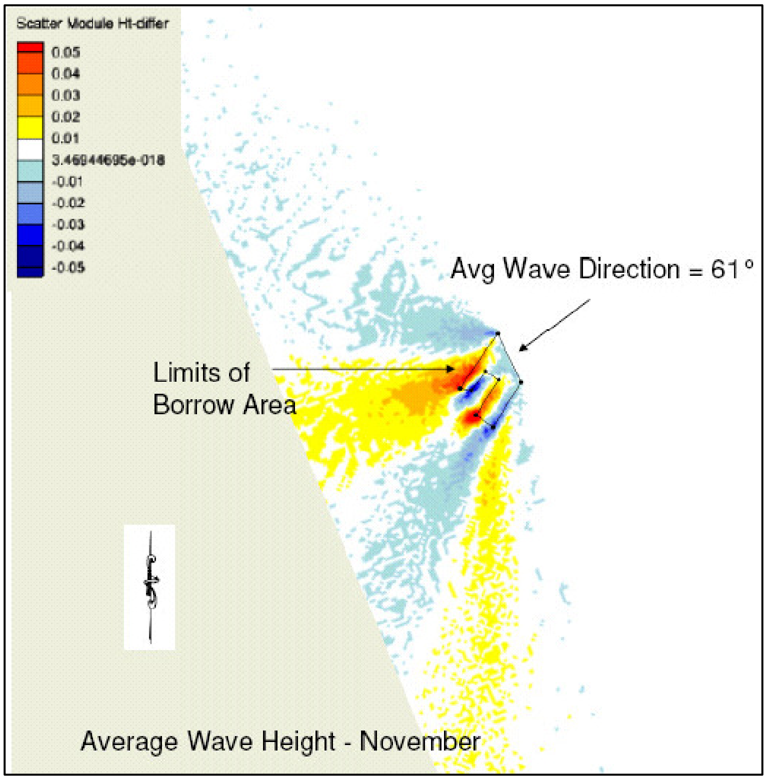


Figure 16: Wave Height Difference in Meters –Average Wave (1.7m at 6.1sec)

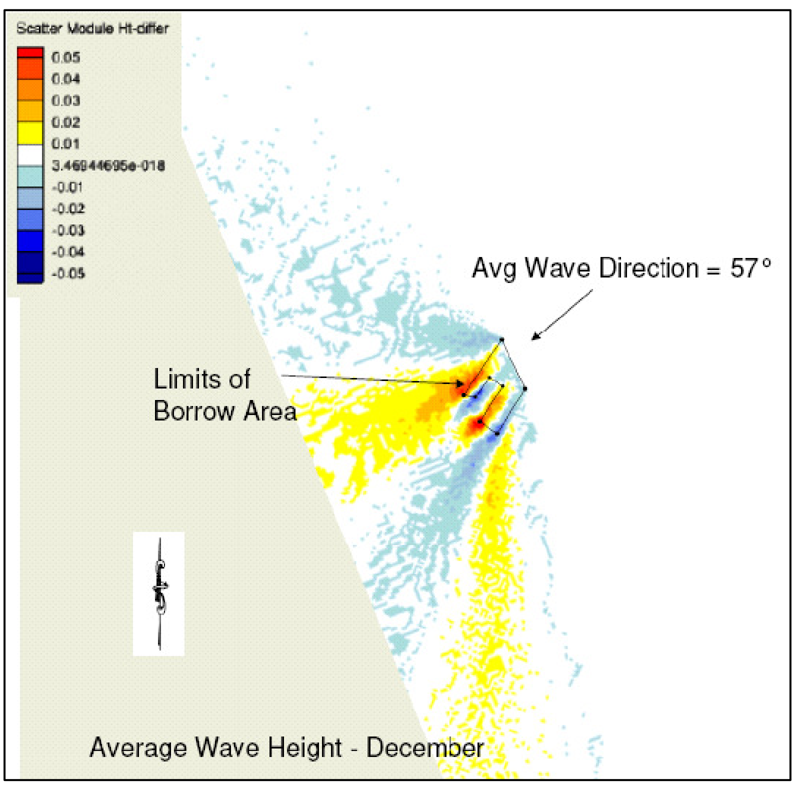


Figure 17: Wave Height Difference in Meters –Average Wave (1.5m at 6.0sec)

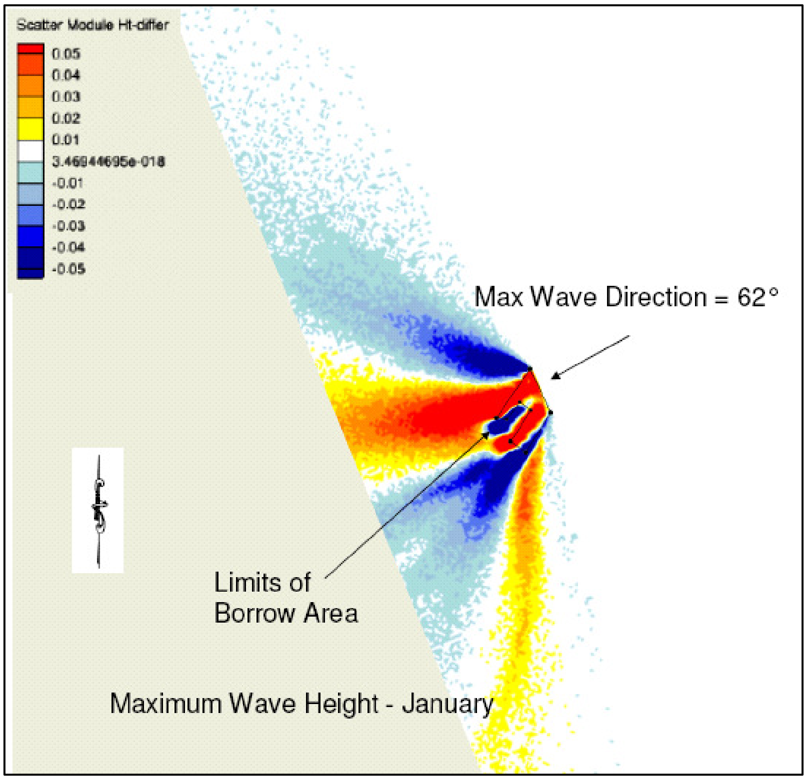


Figure 18: Wave Height Difference in Meters –Max Wave (3.8m at 8.3sec)

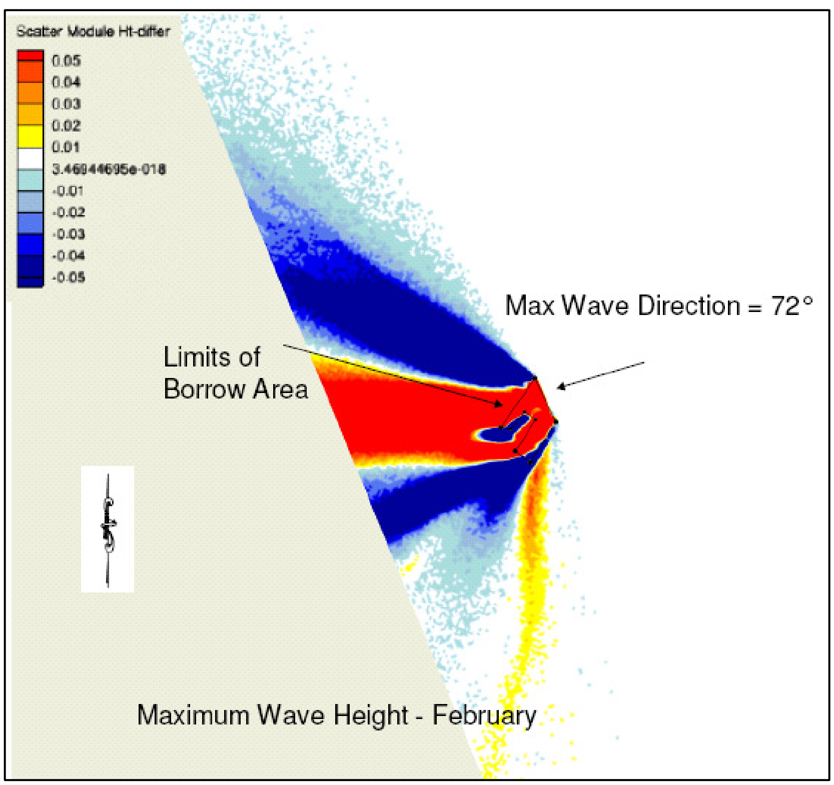


Figure 19: Wave Height Difference in Meters –Max Wave (5.2m at 12.5sec)

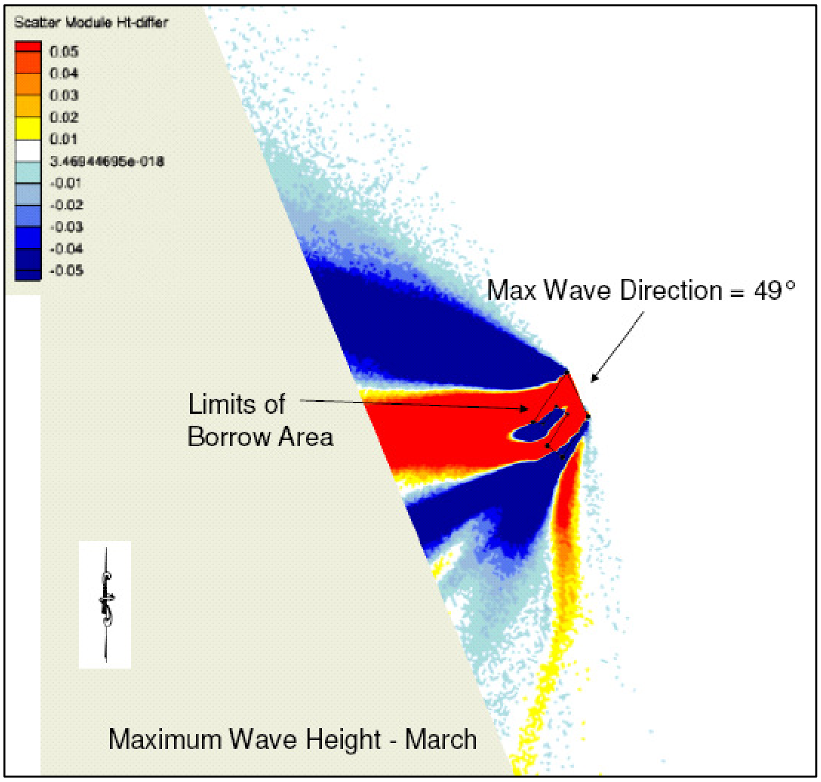


Figure 20: Wave Height Difference in Meters –Max Wave **(7.3m at 14.3sec)**

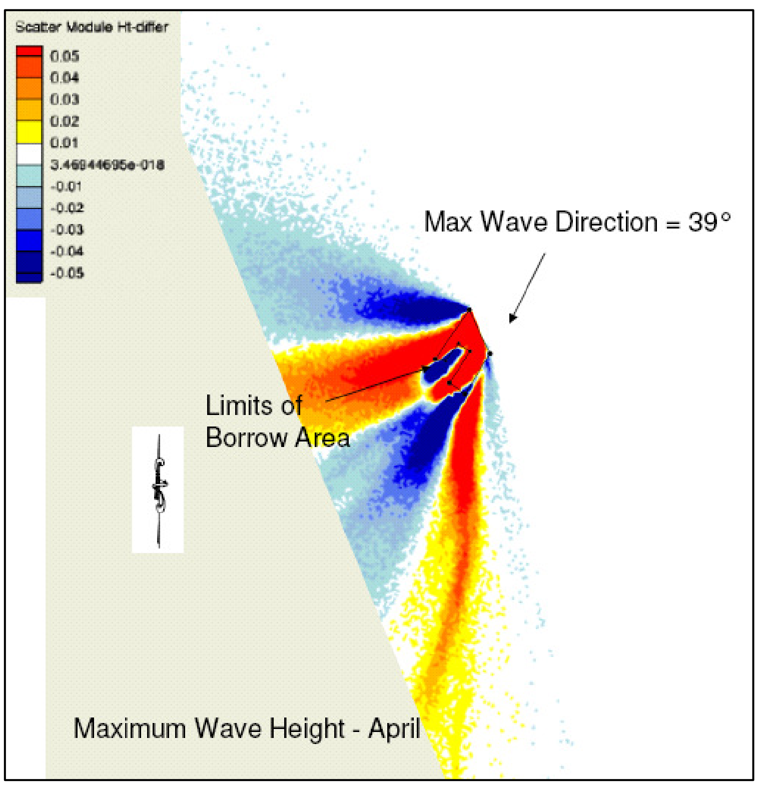


Figure 21: Wave Height Difference in Meters –Max Wave **(3.1m at 10.0sec)**

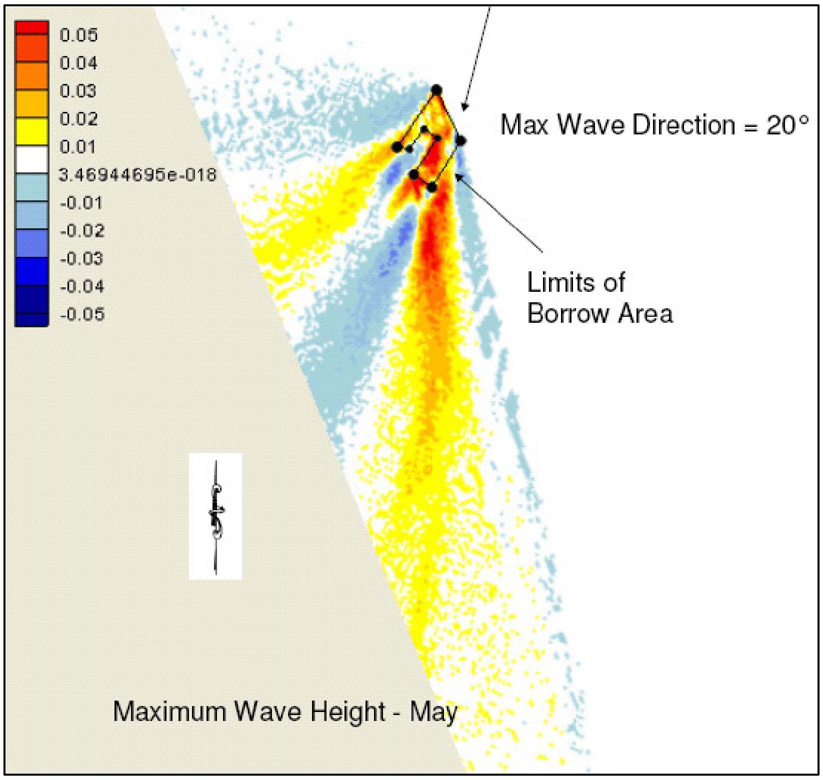


Figure 22: Wave Height Difference in Meters –Max Wave (2,8m at 5.6sec)

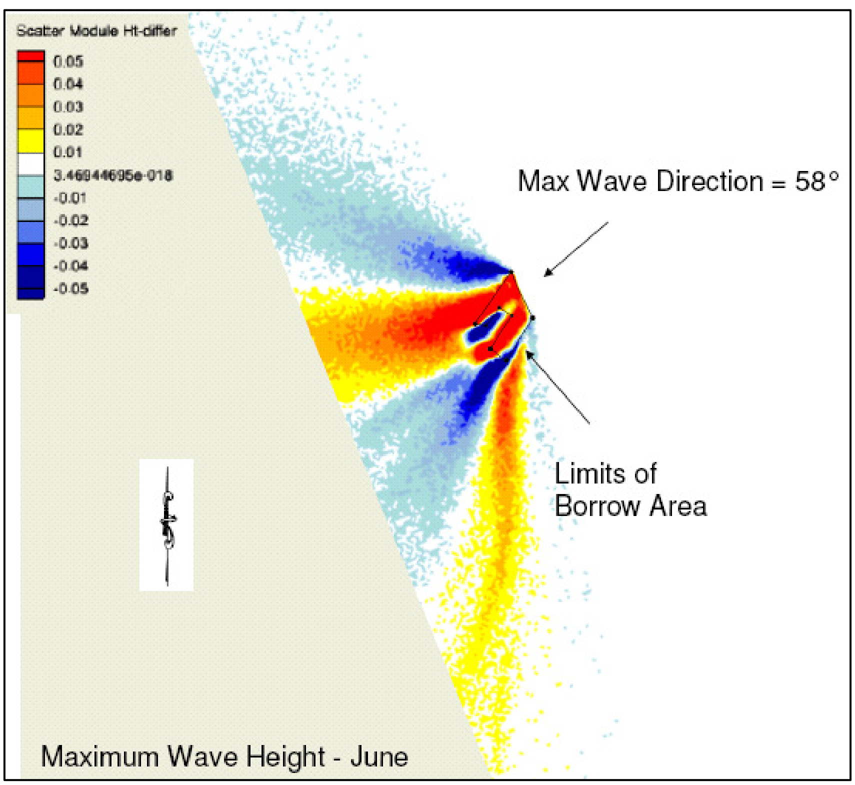


Figure 23: Wave Height Difference in Meters –Max Wave (2.6m at 8.3sec)

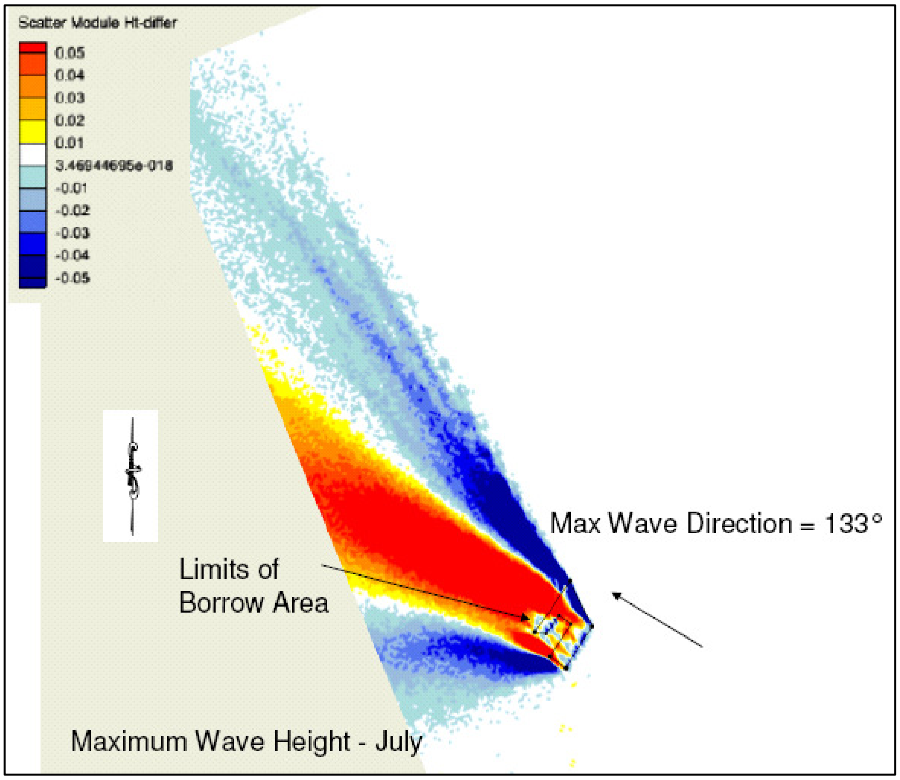


Figure 24: Wave Height Difference in Meters –Max Wave **(3.7m at 8.3sec)**

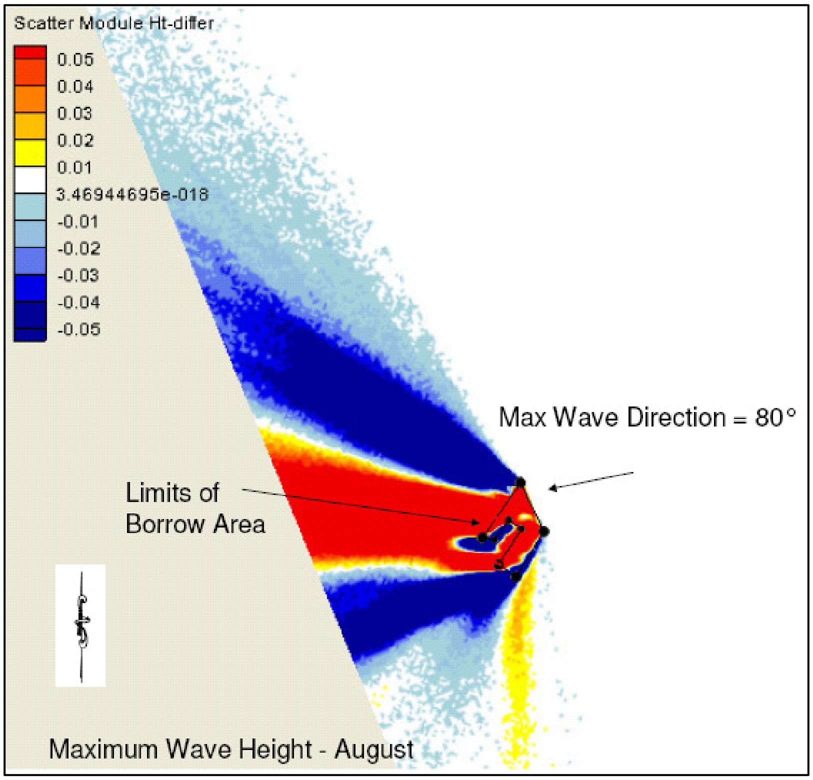


Figure 25: Wave Height Difference in Meters –Max Wave **(6.7m at 11.1sec)**

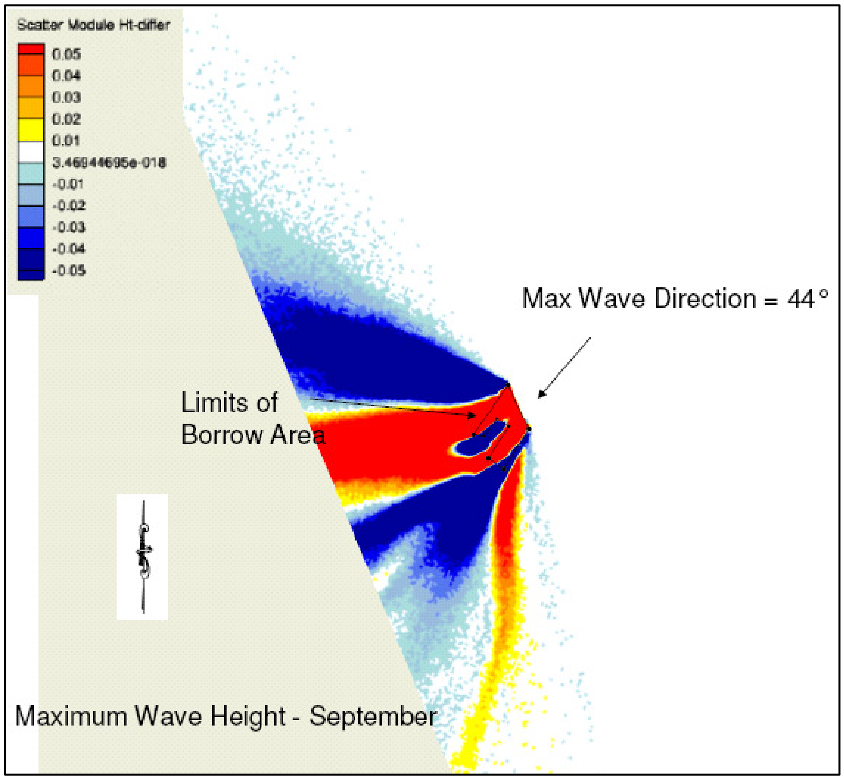


Figure 26: Wave Height Difference in Meters –Max Wave **(7.0m at 12.5sec)**

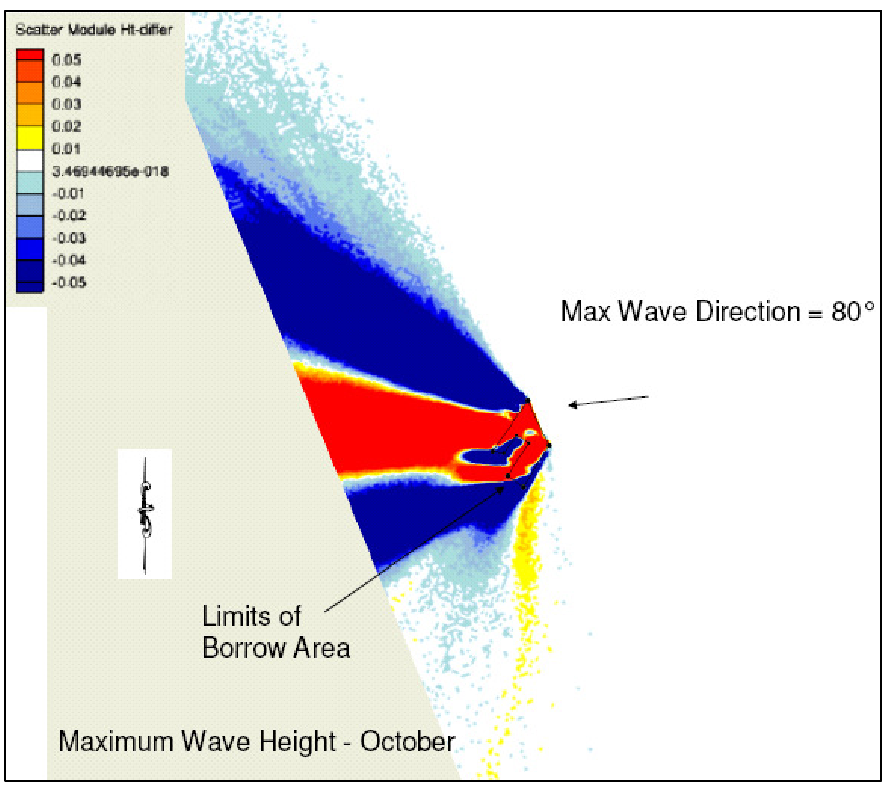


Figure 27: Wave Height Difference in Meters –Max Wave **(8.2m at 12.5sec)**

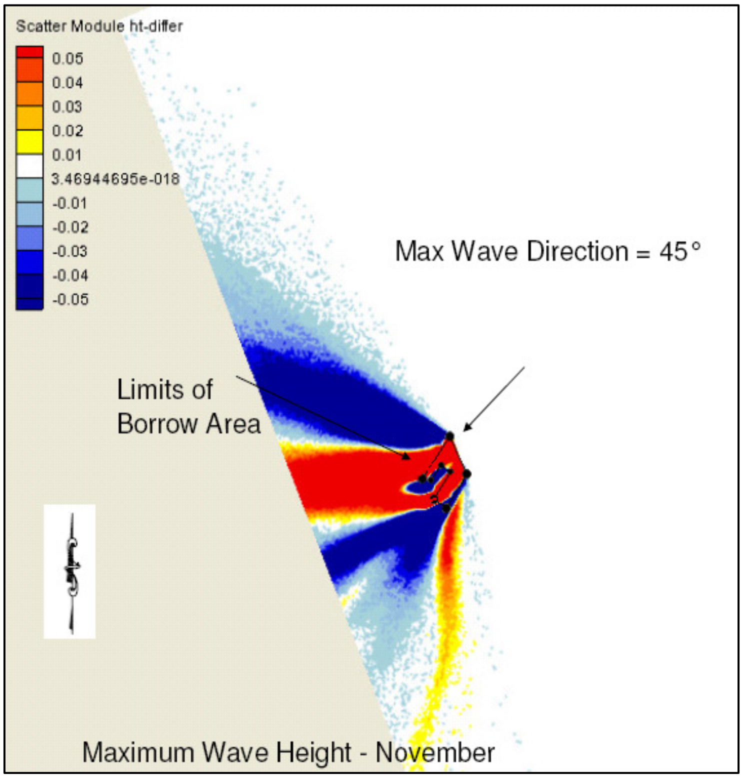


Figure 28: Wave Height Difference in Meters –Max Wave (5.9m at 12.5sec)

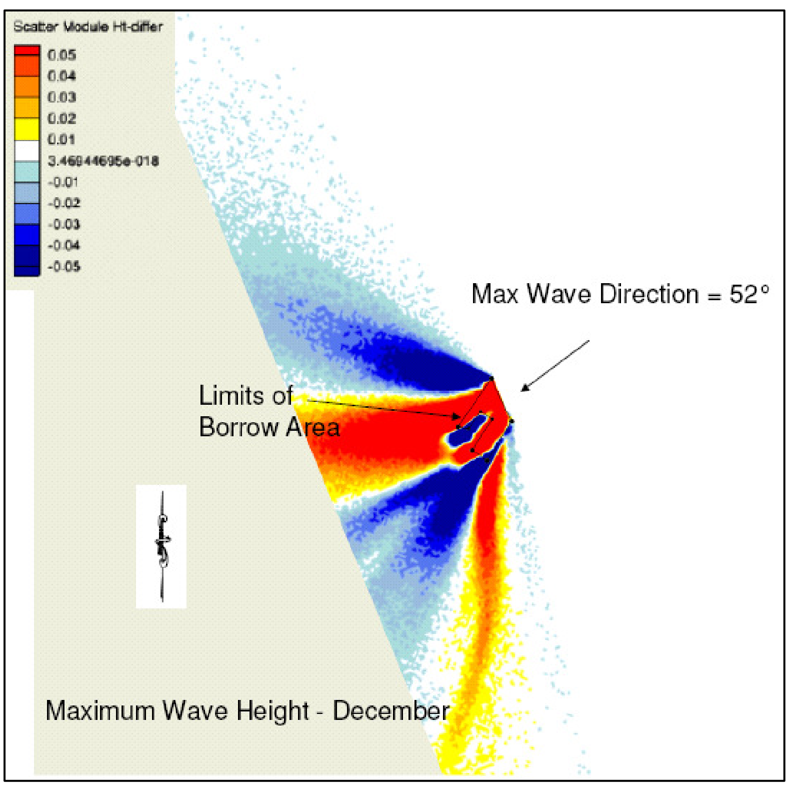


Figure 29: Wave Height Difference in Meters –Max Wave (4.3m at 10.0sec)

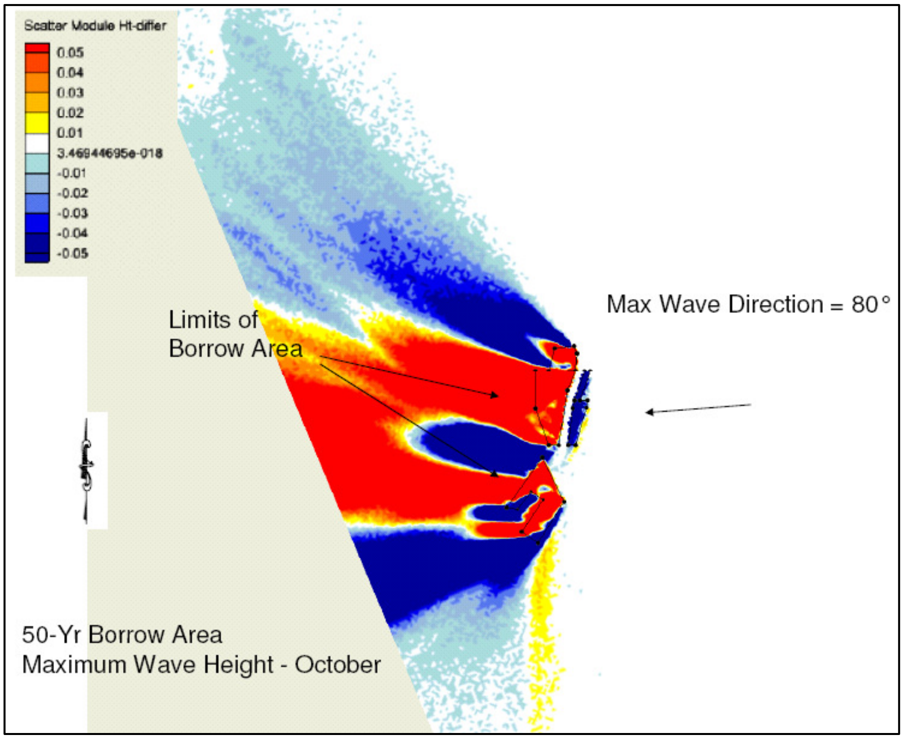


Figure 30: Wave Height Difference in Meters –October Wave **(8.2m at 12.5sec)**

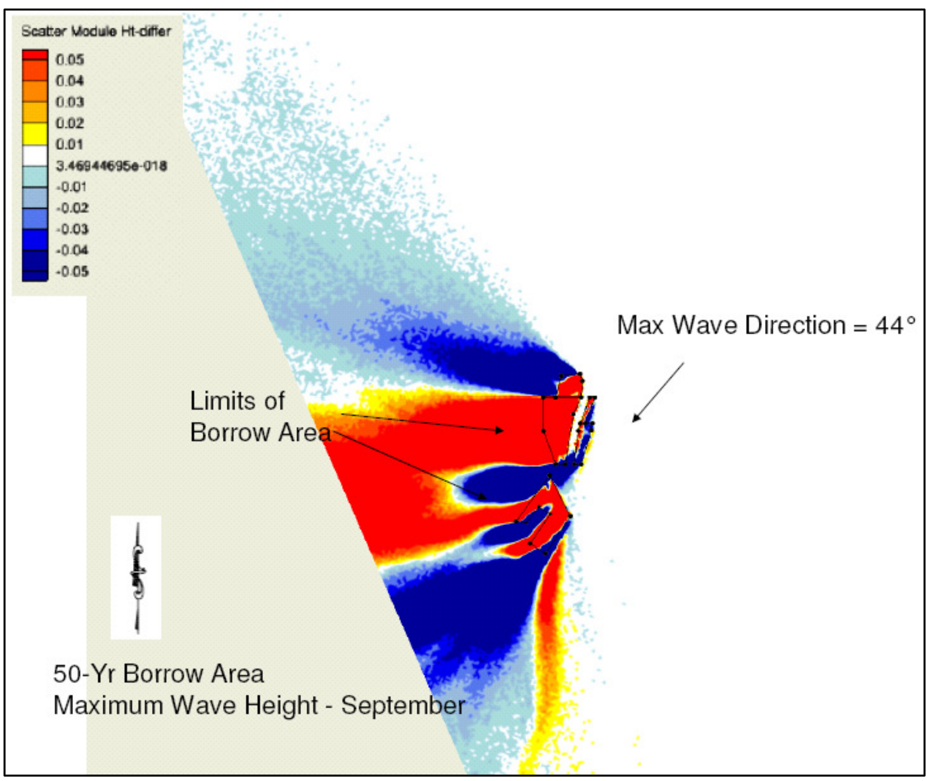


Figure 31: Wave Height Difference in Meters –September Wave **(7.0m at 12.5sec)**

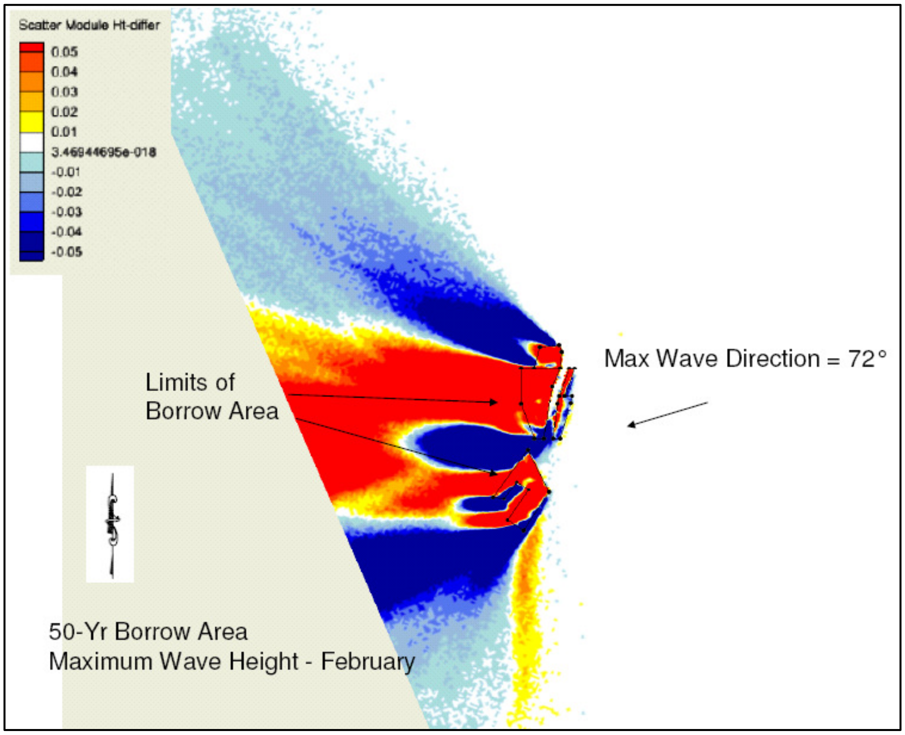


Figure 32: Wave Height Difference in Meters –February Wave **(5.2m at 12.5sec)**

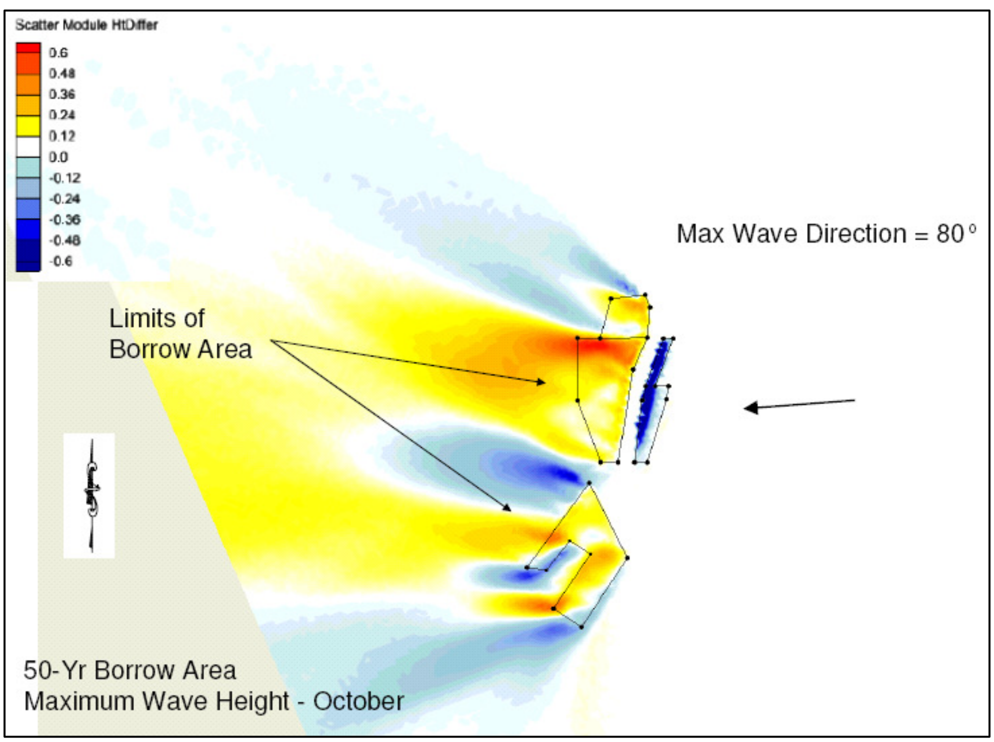


Figure 33: Wave Height Difference Dissipation

References:

Brigham Young University Engineering Computer Graphics Laboratory, 1997, "Surface-Water Modeling System Reference Manual", Brigham Young University, Provo, UT.

Hadley, Lori. 2008, "Influence of Capron Shoal Borrow Site Excavation on Nearshore Wave Climate, St. Lucie County". U.S. Army Corps of Engineers, Jacksonville, FL

Smith, J.M., Resio, D.T., and Zundel, A.K. 1999, "STWAVE: Steady State Wave Model: Report 1 – User's Manual for STWAVE Version 2.0," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

SUB-APPENDIX Q2

WAVE CLIMATE ANALYSIS SUPPLEMENT NO. 1

St. Lucie County

Supplement to

Offshore Borrow Area & Wave Climate Analysis

prepared for

St. Lucie County Florida

by

Coastal Tech
Coastal Technology Corporation

January 31, 2011
(Amended September 29, 2011)

The purpose of this supplemental document is to respond to the U.S. Army Corps of Engineers' (Corps) request for numerical quantification of any change in conditions in the nearshore environment resulting from use of the proposed Borrow Area. Among the review comments provided is a reference to a paper in 2004 by Kelley, Ramsey and Byrnes in which the authors propose a method for quantifying the significance of a shoreline's response to alteration bathymetry by offshore mining. The EIS reviewers contrast this proposed method with that used by Coastal Tech, which was based directly on a previous analysis by USACE (Hadley, 2008) and which was accepted by reviewers at that time.

There are two principal differences between the approach originally used by Coastal Tech (paralleling that by Hadley) and the method described in Kelley et al The first difference, as paraphrased by the EIS reviewer, is that: "*Kelley, et al converts wave height changes to potential longshore transport energy changes*." The second difference is that Kelley et al suggests using a statistical characterization of the inherent variability in transport potential about the mean (in the example cases, one-half of one standard deviation) as a test of the significance of any changes shown by the wave modeling and subsequent transport calculation.

The comparison of changes in wave height alone, instead of extending that comparison to calculated transport potential, does not seem to Coastal Tech to substantially benefit the analysis. In their discussion, Kelley et al refer to prior work by Rosati and Kraus (1991) which pointed to the effects of potential errors associated with wave heights and directions when used to predict longshore transport. However, Rosati and Kraus (1991) clearly state in their introduction the underlying relationship between the wave field and any predicted transport: "*The widely used CERC formula (SPM 1984) for estimating the potential sand transport rate is based on the assumption that Q is proportional to the longshore component of energy flux on the surf zone...*". The energy flux is simply proportional to the square of the wave height, modified by a term accounting for the angle of the waves to the shoreline. It might be noted that Kelley et al refer to previous impact analyses *they* performed (e.g., borrow sites in Alabama and New Jersey) for which changes in wave heights and direction indeed were used to quantify estimates of the significance of potential impacts. Also, Coastal Tech's figures of wave height difference (i.e., Figures 6 through 33) are not only identical to those used in previous analyses by Hadley, but are the same form as Figure 2 in Kelley et al.

The issue of quantifying the significance of any changes, even in the wave climate, does merit some further discussion. Coastal Tech concluded that the predicted changes in the waves resulting from the mining were insignificant based on inspection of the values, both as a percentage of the original wave heights, and as a percentage change in the wave energy term (i.e., squaring the wave heights). However, we have reexamined the actual data and offer the following observations for initial excavation of Area 5:

- The mean of the average monthly wave heights incident on the borrow area is 1.28 meters;
- The standard deviation (σ) in the average incident wave height is 0.34 meters; a 'one-half' σ would then be +/- 0.17 meters;
- The model-predicted maximum change in average wave height was 0.03 meters; this indicates that the change in average wave height resulting from the initial borrow area is significantly less than the typical variability in that same wave height.

Comparable results were calculated for the maximum incident wave heights with the following results:

- The mean maximum wave height was 5.05 meters;
- The standard deviation was 1.93 meters and 'one-half' σ or +/- 0.97 meters.
- These values can be compared to the model-predicted maximum change in maximum wave height for initial excavation of 0.34 meters. As with the mean wave heights, it is clear the predicted change in maximum wave height is appreciably less than the inherent variability in the data.

The data from the same STWAVE analysis *for 50 years of borrow area use* [full depletion of the volume] shows a maximum change (single most energetic month) in maximum wave height of 0.28 meters, which again, is appreciably less than the expected variability of the incident wave record (from above, +/- 0.97 meters)

As noted above, we acknowledge that the wave-induced energy flux is not the only component in predicting sediment transport; the wave crest angle affects the results as well. Changes in the wave direction predicated by STWAVE were examined in Coastal Tech's original analysis and were concluded by inspection to be insignificant in affecting the shoreline. The data has been reexamined and for only the maximum waves modeled which occur in only the three most energetic months in the wave record, the mean change in absolute wave direction resulting from the initial borrow area excavation was 0.021 degrees. For the full 50 years depletion, the mean difference in wave angle was 1.97 degrees. These relatively small changes, even for the maximum condition, are not unexpected because only a small percentage of the incident waves are affected by the borrow area at all and most approach angle differences are 'zero'.

A rough approximation of the influence of this wave angle change might be estimated by inserting the crest angle change into the ($\sin 2\Theta$) term of the CERC transport equation. This returns a 'difference' in potential transport for initial excavation of less than 1 percent. Again, note that this is the difference for the maximum wave heights in only the three most energetic months. The effect under mean wave conditions would be expected to be even less. For full depletion over 50 years, the maximum 'difference' in transport potential would be approximately 6.8 percent. Note that this maximum potential for the 50 year life was calculated for only the single most energetic month and therefore is likely to occur only one-twelfth or 8 percent of the time.

An average annual net transport rate for this section on St. Lucie County is on the order of 100,000 cubic meters. Considering the wave direction angle change for maximum wave conditions as discussed above, the resulting potential increase in sediment transport for initial excavation might then be on the order of 1 percent of that value, or 1000 cubic meters per year. For full 50 years of use, this could be a maximum of 6800 cubic meters. Examination of the wave height change figures suggests that the ‘shadow’ zone of influence of the wave change is on the order of perhaps half of the total 20,000 feet in the project area. Taking this as representative of a conservative case, a potential 1000 cubic meter annual change in transport, distributed on 10,000 feet of shoreline would be on the order of one-tenth of a cubic meter per linear foot; for full depletion over 50 years, it would be eight-tenths of a cubic meter per liner foot. Applying typically accepted ‘rules of thumb’ for volumetric change versus shoreline change, either of these maximum volumetric changes would result in less than a foot of shoreline change.

SUB-APPENDIX Q3

WAVE CLIMATE ANALYSIS SUPPLEMENT NO. 2

St. Lucie County

Supplement to

Offshore Borrow Area & Wave Climate Analysis

prepared for

ST. LUCIE COUNTY FLORIDA

by

COASTAL TECH
COASTAL TECHNOLOGY CORPORATION

January 31, 2011
(Revised October 11, 2011)

Background: The Corps has requested a numerical quantification of any change in conditions in the nearshore environment resulting from use of the proposed Borrow Area. Among the review comments provided is a reference to a paper in 2004 by Kelley, Ramsey and Byrnes in which the authors propose a method for quantifying the significance of a shoreline's response to alteration bathymetry by offshore mining. The EIS reviewers contrast this proposed method with that used by Coastal Tech, which was based directly on a previous analysis by USACE (Hadley, 2008) and which was accepted by reviewers at that time.

There are two principal differences between the approach originally used by Coastal Tech (paralleling that by Hadley) and the method described in Kelley et al. The first difference, as paraphrased by the EIS reviewer, is that: "*Kelley, et al converts wave height changes to potential longshore transport energy changes*." The second difference is that Kelley et al suggests using a statistical characterization of the inherent variability in transport potential about the mean (in the example cases, one-half of one standard deviation) as a test of the significance of any changes shown by the wave modeling and subsequent transport calculation.

The comparison of changes in wave height alone, instead of extending that comparison to calculated transport potential, does not seem to Coastal Tech to substantially benefit the analysis. In their discussion, Kelley et al refer to prior work by Rosati and Kraus (1991) which pointed to the effects of potential errors associated with wave heights and directions when used to predict longshore transport. However, Rosati and Kraus (1991) clearly state in their introduction that the underlying relationship between the wave field and any predicted transport: "*The widely used CERC formula (SPM 1984) for estimating the potential sand transport rate is based on the assumption that Q is proportional to the longshore component of energy flux on the surf zone…*". The energy flux is simply proportional to the square of the wave height, modified by a term accounting for the angle of the waves to the shoreline. It should be noted that Kelley et al refer to previous impact analyses *they* performed (e.g., borrow sites in Alabama and New Jersey) for which changes in wave heights and direction were indeed used to quantify estimates of the significance of potential impacts. Also, Coastal Tech's figures of wave height difference (i.e., Figures 6 through 33) are not only identical to those used in previous analyses by Hadley, but are in the same form as Figure 2 in Kelley et al.

Extended Wave Height Change Discussion: It was on the basis of the above points that Coastal Tech originally presented only the changes in wave heights rather than extending the analysis to direct calculation of longshore sediment transport. In addition, the reference line at which Coastal Tech presented the wave height comparisons, while offshore from the actual breaker line, was still within approximately one-half mile (~2600 feet; ~800 meters) of the shoreline. Specifically, the landward edge of the wave height change figures Coastal Tech presented in the original analysis is only 800 meters off the beach. This location is almost three miles shoreward of the borrow areas and at a location where it was believed that bottom contours were generally plane and regular. The point of this observation was that although "post-excavation" waves that had been altered by changes in the borrow area bathymetry might continue to transform shoreward until breaking, the "pre-excavation" waves would shoal and break in a very similar manner so that comparisons between the pre- and post-conditions were still very valid.

The issue of quantifying the significance of any changes (as suggested by Kelley et al), even in the wave climate, does merit some further discussion. Coastal Tech concluded that the predicted changes in the waves resulting from the mining were insignificant based on inspection of the values, both as a percentage of the original wave heights, and as a percentage of change in the wave energy term (i.e., squaring the wave heights). However, after receiving initial review comments, we have reexamined the actual data and offer the following observations for initial excavation of Area 5:

- The mean of the average monthly wave heights incident on the borrow area is 1.28 meters;
- The standard deviation (σ) in the average incident wave height is 0.34 meters; a 'one-half' σ would then be +/- 0.17 meters;
- The model-predicted maximum change in average wave height was 0.03 meters; this indicates that the change in average wave height resulting from the initial borrow area is significantly less than the typical variability in that same wave height.

Comparable results were calculated for the maximum incident wave heights with the following results:

- The mean maximum wave height was 5.05 meters;
- The standard deviation was 1.93 meters and 'one-half' σ or +/- 0.97 meters.
- These values can be compared to the model-predicted maximum change in maximum wave height of 0.34 meters for the case of initial excavation. As with the mean wave heights, it is clear the predicted change in maximum wave height is appreciably less than the inherent variability in the data.

It should be noted that these very minor changes in the incident waves resulting from the one-time use/excavation of Area 5 are logical given the fact that this site has ambient water depths on the order of 49 feet and the excavation would be entirely in the lee of the proposed long-term borrow site (Area A) where ambient depths are as shallow as 20+ feet. The offshore shoal would be expected to be the dominant feature affecting wave energy.

This expectation is realized in looking at the wave changes associated with *50 years of borrow area use* [full depletion of the volume in the offshore borrow site (Area A)]. The data from the same STWAVE analysis *for 50 years of borrow area use* shows a maximum change (single most energetic month) in maximum wave height of 0.28 meters, which although more significant than for using Area 5 alone, is still appreciably less than the expected variability of the incident wave record (from above, +/- 0.97 meters).

As noted above, we acknowledge that the wave-induced energy flux is not the only component in predicting sediment transport; the wave crest angle affects the results as well. Changes in the wave direction predicated by STWAVE were examined in Coastal Tech's original analysis and were concluded by inspection to be insignificant in affecting the shoreline. The data has been reexamined and for <u>only the maximum waves</u> modeled, which occur in only the three most energetic months in the wave record, the mean change in absolute wave direction resulting from the initial borrow area excavation was 0.021 degrees. For the full 50 years depletion, the mean difference in wave angle was 1.97 degrees. These relatively small changes, even for the maximum condition, are not unexpected because only a small percentage of the incident waves are affected by the borrow area at all and most approach angle differences are 'zero.'

<u>Effect on Longshore Sediment Transport Potential (LST)</u>: Subsequent discussion with the EIS reviewers indicated that there was still a level of discomfort with using only the wave climate change results summarized above as the basis for estimating shoreline change impacts. In order to address this concern and facilitate continued processing of the permit application, Coastal Tech extended the wave change results to representative direct calculation of 'pre-' and 'post-' sediment transport potential and comparison of those estimates.

This calculation was performed by extracting wave characteristics at the offshore reference line (800 meters off the beach) and transforming examples of those data to the wave breaking point. Waves for the pre-excavation case, the initial Area 5 post-excavation case, and the full 50-year depletion case were extracted from points corresponding to the approximate location of 13 FDEP survey reference monuments (i.e., St. Lucie County R-106 to R-115, and three locations downdrift into Martin County). As discussed with the EIS review team, the statistical wave extracted for these cases and used in the analysis below, is the *average maximum wave for the most energetic month* in the 20-year WIS record. Coastal Tech is comfortable using this approach with the caveat that those conclusions drawn from it must be understood to be statistically "exceptional."

Calculation of the breaking wave heights for this site is a relatively difficult process because of the very complex nearshore bathymetry resulting from the presence and variability of nearshore hardbottom. Rather than proceed with an STWAVE grid analysis, individual profiles and wave conditions were transformed using the USACE SBEACH numerical model. This approach provides the advantage of being able to input a beach profile and visually inspect the resulting envelope of wave heights. However, in order to reduce overall analysis time, waves were carried to breaking at only three locations. These locations (R-106; R-111 and R-115) are generally representative of the types of wave changes observed in the wave change plots in the original report/analysis; that is, R-106 and R-11 are in zones where STWAVE predicts wave heights would not change or might actually decrease, while at R-115 the excavations would result in increased wave heights. The following tables summarize the incident wave conditions and the associated breaking waves at each of the three selected FDEP monuments.

Supplement Table 1: Pre-Excavation of Borrow Areas

	STWAVE Output			Calculated Parameters				
FDEP R-Mon	Average Maximum Wave, Ht (m)	Average Maximum Wave, Ht (ft)	Model Output θ (Deg)	True North θ (shoreline Az = 66.5)	Crest Angle (wrt shoreline, α, Deg)	Breaking Wave Ht (Hb, m)	Breaking Wave Ht (Hb, ft)	LST Potential (x 10^7)
106	5.12	16.78	187.81	121.31	-34.69	2.8	9.3	-4.74763
107	5.28	17.32	188.92	122.42	-33.58			
108	5.45	17.89	187.85	121.35	-34.66			
109	5.51	18.07	186.22	119.72	-36.28			
110	5.52	18.10	187.69	121.19	-34.81			
111	5.54	18.18	187.24	120.74	-35.27	3.4	11.2	-7.61234
112	5.43	17.81	187.19	120.69	-35.31			
113	5.62	18.42	186.91	120.41	-35.59			
114	5.70	18.70	188.82	122.32	-33.68			
115	5.81	19.06	188.75	122.25	-33.75	3.1	10.3	-6.05034
1	5.83	19.13	190.06	123.56	-32.44			
2	5.84	19.15	190.61	124.11	-31.89			
3	5.81	19.07	190.77	124.27	-31.73			

Supplement Table 2: Post-Excavation of Area 5 Only

	STWAVE Output			Calculated Parameters				
FDEP R-Mon	Average Maximum Wave, Ht (m)	Average Maximum Wave, Ht (ft)	Model Output θ (Deg)	True North θ (shoreline Az = 66.5)	Crest Angle (wrt shoreline, α, Deg)	Breaking Wave Ht (Hb, m)	Breaking Wave Ht (Hb, ft)	LST Potential (x 10^7)
106	5.12	16.79	187.44	120.94	-35.07	2.7	9.0	-4.39537
107	5.14	16.86	189.65	123.15	-32.85			
108	5.34	17.52	188.56	122.06	-33.95			
109	5.44	17.84	187.15	120.65	-35.35			
110	5.37	17.63	188.06	121.56	-34.44			
111	5.42	17.77	187.66	121.16	-34.84	3.4	11.0	-7.2377
112	5.30	17.37	187.38	120.88	-35.12			
113	5.61	18.41	186.83	120.33	-35.67			
114	5.72	18.76	188.02	121.52	-34.48			
115	5.88	19.28	188.94	122.44	-33.56	3.1	10.3	-6.03359
1	5.94	19.50	190.36	123.86	-32.14			
2	5.89	19.31	190.77	124.27	-31.74			
3	5.83	19.11	191.22	124.72	-31.28			

Supplement Table 3: 50 Year Cumulative Post- Excavation of Borrow Areas

	STWAVE Output			Calculated Parameters				
FDEP R-Mon	Average Maximum Wave, Ht (m)	Average Maximum Wave, Ht (ft)	Model Output θ (Deg)	True North θ (shoreline Az = 66.5)	Crest Angle (wrt shoreline, α, Deg)	Breaking Wave Ht (Hb, m)	Breaking Wave Ht (Hb, ft)	LST Potential (x 10^7)
106	4.99	16.35	187.39	120.89	-30.89	2.8	9.1	-4.23368
107	5.01	16.44	188.76	122.26	-32.26			
108	5.20	17.06	189.65	123.15	-33.15			
109	5.35	17.55	188.28	121.78	-31.78			
110	5.37	17.60	186.86	120.36	-30.36			
111	5.42	17.77	188.35	121.85	-31.85	3.4	11.0	-6.92002
112	5.47	17.94	187.92	121.42	-31.42			
113	5.43	17.82	188.01	121.51	-31.51			
114	5.73	18.81	188.89	122.39	-32.39			
115	5.89	19.33	189.24	122.74	-32.74	3.2	10.5	-6.25117
1	5.87	19.27	189.28	122.78	-32.78			
2	5.96	19.53	190.66	124.16	-34.16			
3	5.90	19.35	191.28	124.78	-34.78			

It can be noted that the changes in wave heights shown in the above tables based on this sampling of the STWAVE output are slightly different (typically *smaller* differences) than quoted in the discussion paragraphs above. The thirteen examples above were extracted from the much larger set (~500) of waves calculated along the full offshore reference line.

Using the above wave results and the CERC formula, Coastal Tech calculated the average maximum longshore sediment transport potential. These results are also summarized in Supplement Tables 1, 2 and 3 (i.e., "LST" column). The negative sign follows the convention of indicating northerly directed transport. In reviewing these results, it is useful to show them in context of other estimates of transport potential. The following Table 1 shows some example estimates for St. Lucie County.

Supplement Table 4: Sample Reported Values of LST for St. Lucie County

Source	***North (yd^3/year)***	***South (yd^3/year)***	***Net Drift (yd^3/year)***
USACE 1962		200,000 – 250,000	
Walton 1979	245,000 – 281,000	260,000 – 387,000	15,000 – 106,000
WES 1955-1975	170,000	185,000	15,000
CP&E 1997		106,000	
USACE 1998		53,000	
Brown 2002		500,000	

Rodriguez and Dean, "*A Sediment Budget Analysis and Management Strategy for Ft. Piece Inlet,"* 2005.

As a conclusion to their analysis, Rodriguez and Dean (2005) estimated that *"...57,000 cubic yards per year leave the south boundary of St. Lucie County*; "presumably this is intended to represent "net transport." As part of the design development for the present St. Lucie County fill project, Coastal Tech performed numerical modeling of the potential fill performance. As part of the calibration and verification of the MIKE21 model the transport potential was calculated to be 277 cubic meters per day (~132,000 cubic yards annually).

It can be seen both by inspection and in comparison to the above examples that the predicted transport potentials in Tables 1, 2 and 3 are exceptionally large. This is due in part to the caveat noted previously that the waves used are the average maximum conditions. Even at breaking these waves are on the order of ~3 meters and an associated calculated *potential* LST of the order shown is not an unreasonable mathematical result.

The premise for considering these exceptionally large values in any further conclusion is the fact that we are interested primarily in the *change in potential values* resulting from the wave field modification, not necessarily in the actual values. For example, comparing the pre-excavation LST at R-106 (-4.74763 (all values x 10^07)) to that at the same location following excavation of Area 5 (-4.39537) indicated a "difference" of ~0.35, which is a potential 7.4 decrease in northerly transport. Similar results were calculated for other comparisons with the following outcomes:

- R-106: 7.4 percent decrease for Area 5; 10.8 percent decrease for 50 years
- R-111: 4.9 percent decrease for Area 5; 9.1 percent decrease for 50 years
- R-115: 0.3 percent decrease for Area 5; 3.3 percent increase for 50 years

Again, the effect under mean wave conditions would be expected to be even less. The effect on any actual shoreline position depends very much on how the above values are interpreted and at what location. For a net southerly transport, a decrease in the northerly directed component could represent an increase on net movement away from that location.

Conclusion: Returning to the values in Table 4, the 'actual' and reasonable average annual net transport rates for St. Lucie County is on the order of 100,000 cubic meters (~130,000 cubic yards). Considering the "differences" in computed LST for the maximum wave case as discussed above, the resulting potential change in sediment transport for initial excavation of Area 5 might then be on the order of 7.4 percent of that value, or 7400 cubic meters per year. For full 50 years of use, this could be a maximum of 10800 cubic meters. Examination of the wave height change figures suggests that the 'shadow' zone of influence of the wave change is on the order of perhaps half of the total 20,000 feet in the project area. Taking this as representative of a conservative case, a potential 7400 cubic meter annual change in transport, distributed on 10,000 feet of shoreline would be on the order of seven-tenths of a cubic meter per linear foot; for full depletion over 50 years it would be just over one cubic meter per liner foot. Applying typically accepted 'rules of thumb' for volumetric change versus shoreline change, either of these maximum volumetric changes would result in roughly one foot of shoreline change. Based on these values and the fact that the analysis used "exceptional" values of wave heights, it is extremely unlikely that the excavation of Area 5 or full depletion of the outer borrow site will have a significant impact to sediment transport rates or shoreline positions within the project limits.