

FINAL REPORT – November 2001

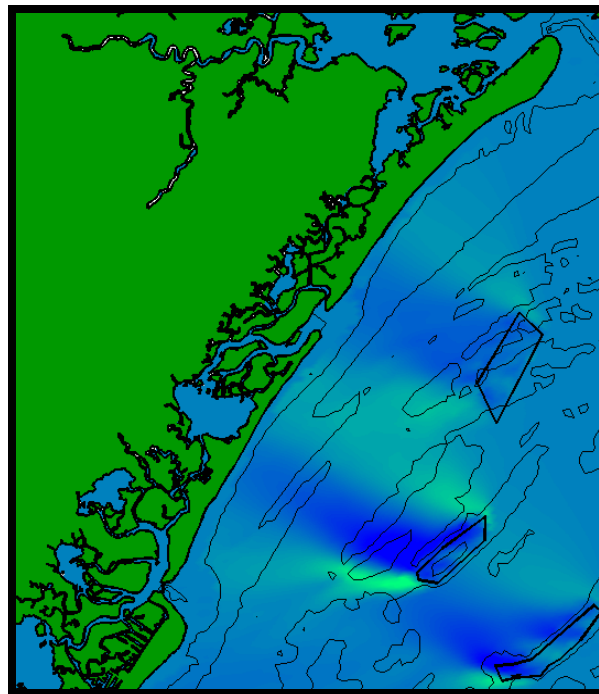
NUMERICAL MODELING EVALUATION OF THE CUMULATIVE PHYSICAL EFFECTS OF OFFSHORE SAND DREDGING FOR BEACH NOURISHMENT

Prepared by:

Sean W. Kelley
John S. Ramsey
Mark R. Byrnes



Applied Coastal Research and Engineering, Inc.
766 Falmouth Road, Suite A-1
Mashpee, MA 02649



Prepared for:

U.S. Department of the Interior
Minerals Management Service
International Activities and Marine
Minerals Division (INTERMAR)



Funded Under Contract Number 1435-01-99-CT-30993

DISCLAIMER

This report has been reviewed by the Minerals Management Service and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Service, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

SUGGESTED CITATION

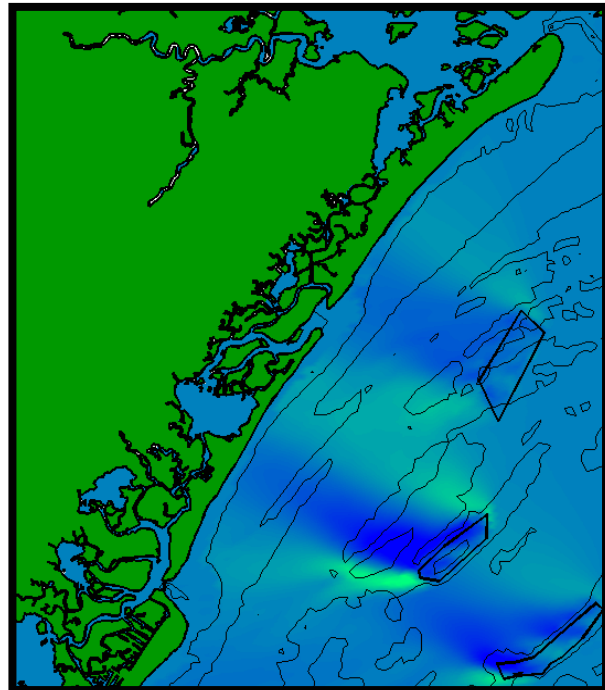
Kelley, S.W., J.S. Ramsey, M.R. Byrnes, 2001. Numerical Modeling Evaluation of the Cumulative Physical Effects of Offshore Sand Dredging for Beach Nourishment. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 2001-098, 95 pp. + 106 pp. appendices.

FINAL REPORT

Numerical Modeling Evaluation Of The Cumulative Physical Effects Of Offshore Sand Dredging For Beach Nourishment

November 2001

Sean W. Kelley
John S. Ramsey
Mark R. Byrnes



Prepared by:

Applied Coastal Research and Engineering, Inc.
766 Falmouth Road, Suite A-1
Mashpee, MA 02649

Prepared for:

U.S. Department of the Interior
Minerals Management Service
International Activities and Marine
Minerals Division (INTERMAR)



Funded Under Contract Number 1435-01-99-CT-30993

ACKNOWLEDGMENTS

This project was funded by the U.S. Department of the Interior (DOI), Minerals Management Service (MMS), International Activities and Marine Minerals Division (INTERMAR) under Contract #1435-01-99-CT-30993. Mr. Barry S. Drucker was the MMS Contracting Officer's Technical Representative (COTR) and provided valuable assistance throughout the project. Ms. Jane Carlson served as the MMS Contracting Officer. Mr. Barry Drucker and Mr. Roger Amato of the MMS reviewed the draft document.

Mr. Sean W. Kelley authored Sections 3.0 (Modeling Approach and Applications), 4.0 (Cumulative Impacts), and Appendices B through E. Mr. John S. Ramsey authored Sections 2.0 (Physical Processes) and 5.0 (Conclusions). Dr. Mark R. Byrnes served as Project Manager and Editor of the report, and authored Section 1.0 (Introduction). Ms. Elizabeth Hunt was responsible for report compilation and editorial assistance during production of the report.

TABLE OF CONTENTS

1.0 INTRODUCTION.....	1
1.1 STUDY PURPOSE.....	2
1.2 STUDY AREAS AND BORROW SITE CHARACTERISTICS	2
1.3 STUDY APPROACH	6
1.4 DOCUMENT ORGANIZATION	7
2.0 PHYSICAL PROCESSES.....	8
2.1 NEARSHORE WAVE TRANSFORMATION	8
2.2 NEARSHORE SEDIMENT TRANSPORT PATTERNS.....	10
2.3 IDEALIZED OFFSHORE BORROW SITE	11
2.4 SIGNIFICANCE OF BORROW SITE IMPACTS	16
2.4.1 Available Methods for Assessing Borrow Site Impacts.....	17
2.4.2 Reference Line Statistical Approach.....	18
2.4.3 Potential Uncertainties in Wave Information Approach	19
2.4.4 Spatial and Temporal Variations in Wave Climate Approach	20
3.0 MODELING APPROACH AND APPLICATIONS.....	23
3.1 ANALYSIS APPROACH.....	23
3.1.1 Wave Modeling	23
3.1.2 Input Spectra Development	25
3.1.2.1 Southern New Jersey WIS Data.....	25
3.1.2.2 Southeastern Virginia WIS Data.....	25
3.1.2.3 North Carolina WIS Data.....	27
3.1.2.4 Cape Canaveral WIS Data.....	28
3.1.2.5 Development of Model Spectra from WIS Data	28
3.1.2.6 Spectral Development from Wave Buoy Data.....	33
3.1.3 Grid Development.....	35
3.1.4 Sediment Transport Potential	44
3.2 MODEL RESULTS	45
3.2.1 Wave Modeling	45
3.2.1.1 Offshore New Jersey.....	48
3.2.1.2 Offshore Southeastern Virginia	52
3.2.1.3 Offshore North Carolina	57
3.2.2 Sediment Transport Potential	64
3.2.2.1 Model Comparison with Historical Shoreline Change	64
3.2.2.2 Modeled Transport and Dredging Impacts	73
3.2.2.3 Dredging Impacts at East Coast Sites.....	80
4.0 CUMULATIVE IMPACTS	82
4.1 SITES IN CLOSE PROXIMITY.....	82
4.2 MULTIPLE DREDGING EVENTS AT A SINGLE SITE	85
5.0 CONCLUSIONS.....	88
5.1 WAVE MODEL ASSESSMENT.....	88
5.2 MANAGEMENT TOOL FOR ASSESSING IMPACT SIGNIFICANCE.....	89
5.3 WAVE AND SEDIMENT TRANSPORT ANALYSIS	90
5.4 APPLICATION OF MANAGEMENT TOOL	91
5.5 CUMULATIVE EFFECTS	92
6.0 REFERENCES.....	93

**APPENDIX A: COMPARISON OF NUMERICAL SPECTRAL WAVE
TRANSFORMATION MODELS FOR EVALUATING THE
PHYSICAL ENVIRONMENTAL IMPACTS OF OFFSHORE
SAND MINING..... A-1**

APPENDIX B: NEW JERSEY WAVE MODEL OUTPUT..... B-1

APPENDIX C: VIRGINIA WAVE MODEL OUTPUT C-1

APPENDIX D: NORTH CAROLINA WAVE MODEL OUTPUT..... D-1

APPENDIX E: FLORIDA WAVE MODEL OUTPUT..... E-1

LIST OF FIGURES

Figure 1-1.	Location diagram illustrating sand borrow sites M8 (USACE designation), A1 and A2 (NJ State designation), and State-Federal boundary relative to 1934/77 bathymetry.	3
Figure 1-2.	Location diagram illustrating sand borrow sites A and B and State-Federal boundary relative to 1934/77 bathymetry.	4
Figure 1-3.	Location diagram illustrating sand borrow sites 3 West and 3 East and State-Federal boundary relative to 1934/77 bathymetry.	5
Figure 1-4.	Location diagram illustrating sand Borrow Site II and State-Federal boundary relative to 1934/77 bathymetry.	6
Figure 2-1.	Diagram illustrating the effects of refraction and diffraction as waves approach the coastline (from Svendsen and Jonsson, 1976).	10
Figure 2-2.	Surface plot with 2.5 m contours of bathymetry grid used for idealized borrow site model runs.	12
Figure 2-3.	Example color contour plot of modeled wave heights, with vectors indicating mean wave direction for idealized borrow site (incident wave height of 1.2 m and period of 8 sec approaching shoreline at -30° from shore-normal).	13
Figure 2-4.	Color surface plot of wave height difference ($H_{\text{post}} - H_{\text{pre}}$) resulting from borrow site excavation, for wave case shown in Figure 2-3.	13
Figure 2-5.	Computed annualized longshore sediment transport potential for idealized borrow site for five wave cases.	14
Figure 2-6.	Change in computed longshore sediment transport potential for idealized borrow site.	14
Figure 2-7.	Computed cross-shore change in shoreline position based on modifications to longshore sediment transport potential by idealized borrow site.	15
Figure 2-8.	Change in computed longshore sediment transport potential based on alternate distribution of wave percent occurrences.	16
Figure 2-9.	Computed cross-shore change in shoreline position based on modifications to longshore sediment transport potential using alternate distribution of wave percent occurrences.	16
Figure 2-10.	Percent change in wave energy showing regions of acceptance and rejection of the null-hypothesis using ≥ 4.0 percent as the cut-off value (from Basco, 1999).	18
Figure 2-11.	Example of results for spatial/temporal variability method for determining significance of borrow site dredging impacts. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore Sandbridge, Virginia. Middle plot shows dredging significance criterion envelope ($\pm\sigma$) determined for this shoreline. The left plot of the shoreline is given for reference.	21
Figure 3-1.	Diagram of wave and current vectors used in STWAVE (from Smith et al., 1999). Subscript <i>a</i> denotes values in the <i>absolute</i> frame of reference, and subscript <i>r</i> denotes values in the <i>relative</i> frame of reference (with currents).	24

Figure 3-2. Shoreline from New Jersey to North Carolina with coarse grid limits and wave input data stations used to determine dredging impacts from offshore sand mining..... 26

Figure 3-3. Wave height and period for hindcast data from WIS station AU2067 (offshore New Jersey) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction..... 27

Figure 3-4. Wave height and period for hindcast data from WIS station AU2058 (offshore southern Virginia) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction..... 27

Figure 3-5. Wave height and period for hindcast data from WIS station AU2056 (offshore North Carolina) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction..... 28

Figure 3-6. East Florida shoreline at Cape Canaveral with coarse grid limits and wave input data station used to determine dredging impacts from offshore sand mining..... 29

Figure 3-7. Wave height and period for hindcast data from WIS station AU2019 (Cape Canaveral) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction..... 29

Figure 3-8. Example of STWAVE input spectrum developed using WIS 20-year hindcast data and Goda method of computing frequency and direction spectrum. Plots show a) frequency distribution of energy at peak direction, b) directional distribution of energy at peak frequency, and c) surface plot of two-dimensional energy spectrum. Example is model case 5 ($H_{mo} = 0.9$ m, $\theta_{mean} = 130^\circ$ grid relative)..... 31

Figure 3-9. Wave height and wave period roses for data recorded by NDBC buoy 44014 (offshore Virginia Beach) for the 5-year period between January 1996 and December 2000. Direction indicates the direction waves were propagating from relative to true north. Radial length of gray tone segments indicates percent occurrence of each range of wave condition (height or period). Combined length of segments in each sector indicates percent occurrence of all waves from that direction. 33

Figure 3-10. Color contour plot of coarse model grid (200 m x 200 m grid spacing) of offshore New Jersey. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line..... 36

Figure 3-11. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) used with STWAVE for offshore New Jersey. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line. 37

Figure 3-12. Color contour plot of coarse model grid (200 m x 200 m grid spacing) of offshore southeastern Virginia. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line..... 38

Figure 3-13. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) of offshore southern Virginia used with STWAVE. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line. 39

Figure 3-14. Color contour plot of coarse model grid (200 m x 200 m grid spacing) for offshore North Carolina. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line..... 40

Figure 3-15. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) for offshore North Carolina. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line..... 41

Figure 3-16. Color contour plot of coarse model grid (200 m x 200 m grid spacing) for offshore Cape Canaveral, FL. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line..... 42

Figure 3-17. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) for offshore Cape Canaveral, FL. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line..... 43

Figure 3-18. Example of coarse grid wave height difference plot between existing and post-dredging bathymetry conditions offshore Townsends Inlet, NJ. This result is for NJ wave case 7; 1.6 m wave height and 11.1 sec period..... 46

Figure 3-19. Example of fine grid wave height difference plot between existing and post-dredging bathymetry conditions offshore Townsends Inlet, NJ. This result is for NJ wave case 7; 1.6 m wave height and 11.1 sec period. 47

Figure 3-20. Coarse grid model results for offshore North Carolina (wave case 9; 1.3 m wave height, 11.3 sec period) illustrating area of reduced wave heights resulting from refraction of wave energy due to bottom bathymetry..... 48

Figure 3-21. Coarse grid model results for Sandbridge Shoal, Virginia for wave case 10 (1.8 m wave height, 10.0 sec wave period) showing wave focusing effect of natural shoal deposits and area of reduced wave heights to the southwest of the shoals. 49

Figure 3-22. Fine grid model results for Sandbridge Shoal, Virginia for the same wave case presented in Figure 3-21. Detailed analysis illustrates nearshore refraction of waves and wave height reductions through the width of the surf zone..... 49

Figure 3-23. Plot of STWAVE model output for southern New Jersey wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.1$ sec, $\theta_{peak}=131$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 50

Figure 3-24. Plot of STWAVE model output for southern New Jersey wave Case 7 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=81$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 51

Figure 3-25. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites for STWAVE model output of southern New Jersey wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.1$ sec, $\theta_{peak}=131$ deg)..... 52

Figure 3-26. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites for STWAVE model output of southern New Jersey wave Case 7 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=81$ deg)..... 53

Figure 3-27. Plot of STWAVE model output for southeastern Virginia wave Case 7 ($H_s=2.8$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=39$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 54

Figure 3-28. Plot of STWAVE model output for southeastern Virginia wave Case 10 ($H_s=1.8$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=134$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. 55

Figure 3-29. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites A and B for STWAVE model output for southeastern Virginia wave Case 7 ($H_s=2.8$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=39$ deg)..... 56

Figure 3-30. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites A and B for STWAVE model output for southeastern Virginia wave Case 10 ($H_s=1.8$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=134$ deg)..... 57

Figure 3-31. Plot of STWAVE model output for offshore North Carolina wave Case 2 ($H_s=1.9$ m, $T_{peak}=6.0$ sec, $\theta_{peak}=21$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 58

Figure 3-32. Plot of STWAVE model output for offshore North Carolina wave Case 8 ($H_s=1.5$ m, $T_{peak}=12.8$ sec, $\theta_{peak}=71$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 59

Figure 3-33. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites 3 East and 3 West for STWAVE model output for offshore North Carolina wave Case 2 ($H_s=1.9$ m, $T_{peak}=6.0$ sec, $\theta_{peak}=21$ deg)..... 60

Figure 3-34. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites 3 East and 3 West for STWAVE model output for offshore North Carolina wave Case 8 ($H_s=1.5$ m, $T_{peak}=12.8$ sec, $\theta_{peak}=71$ deg)..... 61

Figure 3-35. Plot of STWAVE model output for Cape Canaveral, Florida wave Case 3 ($H_s=1.0$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=100$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 62

Figure 3-36. Plot of STWAVE model output for Cape Canaveral, Florida wave Case 6 ($H_s=1.6$ m, $T_{peak}=14.3$ sec, $\theta_{peak}=65$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... 63

Figure 3-37. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at Borrow Site 2 for STWAVE model output for Cape Canaveral, Florida wave Case 3 ($H_s=1.0$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=100$ deg)..... 65

Figure 3-38. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at Borrow Site 2 for STWAVE model output for Cape Canaveral, Florida wave Case 6 ($H_s=1.6$ m, $T_{peak}=14.3$ sec, $\theta_{peak}=65$ deg)..... 66

Figure 3-39. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the southern New Jersey shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional..... 69

Figure 3-40. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the southeastern Virginia shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional..... 70

Figure 3-41. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the North Carolina shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional..... 71

Figure 3-42. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the Cape Canaveral shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional..... 72

Figure 3-43. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore southern New Jersey. The middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference..... 75

Figure 3-44. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore southeastern Virginia, the middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference..... 76

Figure 3-45. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore North Carolina, north of Oregon Inlet. The middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference. 77

Figure 3-46. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore Florida, near Cape Canaveral. The middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference. 78

Figure 4-1. Difference plot of wave heights for existing and post-dredging conditions at sites A and B for Sandbridge model wave case 3..... 83

Figure 4-2. Difference plot of wave heights for existing and post-dredging conditions at sites 3 East and 3 West for North Carolina model wave case 4..... 84

Figure 4-3. Plot of sediment transport potential difference between existing and post-dredging model runs including Sites A and B (southeastern Virginia) modeled together (solid black line) and separately (solid blue and red lines). The sum of transport difference computed for the separate runs of A and B (dotted black line) is presented for comparison with the curve of A and B modeled together (coefficient of determination, $r^2=0.970$)..... 84

Figure 4-4. Plot of sediment transport potential difference between existing and post-dredging model runs including sites 3 East and 3 West (North Carolina) modeled together (solid black line) and separately (solid blue and red lines). The sum of transport difference computed for the separate runs of 3 East and 3 West (dotted black line) is presented for comparison to the curve of 3 East and 3 West modeled together (coefficient of determination, $r^2=0.990$)..... 85

Figure 4-5. Plot of change in sediment transport potential computed for five excavated depths at site M8, offshore Corsons Inlet, New Jersey. The shaded area represents the envelope of maximum transport influence that is allowed by the impact significance criterion. 86

Figure 4-6. Plot of excavation depth *versus* change in modeled sand transport potential. Dotted lines represent linear least squares fits of the model output (for black line $r^2=0.999$, and for the red line $r^2=0.954$)..... 87

APPENDIX B: NEW JERSEY WAVE MODEL OUTPUT

Figure B-1. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 1 ($H_s=1.4$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=61$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-1

Figure B-2. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 2 ($H_s=1.1$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=86$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-2

Figure B-3. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 3 ($H_s=1.2$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=111$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-3

Figure B-4. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.1$ sec, $\theta_{peak}=131$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-4

Figure B-5. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 5 ($H_s=0.8$ m, $T_{peak}=5.0$ sec, $\theta_{peak}=161$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-5

Figure B-6. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 6 ($H_s=1.3$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=61$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-6

Figure B-7. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 7 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=81$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-7

Figure B-8. Plot of STWAVE model output for southern New Jersey, existing conditions, wave Case 8 ($H_s=2.0$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=96$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.....B-8

Figure B-9. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 1 ($H_s=1.4$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=61$ deg).....B-9

Figure B-10. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 2 ($H_s=1.1$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=86$ deg).....B-10

Figure B-11. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 3 ($H_s=1.2$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=111$ deg).....B-11

Figure B-12. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.1$ sec, $\theta_{peak}=131$ deg).....B-12

Figure B-13. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 5 ($H_s=0.8$ m, $T_{peak}=5.0$ sec, $\theta_{peak}=161$ deg).....B-13

Figure B-14. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 6 ($H_s=1.3$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=61$ deg).....B-14

Figure B-15. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 7 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=81$ deg).....B-15

Figure B-16. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of New Jersey wave Case 8 ($H_s=2.0$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=96$ deg).....B-16

APPENDIX C: VIRGINIA WAVE MODEL OUTPUT

Figure C-1. Plot of STWAVE model output for Virginia, existing conditions, wave Case 1 ($H_s=1.6$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=359$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-1

Figure C-2. Plot of STWAVE model output for Virginia, existing conditions, wave Case 2 ($H_s=1.6$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=34$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-2

Figure C-3. Plot of STWAVE model output for Virginia, existing conditions, wave Case 3 ($H_s=1.4$ m, $T_{peak}=9.1$ sec, $\theta_{peak}=54$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-3

Figure C-4. Plot of STWAVE model output for Virginia, existing conditions, wave Case 4 ($H_s=1.1$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=104$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-4

Figure C-5. Plot of STWAVE model output for Virginia, existing conditions, wave Case 5 ($H_s=1.1$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=119$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-5

Figure C-6. Plot of STWAVE model output for Virginia, existing conditions, wave Case 6 ($H_s=1.2$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=149$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-6

Figure C-7. Plot of STWAVE model output for Virginia, existing conditions, wave Case 7 ($H_s=2.8$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=39$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-7

Figure C-8. Plot of STWAVE model output for Virginia, existing conditions, wave Case 8 ($H_s=2.0$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=64$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-8

Figure C-9. Plot of STWAVE model output for Virginia, existing conditions, wave Case 9 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=79$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-9

Figure C-10. Plot of STWAVE model output for Virginia, existing conditions, wave Case 10 ($H_s=1.8$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=134$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-10

Figure C-11. Plot of STWAVE model output for Virginia, existing conditions, wave Case 7 ($H_s=2.4$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=144$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. C-11

Figure C-12. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 1 ($H_s=1.6$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=359$ deg). C-12

Figure C-13. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 2 ($H_s=1.6$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=34$ deg). C-13

Figure C-14. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 3 ($H_s=1.4$ m, $T_{peak}=9.1$ sec, $\theta_{peak}=54$ deg). C-14

Figure C-15. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 4 ($H_s=1.1$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=104$ deg). C-15

Figure C-16. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 5 ($H_s=1.1$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=119$ deg). C-16

Figure C-17. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 6 ($H_s=1.2$ m, $T_{peak}=8.3$ sec, $\theta_{peak}=149$ deg). C-17

Figure C-18. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 7 ($H_s=2.8$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=39$ deg). C-18

Figure C-19. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 8 ($H_s=2.0$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=64$ deg). C-19

Figure C-20. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 9 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=79$ deg). C-20

Figure C-21. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 10 ($H_s=1.8$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=134$ deg). C-21

Figure C-22. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Virginia wave Case 11 ($H_s=2.4$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=144$ deg). C-22

APPENDIX D: NORTH CAROLINA WAVE MODEL OUTPUT

Figure D-1. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 1 ($H_s=1.1$ m, $T_{peak}=5.1$ sec, $\theta_{peak}=1$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-1

Figure D-2. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 2 ($H_s=1.9$ m, $T_{peak}=6.0$ sec, $\theta_{peak}=21$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-2

Figure D-3. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 3 ($H_s=1.5$ m, $T_{peak}=6.7$ sec, $\theta_{peak}=56$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-3

Figure D-4. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.4$ sec, $\theta_{peak}=86$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-4

Figure D-5. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 5 ($H_s=0.9$ m, $T_{peak}=7.6$ sec, $\theta_{peak}=106$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-5

Figure D-6. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 6 ($H_s=0.6$ m, $T_{peak}=4.6$ sec, $\theta_{peak}=131$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-6

Figure D-7. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 7 ($H_s=1.9$ m, $T_{peak}=11.5$ sec, $\theta_{peak}=66$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-7

Figure D-8. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 8 ($H_s=1.5$ m, $T_{peak}=12.8$ sec, $\theta_{peak}=71$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-8

Figure D-9. Plot of STWAVE model output for North Carolina, existing conditions, wave Case 9 ($H_s=1.3$ m, $T_{peak}=11.3$ sec, $\theta_{peak}=101$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation..... D-9

Figure D-10. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 1 ($H_s=1.1$ m, $T_{peak}=5.1$ sec, $\theta_{peak}=1$ deg)..... D-10

Figure D-11. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 2 ($H_s=1.9$ m, $T_{peak}=6.0$ sec, $\theta_{peak}=21$ deg)..... D-10

Figure D-12. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 3 ($H_s=1.5$ m, $T_{peak}=6.7$ sec, $\theta_{peak}=56$ deg)..... D-11

Figure D-13. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.4$ sec, $\theta_{peak}=86$ deg)..... D-11

Figure D-14. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 5 ($H_s=0.9$ m, $T_{peak}=7.6$ sec, $\theta_{peak}=106$ deg)..... D-12

Figure D-15. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 6 ($H_s=0.6$ m, $T_{peak}=4.6$ sec, $\theta_{peak}=131$ deg)..... D-12

Figure D-16. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 7 ($H_s=1.9$ m, $T_{peak}=11.5$ sec, $\theta_{peak}=66$ deg)..... D-13

Figure D-17. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 8 ($H_s=1.5$ m, $T_{peak}=12.8$ sec, $\theta_{peak}=71$ deg)..... D-13

Figure D-18. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of North Carolina wave Case 9 ($H_s=1.3$ m, $T_{peak}=11.3$ sec, $\theta_{peak}=101$ deg)..... D-14

APPENDIX E: FLORIDA WAVE MODEL OUTPUT

Figure E-1. Plot of STWAVE model output for Cape Canaveral, Florida, existing conditions, wave Case 1 ($H_s=1.7$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=55$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-1

Figure E-2. Plot of STWAVE model output for Cape Canaveral, Florida, existing conditions, wave Case 2 ($H_s=1.4$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=80$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-2

Figure E-3. Plot of STWAVE model output for Cape Canaveral, Florida, existing conditions, wave Case 3 ($H_s=1.0$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=100$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-3

Figure E-4. Plot of STWAVE model output for Cape Canaveral, Florida, existing conditions, wave Case 4 ($H_s=1.5$ m, $T_{peak}=6.3$ sec, $\theta_{peak}=130$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-4

Figure E-5. Plot of STWAVE model output for Cape Canaveral, Florida, existing conditions, wave Case 5 ($H_s=1.7$ m, $T_{peak}=12.5$ sec, $\theta_{peak}=60$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-5

Figure E-6. Plot of STWAVE model output for Cape Canaveral, Florida, existing conditions, wave Case 6 ($H_s=1.6$ m, $T_{peak}=14.3$ sec, $\theta_{peak}=65$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-6

Figure E-7. Plot of STWAVE model output for Cape Canaveral, Florida, pre-dredge conditions, wave Case 7 ($H_s=1.5$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=100$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.E-7

Figure E-8. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 1 ($H_s=1.7$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=55$ deg).....E-8

Figure E-9. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 2 ($H_s=1.4$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=80$ deg).....E-9

Figure E-10. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 3 ($H_s=1.0$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=100$ deg).....E-10

Figure E-11. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 4 ($H_s=1.5$ m, $T_{peak}=6.3$ sec, $\theta_{peak}=130$ deg).....E-11

Figure E-12. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 5 ($H_s=1.7$ m, $T_{peak}=12.5$ sec, $\theta_{peak}=60$ deg).....E-12

Figure E-13. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 6 ($H_s=1.6$ m, $T_{peak}=14.3$ sec, $\theta_{peak}=65$ deg).....E-13

Figure E-14. Plot of wave height change between pre- and post-dredge ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites, for STWAVE model output of Cape Canaveral, Florida wave Case 1 ($H_s=1.5$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=100$ deg).....E-14

LIST OF TABLES

Table 1-1.	Borrow site characteristics for the four sand resource areas.	4
Table 2-1.	Redistributed wave energy for idealized borrow site case illustrating the effects of a case dominated by one wave direction.....	15
Table 3-1.	Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for New Jersey model grid.	32
Table 3-2.	Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for Virginia model grid.....	32
Table 3-3.	Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for North Carolina model grid.	32
Table 3-4.	Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for Florida model grid.....	33
Table 3-5.	Significant parameters for input wave spectra used for existing and post-dredging STWAVE model runs for offshore southeastern Virginia sites.	35
Table 3-6.	Maximum estimated cumulative borrow site excavation dimensions for the four sand resource areas.	37
Table 3-7.	Numerical grid dimensions for offshore (coarse) and nearshore (fine) grids. Dimensions are given as (cross-shore x alongshore).	44

1.0 INTRODUCTION

The Minerals Management Service (MMS), a bureau within the U.S. Department of the Interior, has responsibility for managing all mineral resources on the Federal Outer Continental Shelf (OCS), a zone that extends three (3) miles seaward from State coastline boundaries to 200 miles offshore. Although most interest in this zone relates to oil and gas resources, the potential for exploitation of sand resources as a source for beach and barrier island restoration has grown rapidly in the last several years as similar resources in State waters are being depleted or polluted. Extraction of sand resources in Federal waters may be preferred relative to State waters due to concerns over changes in physical oceanographic conditions resulting from large quantities of material dredged from resource sites impacted by waves and currents. This has generated a need for technical information to ensure that offshore minerals are developed with due concern for potential environmental considerations.

In 1983, the MMS established the Office of Strategic and International Minerals for evaluating the prospects for and conditions under which sand and gravel mining would develop in the U.S. In 1991, the Office of International Activities and Marine Minerals (INTERMAR; now referred to as the International Activities and Marine Minerals Division) was created to develop strategies for addressing specific concerns regarding offshore sand and gravel mining operations (Hammer et al., 1993). The MMS has significant responsibilities with respect to potential environmental impacts of sand and gravel mining. Existing regulations governing sand and gravel mining provide a framework for comprehensive environmental protection during operations. Specific requirements exist for evaluations and lease stipulations that include appropriate mitigation measures (Hammer et al., 1993). Guidelines for protecting the environment stem from a wide variety of laws, including the OCS Lands Act (OCSLA), National Environmental Policy Act (NEPA), and others. Regulations require activities to be conducted in a manner which prevents or minimizes the likelihood of any occurrences that may cause damage to the environment. The MMS takes a case-by-case approach in conducting environmental analyses, as required by NEPA and the Council on Environmental Quality (CEQ) regulations.

In recent years, there has been increasing interest in sand and gravel mining on the OCS. Currently, eight State-Federal task forces, several cooperative agreements, at least five negotiated agreements, and seven environmental surveys exist to ensure substantive government and public involvement and attention to regional, State, and local concerns regarding leasing, engineering, economic, and environmental aspects of sand and gravel mining (to obtain specific information regarding these activities, visit <http://www.mms.gov/intermar/marineac.htm>). Under the OCSLA, the MMS is required to conduct environmental studies to obtain information useful for decisions related to negotiated agreements and lease activities. As such, the MMS pursues its responsibilities for management of offshore sand and gravel mining vigorously by:

- protecting ocean and coastal environments by ensuring that all OCS sand and gravel mining activities are environmentally acceptable;
- ensuring the OCS sand and gravel activities are compatible with other uses of the ocean;
- involving coastal States in all aspects of sand and gravel mining activities; and
- evaluating the potential of the OCS as a domestic source for sand and gravel.

1.1 STUDY PURPOSE

The overall study purpose addresses the need for physical environmental information to support potential lease decisions offshore the east coast of the U.S. from southern New Jersey to Cape Canaveral, Florida. Specifically, the study examines the potential for negative impacts to coastal and nearshore environments, particularly from alterations to the local wave and sediment transport regime, due to long-term dredging and significant removal of sand from shoals offshore southern New Jersey, southeastern Virginia (Sandbridge Shoal), North Carolina (north of Oregon Inlet), and Cape Canaveral, Florida. Shoals in these areas are expected to serve as long-term and continual sources of borrow material, due to existing beach renourishment cycles, and to repair damage from severe coastal storms. In certain instances, such as Sandbridge Shoal offshore southeastern Virginia, several jurisdictions or entities want to use the same borrow area(s) on different cycles. This raises the issue of cumulative effects of multiple sand dredging events and/or dredging at multiple sites, particularly related to alterations to the local wave and sediment transport regime. In natural continental shelf settings, wave energy typically concentrates at shoals and diverges at holes due to wave refraction and diffraction. The interaction between waves and bathymetric surface geometry dictates the resultant pattern of wave energy propagation. As such, patterns of wave energy transformation across the continental shelf depend on changes in bathymetry and the level of incident energy.

The most effective means of quantifying incremental and cumulative physical environmental effects of sand dredging from shoals on the continental shelf is through the use of wave transformation numerical modeling tools that recognize the random nature of incident waves as they propagate onshore. Spectral wave models, such as STWAVE, REF/DIF-S, SWAN, and others, typically provide more realistic results than monochromatic wave models relative to field measurements (see Appendix A). As such, spectral wave transformation modeling was applied in this study to evaluate the potential negative impacts to coastal and nearshore sites from long-term dredging and significant removal of sand from offshore sand borrow sites. Although the interpretation of wave modeling results is relatively straightforward, evaluating the significance of predicted changes for accepting or rejecting a borrow site is more complicated. A substantial part of this study was aimed at assessing the significance of simulated changes between existing and post-dredging conditions versus natural variability in wave climate and potential sediment transport rates to determine the relative importance of predicted changes. It is expected that information generated will enable the MMS to assess potential impacts of long-term offshore dredging and to identify potential dredging alternatives aimed at minimizing or precluding adverse physical environmental impacts.

1.2 STUDY AREAS AND BORROW SITE CHARACTERISTICS

The inshore portion of the continental shelf, seaward of the State-Federal OCS boundary and within the Exclusive Economic Zone (EEZ), encompasses the project study areas offshore southern New Jersey (Figure 1-1), southeastern Virginia (Figure 1-2), North Carolina (north of Oregon Inlet; Figure 1-3), and Cape Canaveral, Florida (Figure 1-4). The seaward limit of all borrow sites is generally within about 30 km of the shoreline and located between the 10- and 20-m depth contours.

The continental shelf surface offshore southern New Jersey contains many first-, second-, and third-order morphologic features formed during the Holocene transgression (McKinney et al., 1974; Figure 1-1). Sand ridges 2- to 5-m high and 0.5- to 1.5-km apart

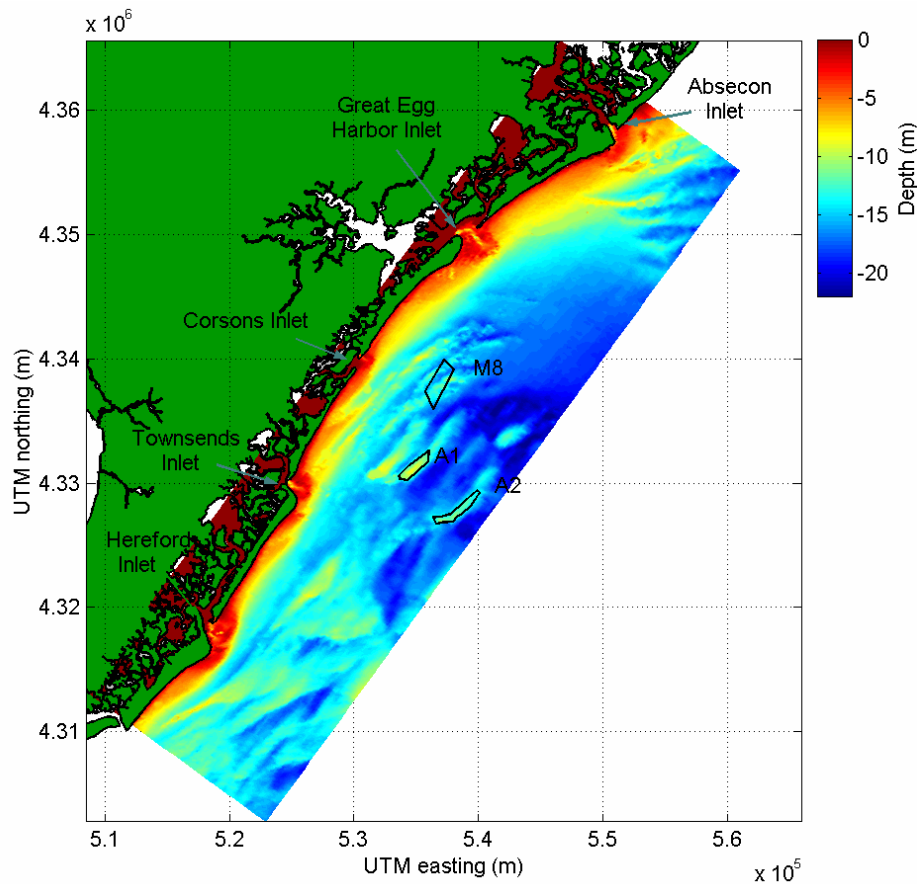


Figure 1-1. Location diagram illustrating sand borrow sites M8 (USACE designation), A1 and A2 (NJ State designation), and State-Federal boundary relative to 1934/77 bathymetry.

represent second-order features that are the primary sand resource targets of this study. Average shoal relief is about 3 m. Three potential borrow sites were modeled for southern New Jersey to evaluate the cumulative effects of multiple simultaneous dredging operations and repetitive dredging with time at one site. Table 1-1 lists proposed maximum dredging volumes and depths for sites A-1, A-2, and M8.

Continental shelf topography offshore southeastern Virginia is dominated by ridge and swale features formed during the Holocene (Williams et al., 1987; Kimball et al., 1991). Many potential sand resource sites are associated with ridges approximately 20 km offshore Virginia Beach (known as the Virginia Beach Ridges) and seaward of False Cape (False Cape Ridges). Kimball and Dame (1989) identified Sandbridge Shoal as a viable sand resource site for beach nourishment along the southeastern Virginia coast. The horseshoe-shaped shoal was characterized as a northward and eastward thinning wedge of sand approximately 48 km² in area and up to 6 m thick. Maximum relief over the ambient shelf surface was about 4 m (Kimball et al., 1991). Two sand borrow sites were identified on this shoal (Sites A and B; Figure 1-2), and approximately 1.5 MCY has been extracted from Site A for beach nourishment along Dam Neck Beach and Sandbridge Beach to date. Table 1-1 lists proposed maximum dredging volumes and depths for sites A and B.

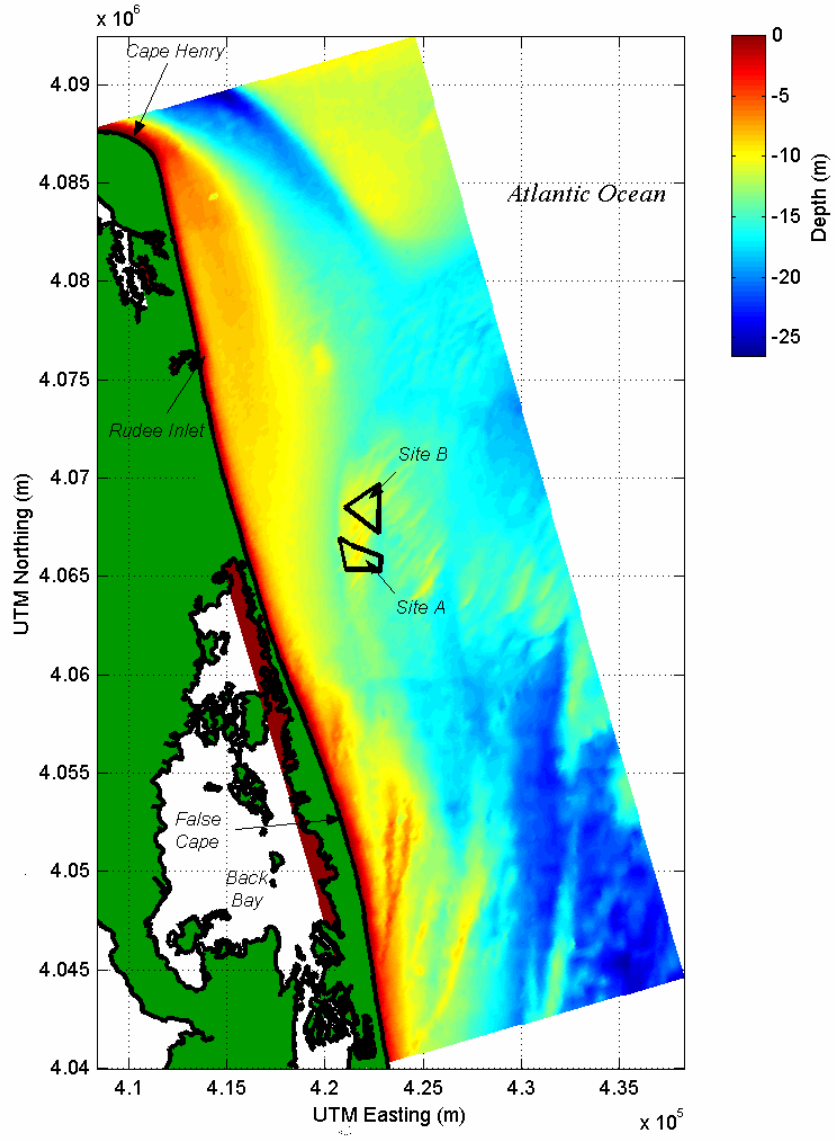


Figure 1-2. Location diagram illustrating sand borrow sites A and B and State-Federal boundary relative to 1934/77 bathymetry.

Table 1-1. Borrow site characteristics for the four sand resource areas.				
Region	Site Designation	Volume (10 ⁶ m ³)	Area (10 ⁶ m ²)	Average Excavation Depth (m)
Southern New Jersey	A1	8.8	2.2	4.0
	A2	7.8	2.6	3.0
	M8	8.0	4.0	2.0
Southeastern Virginia	A	5.3	1.8	3.0
	B	6.9	2.3	3.0
North Carolina	3 East	1.4	0.7	2.0
	3 West	2.5	0.8	3.0
Offshore Cape Canaveral, Florida	2	26.0	5.0	5.2

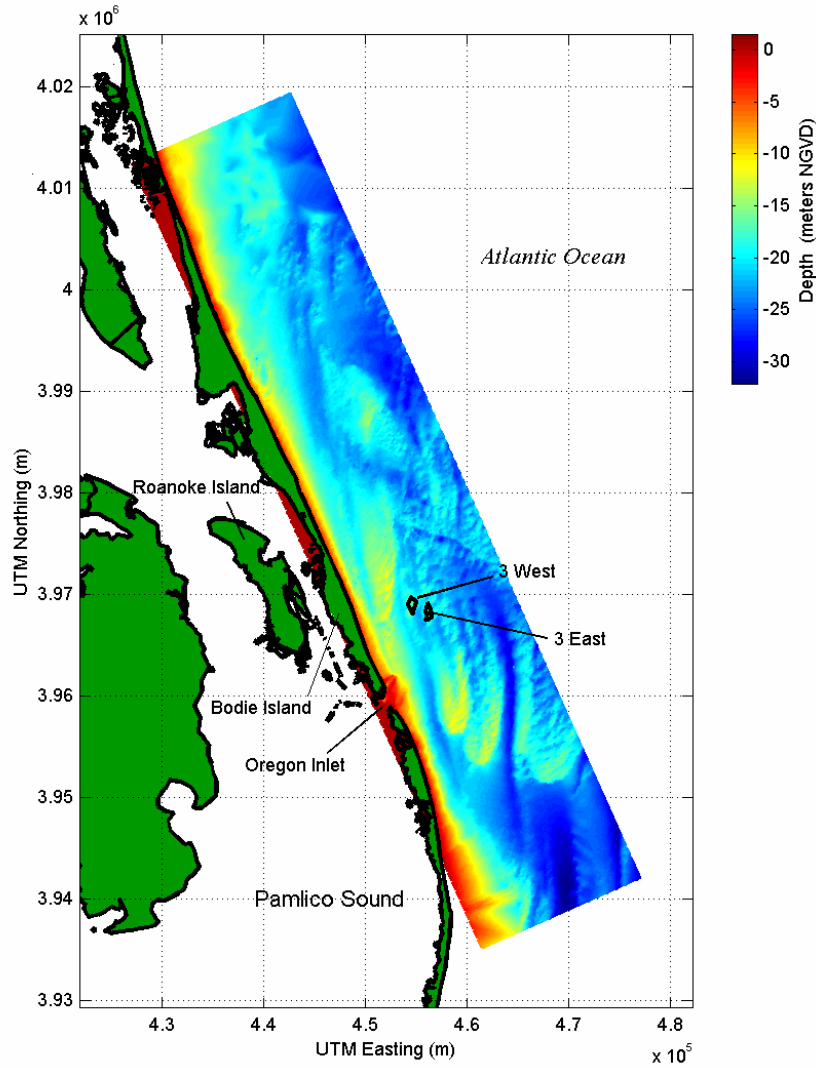


Figure 1-3. Location diagram illustrating sand borrow sites 3 West and 3 East and State-Federal boundary relative to 1934/77 bathymetry.

In the vicinity of Oregon Inlet, North Carolina shelf topography is characterized by sub-parallel ridges and swales that trend approximately north-south making an angle of about 20° to 30° with the shoreline trend (Inman and Dolan, 1989). The ridges are about 1.5 to 6 km apart, extend 12 to 60 km, and have an average relief of 2 to 6 m (Swift et al., 1972). The North Carolina Geological Survey identified four sand resource areas in OCS waters northeast of Oregon Inlet (Hoffman, 1998). Two sand borrow sites were selected in Resource Area 3 (3 East and 3 West; Figure 1-3) for evaluating the potential impact of simultaneous dredging at multiple sites on coastal wave and sediment transport processes. Table 1-1 lists proposed maximum dredging volumes and depths for sites 3 West and 3 East.

Cape Canaveral Shoals was the fourth sand resource area evaluated in this study. A potential offshore borrow site was identified by the U.S. Army Corps of Engineers, Jacksonville District, (USACE, 1999). Borrow Area 2 is located along the seaward margin of Canaveral Shoals about 15 to 20 km offshore in an area referred to

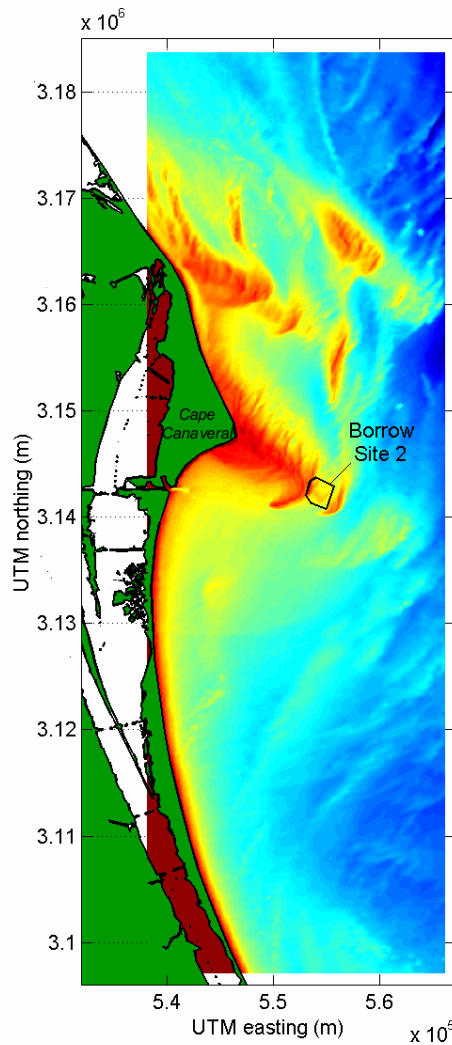


Figure 1-4. Location diagram illustrating sand Borrow Site II and State-Federal boundary relative to 1934/77 bathymetry.

as “Southeast Shoals”, in water depths ranging from 7 to 14 m (Figure 1-4). Core data from the borrow site suggest that beach quality sand is present at thicknesses of 3 to 5 m. Average median grain size is about 0.35 mm. Table 1-1 lists the proposed maximum dredging volume and depth for sand Borrow Site 2.

1.3 STUDY APPROACH

To address the overall study purpose, a four-phase approach was implemented. First, a detailed evaluation of three readily-available, project-tested spectral wave models was conducted to determine the most effective simulation routine for predicting potential wave impacts due to dredging at offshore borrow sites. Appendix A contains the final report for the spectral wave model evaluation task. Our analysis recommended that the U.S. Army Corps of Engineer STeady-state spectral WAVE model (STWAVE) be used on future MMS wave transformation modeling studies. Second, a standard method was developed to qualify the significance of changes associated with borrow site

excavation to determine the influence of borrow site geometry on local wave refraction and sediment transport patterns. Because large natural spatial and temporal variability exists within the wave climate at a particular site, determination of physical impacts associated with sand mining must consider the influence of process variability. The method developed for this study is based on historical wave climate variability, as well as local wave climate changes directly attributable to borrow site excavation.

The third phase of the project focused on wave spectra development, wave transformation modeling, and coastal sediment transport calculations. This phase of the project represents the bulk of analyses performed to document potential impacts associated with dredging at selected offshore sand borrow sites. Wave transformation modeling and sediment transport potential calculations were performed for existing and post-dredging bathymetric conditions. Comparison of computations for existing and post-dredging conditions are used to illustrate the relative maximum impact of borrow site excavation on wave-induced coastal processes.

The fourth and most significant phase of the project addressed potential cumulative effects and significance of sand dredging from offshore sand borrow sites. A site-specific determination of acceptable limits of borrow site impacts relative to sediment transport potential was determined for each case. In addition to the site-specific investigations, two model studies of incremental cumulative impacts from different borrow site configurations were investigated. The first study group of incremental impacts involved the interaction of multiple sites in close proximity to one another, such that overlapping areas of shoreline impact exist. The second study grouping of incremental impacts involves multiple dredging events at a single site, and how effects vary as excavation depth is increased (e.g., due to multiple dredging events over time). These analyses were designed to determine how potential wave impacts at individual sites may interact to produce additive physical environmental effects along the coast.

1.4 DOCUMENT ORGANIZATION

Information presented in this document represents the culmination of a year and a half of work among experts in the fields of oceanography, coastal processes, and numerical wave and sediment transport modeling, under the direction of Mr. Barry Drucker (MMS INTERMAR). This document was organized into six major sections as follows:

- Introduction
- Physical Processes
- Modeling Approach and Applications
- Cumulative Effects
- Conclusions
- Literature Cited

In addition to the main document, appendices were prepared in support of many of the analyses presented in each section of the report. Furthermore, an Executive Summary, a Technical Summary, and a Non-Technical Summary will be prepared as separate documents to provide a brief description of study methods and findings for audiences ranging from researchers to non-technical people.

2.0 PHYSICAL PROCESSES

During the past few decades, there has been increased focus on the nearshore zone due to rapid development of this region and the need to protect infrastructure from devastating storm impacts and long-term coastal erosion. A significant portion of this effort has been concentrated on developing analytical tools to evaluate the transformation of waves in shallow water and to quantify sediment transport induced by breaking waves along the shoreline. Although our understanding has improved, evaluation of coastal processes still requires a blend of analytical capability, interpretation of many complex and often apparently conflicting data sets, and experience gained from analyzing a variety of shorelines. The primary reason for this relevance on qualitative and quantitative approaches is that the equations governing sediment movement by waves are not yet fully known.

The primary quantitative technique used to evaluate nearshore processes is wave transformation modeling. Wave models have been developed to numerically solve the equations governing changes in wave height and direction (through processes such as refraction, shoaling, and breaking). As better offshore wave data sets become available (e.g., wave gauge and hindcast information), wave transformation models have become standard tools for evaluating changes in nearshore wave climate. Due to the complexities of surf zone hydrodynamics, sediment transport analysis techniques typically depend on information from wave models at the line of wave breaking. Unfortunately, calculations involving sediment transport are dependent on empirical or semi-empirical relationships; therefore, these techniques are not as theoretically rigorous as wave modeling. In addition, shoreline modifications (e.g., coastal engineering structures, natural hardbottom, and beach nourishment projects) are not included and sediment transport equations assume that an infinite supply of material is available, hence the term “sediment transport potential”. Although these simplifications can limit the applicability of the approach, proper interpretation of wave modeling and associated longshore sediment transport analysis results can provide a powerful tool for coastal engineering design and assessment of shoreline dynamics.

The analysis techniques presented in this report involve spectral wave modeling, based primarily on wave hindcast information, combined with standard longshore sediment transport equations to evaluate impacts associated with offshore sand mining. A general description of nearshore wave transformation and longshore sediment transport is provided. In addition, nearshore wave transformations and alterations to longshore sediment transport potential are shown for an idealized borrow site.

2.1 NEARSHORE WAVE TRANSFORMATION

Open ocean waves primarily are generated by wind that induces drag across the water surface. Over time, persistent strong winds can generate long waves with large heights, replacing less energetic waves initially created. Because wind patterns are complex, blowing in various directions with different speeds for varying amounts of time, the resulting sea is complicated as well. Due to the restoring force provided by gravity, ocean waves can travel long distances across the surface of the ocean with relatively little change in shape. As waves travel, energy is exchanged between the different component waves of the spectrum, and a small amount of wave energy is dissipated through surface tension and whitecapping. However, waves in the open ocean remain fairly uniform as they travel through deep water. As waves propagate into intermediate

and shallow water depths, the effects of the seafloor tend to dominate wave transformations. Although a small amount of energy is lost through bottom stresses (frictional drag), most nearshore wave transformation results from six processes: 1) refraction, 2) shoaling, 3) breaking, 4) diffraction, 5) reflection, and 6) wave-current interactions. These processes determine the size and incident angle of breaking waves, the dominant driving force for nearshore sediment transport. Although minor wave diffraction and reflection may occur at an offshore borrow site, wave refraction, shoaling, and breaking dominate transformation processes associated with offshore sand mining. Therefore, consideration of wave refraction, shoaling, and breaking are critical components of any spectral analysis used to evaluate alterations to a wave field associated with offshore sand mining.

As a wave propagates into shallow water, the wavelength shortens and the wave period remains constant (assuming the wave field is constant in time). The wave period is defined as the time required for successive wave crests to pass a particular location. Consequently, waves travel at slower speeds in shallow water. This process causes wave crests to bend, or refract, toward regions of shallow water and away from regions of deep water. As shown in Figure 2-1, wave crests approaching the beach at an angle become more parallel to the shoreline as they approach the beach and the water depth decreases. Refraction also serves to focus wave energy on headlands, reefs, and shoals, while diverting energy from deep holes and channels. This, in turn, directly impacts the erosional pressures on the shoreline. Because longshore sediment transport rates are dependent upon the wave angle at breaking, determined by the effects of refraction, underwater features such as troughs and ridges can serve to exacerbate erosion in certain regions. These erosional *hot spots* will exist where the bathymetry tends to focus wave energy. Along a wave crest, variations in wave height may occur due to a focusing of wave energy from refraction processes, a change in wave height from shoaling processes, or a shielding of wave energy from an obstruction.

Neglecting small energy losses due to frictional effects, the total energy in a propagating waveform is conserved. As a wave enters shallow water its propagation speed tends to slow. Because wave energy is dependent upon wave height and wave speed, and wave speed slows with decreasing depth, wave height increases as the wave propagates into shallow water. Depending on offshore bottom slope, the change in wave height due to shoaling can be significant. Computation of the longshore transport rate is dependent on the incident wave angle at breaking and wave height. Therefore, shoaling characteristics are important for evaluating beach erosion. In general, areas with relatively gentle offshore slopes allow wave energy to concentrate over a wide surf zone, and sediment transport volumes are high relative to incident wave height. However, beaches with gentle slopes usually have a significant sediment volume in storage, and because the wide surf zone causes transport to be distributed over a large area, the effects of sediment movement may not be evident. Conversely, beaches with very steep offshore slopes do not allow waves to completely shoal before breaking takes place. Thus, wave heights at breaking are reduced; however, breaking wave energy is dissipated within a narrow surf zone. Although transport volumes may not be as high as beaches with gentle slopes, the concentration of transport within a narrow region may cause the effects of beach erosion to be more pronounced.

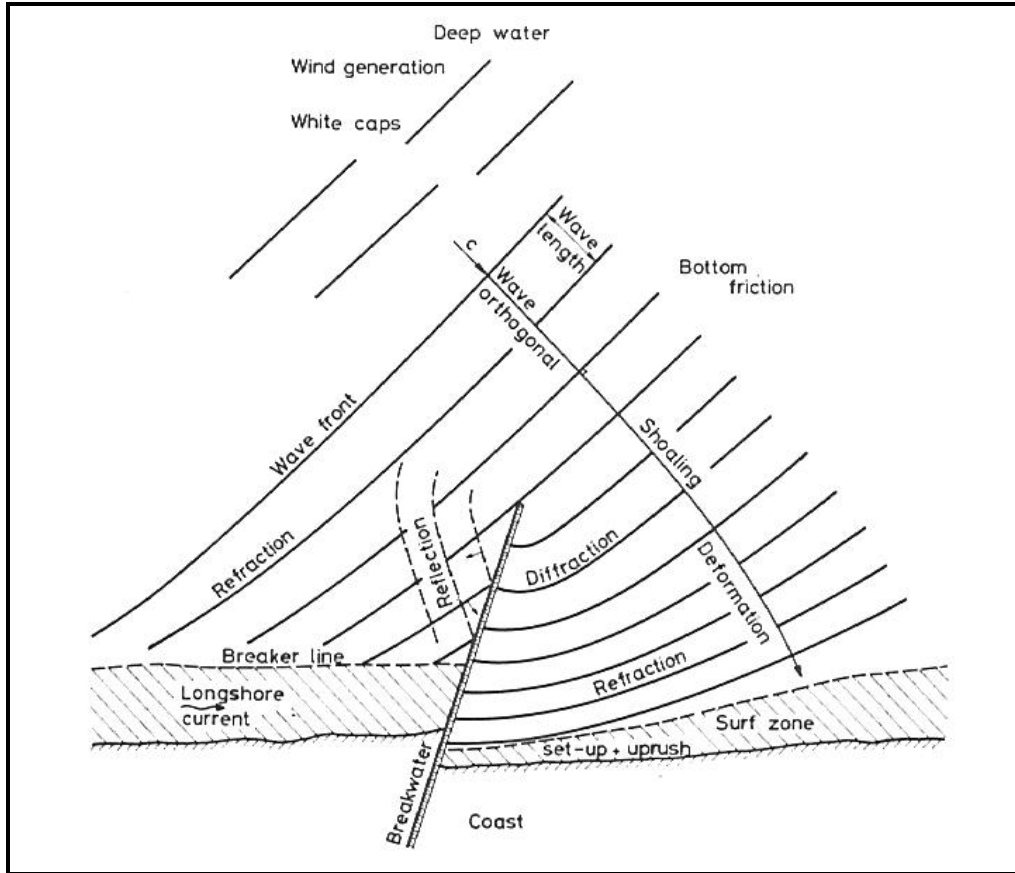


Figure 2-1. Diagram illustrating the effects of refraction and diffraction as waves approach the coastline (from Svendsen and Jonsson, 1976).

The most significant nearshore wave transformation occurs when waves break. In very shallow water (proportional to the wave height), the combined effects of refraction, shoaling, diffraction, and reflection produce a wave form that is unstable. When a wave becomes too steep, and the speed of the crest exceeds that of the entire wave form, the wave topples over and breaks. Breaking drastically reduces the wave height. Much of the wave energy is dissipated through the breaking process in a very narrow surf zone, where large amounts of sediment are lifted from the bottom and transported by nearshore waves and currents.

2.2 NEARSHORE SEDIMENT TRANSPORT PATTERNS

Nearshore wave and current motions are complex, and the surf zone system is further complicated by the capability of these motions to lift and transport beach sediment. An integrated study of wave processes, shoreline geometry, and sediment characteristics is required for predicting erosional trends and naturally occurring beach profile and planform shapes. Qualitatively, an understanding of the nearshore littoral system is obtained by focusing on cross-shore and longshore sediment transport trends, and on the influence of severe storm events versus typical wave conditions.

Generally, beach profile shape is governed by relatively short-term catastrophic events such as severe storms. For example, on the East Coast of the United States, beach profile shapes are dramatically changed by northeast storms and hurricanes.

Large volumes of sand are eroded from the beach face and deposited offshore in sand bars during these storm events. However, much of this material is recovered over longer time scales as milder waves move sediment landward, causing the beach face to accrete. Seasonal trends in wave climate influence cross-shore sediment transport as well. Typically, larger winter waves erode the beach face and milder summer waves build the beach. Therefore, the beach profile is dynamic, and the best estimate of a typical profile is the stable beach shape that forms when exposed to average annual waves. A stable beach is defined as an equilibrium condition and may be predicted using coastal engineering analyses. Cross-shore transport (or profile) modeling is usually based on the concept of equilibrium conditions forming a "stable" profile. This condition is used as a baseline for determining the potential changes in shoreline position due to a severe storm.

While large volumes of beach sediment are moved during isolated storm events, it is seasonal or average annual waves that dictate beach planform shape. Planform shape can be evaluated using longshore sediment transport models based on average annual wave conditions. Although large storm events may transport large volumes of sand along the coast, the short-term effects of storms tend to be minimal when long-term transport is evaluated. Waves incident from the north transport sediment to the south and vice-versa. Seasonal trends exist on the East Coast because winter waves generally are incident from the north, and summer waves generally are incident from the south. Of course, transport trends are highly dependent upon shoreline orientation. Varying volumes of sediment transported north and south may be estimated over time and superimposed to determine the net annual longshore sediment transport direction and volume. Another approach is to estimate the net annual transport from average annual wave conditions.

2.3 IDEALIZED OFFSHORE BORROW SITE

To assess alterations to wave patterns and associated longshore sediment transport processes, evaluation of an idealized offshore borrow site was performed using the spectral wave model STWAVE (described in Section 3) and standard sediment transport potential equations. A comparison of wave/sediment transport modeling results between transformations resulting from typical nearshore bathymetric conditions and those created by the existence of an offshore borrow site reveals the potential influence of sand mining on the littoral system.

First, a bathymetric grid was developed to represent generalized variations in water depth. Based on a typical cross-shore profile for New Jersey (Dean, 1977), the grid was developed assuming straight and parallel bathymetric contours using the equation: $h = Ay^m$, where h is the water depth, y is the distance offshore, A is a profile scale factor (indirectly related to beach grain size), and m is profile shape factor. For the southern New Jersey shoreline example, A was set at 0.0793 and m was set at 0.822. The idealized borrow site was centered on the 10 m bathymetric contour (see Figure 2-2) and consisted of an excavation of approximately 3 m. The borrow site was assumed to be square in the x-y direction with dimensions of 225 by 225 m. Total volume of the borrow site was approximately 153,000 cu m (200,000 cu yds).

The grid used for spectral wave refraction modeling extended 2,000 m alongshore and 850 m in the cross-shore direction, with a grid spacing of 5 m. A series of wave model runs were developed to provide conditions consistent with the southern New

Jersey shoreline: an incident spectral significant wave height of 1.2 m, a peak wave period of 8 sec, relatively narrow directional spreading, and a frequency distribution based on the work of Bretschneider (1968) and Mitsuyasu (1975). Wave model runs were performed for conditions with no borrow site (referred to as existing conditions) and for conditions with the borrow site described above (referred to as post-dredging conditions). To assess the range of wave transformations possible, wave spectra centered at -30° , -15° , 0° , 15° , and 30° relative to shore normal were modeled.

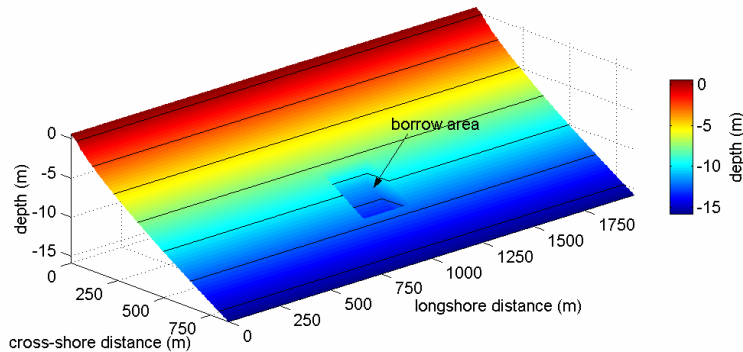


Figure 2-2. Surface plot with 2.5 m contours of bathymetry grid used for idealized borrow site model runs.

As an example of the wave modeling results, Figure 2-3 illustrates the influence of the idealized borrow site on the nearshore wave field for the -30° condition. Waves propagating across the borrow site tend to refract toward shallower water along the edges; therefore, areas of wave energy focusing (increase in wave heights) occur along each side of the borrow site. In addition, the wave refraction effect for the various spectral components generally creates a shadow zone landward of the borrow site. Due to the proximity of this borrow site to the beach (approximately 350 m offshore), the influence of the idealized borrow site on nearshore wave processes is much more pronounced than for a sand borrow site further offshore. However, the nearshore location of the borrow site creates a rather limited longshore region of influence. For the wave model case shown in Figure 2-3, the influence of the borrow site on the wave climate can be seen most clearly by comparing existing and post-dredging conditions as shown in Figure 2-4 ($H_{\text{post}} - H_{\text{pre}}$). For this wave modeling case, the longshore influence of the borrow site extends for an approximate distance of 900 m measured at the breaker line. In addition, the maximum increase and decrease in wave height created by the borrow site excavation are of similar magnitude (approximately ± 0.3 m).

Although the influence of a borrow site excavation on the wave field is important, an evaluation of the wave field alterations alone does not directly provide information needed to assess potential borrow site impacts. Calculation of longshore sediment transport potential for a series of wave cases provides a method for determining the extent and magnitude of alterations to nearshore processes. For the idealized borrow site, annualized sediment transport potential curves were generated for each of the five spectral wave conditions (Figure 2-5). As expected, the influence of the borrow site for the 0° case is distributed evenly, where positive sediment transport is from left-to-right. Cases with a negative approach angle relative to shore normal (-15° and -30°) illustrate

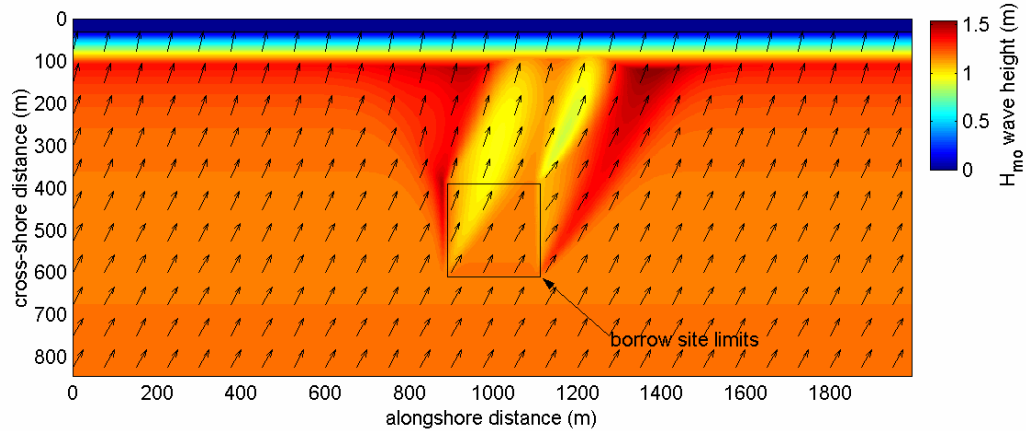


Figure 2-3. Example color contour plot of modeled wave heights, with vectors indicating mean wave direction for idealized borrow site (incident wave height of 1.2 m and period of 8 sec approaching shoreline at -30° from shore-normal).

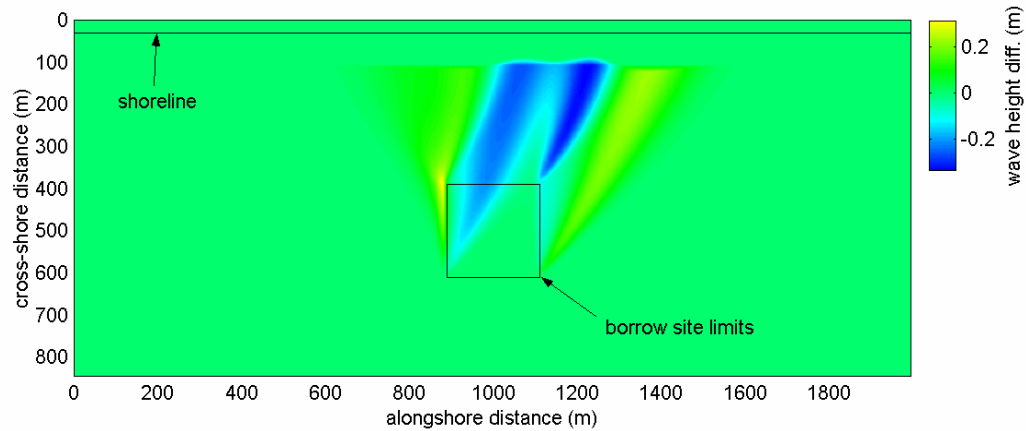


Figure 2-4. Color surface plot of wave height difference ($H_{\text{post}} - H_{\text{pre}}$) resulting from borrow site excavation, for wave case shown in Figure 2-3.

the influence of the borrow site shifted to the right and a left-to-right transport potential. Cases with a positive approach angle relative to shore normal (15° and 30°) show the opposite trend.

As part of the idealized borrow site evaluation, it first was assumed that each of the five modeled wave conditions occurred for 20% of the time. By superimposing each of the sediment transport potential curves shown in Figure 2-5 and weighting them by the appropriate percent occurrence (20%), a composite sediment transport potential curve can be developed (Figure 2-6). Because the modeled borrow site is so close to the shoreline, the influence of the borrow site on wave refraction and associated nearshore sediment transport patterns is substantial. Without the borrow site influence,

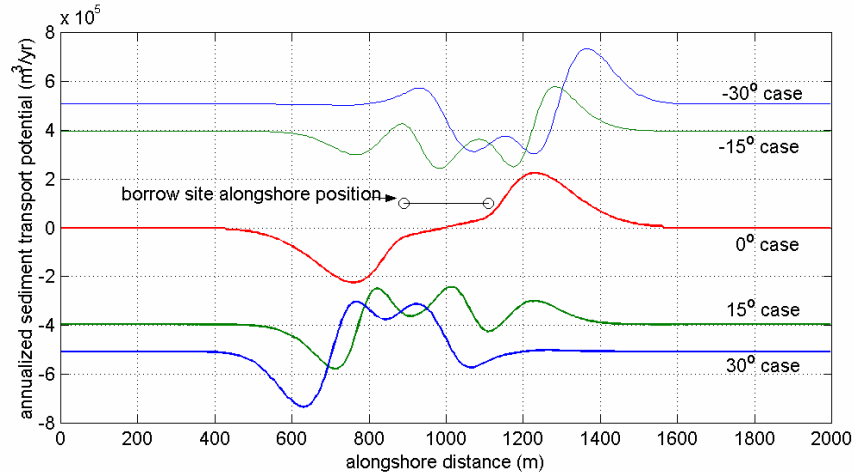


Figure 2-5. Computed annualized longshore sediment transport potential for idealized borrow site for five wave cases.

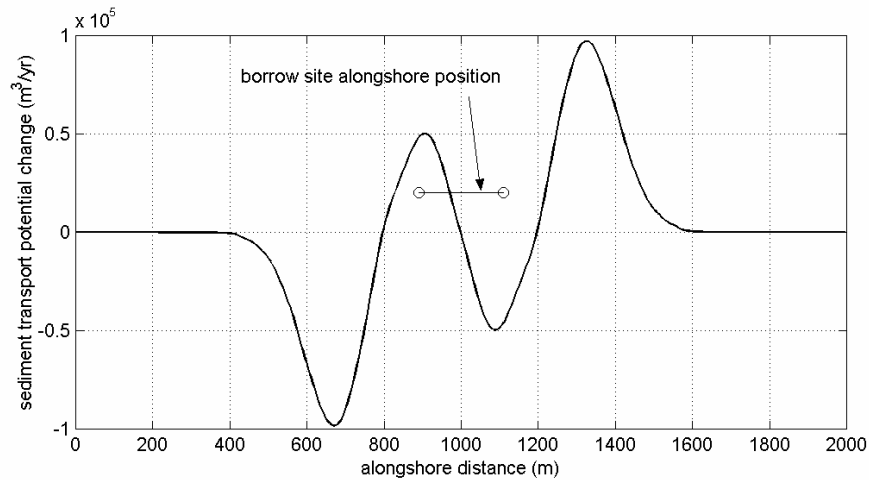


Figure 2-6. Change in computed longshore sediment transport potential for idealized borrow site.

the even distribution of wave conditions would cause a net sediment transport potential of zero for this shoreline; however, Figure 2-6 indicates that peak transport rates would increase to nearly 100,000 cu m annually at an alongshore distance of approximately 350 m from the center of the borrow site. These large increases in sediment transport potential directed away from the borrow site are a result of wave focusing. In contrast, the small peaks in sediment transport potential in between the two large peaks result from the “shadowing” effect of the borrow site created by the wave condition combinations. For example, waves propagating over the borrow site from the right (15° and 30° wave conditions) create a shadow region along the shoreline that is centered slightly to the left of the borrow site (the +50,000 cu m/yr transport peak in Figure 2-6). This shadow region is characterized by a decrease in left-directed sediment transport for these cases. Therefore, the overall effect is to create an increase in net right-directed (left-to-right) transport.

By computing the change in sediment transport potential over the shoreline distance (dQ/dy), a normalized curve of anticipated shoreline change resulting from excavation of an offshore borrow site can be developed. Figure 2-7 illustrates shoreline

change resulting from wave conditions presented above. Due to wave focusing caused by the borrow site configuration, increased erosion occurs along the shoreline on either side of the borrow site. Material eroded from these two areas feeds the central “shadow zone”, as well as shoreline regions further from the borrow site center.

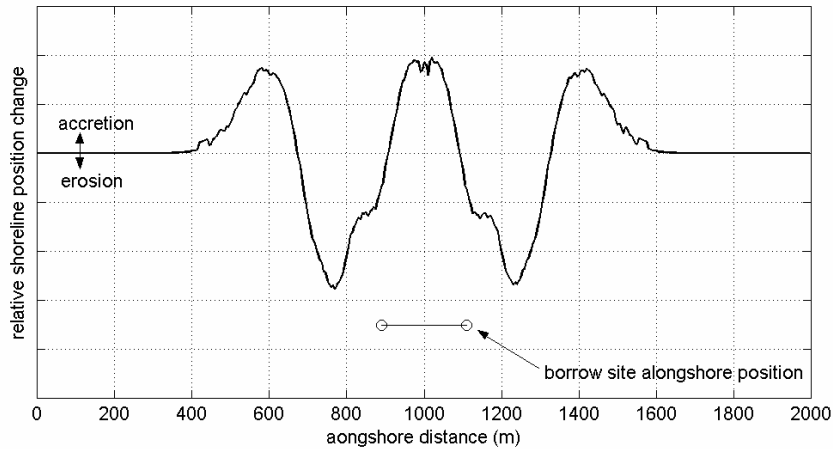


Figure 2-7. Computed cross-shore change in shoreline position based on modifications to longshore sediment transport potential by idealized borrow site.

To illustrate the influence of variable wave conditions on nearshore sediment transport dynamics, a second evaluation for the idealized borrow site was performed with a different distribution of input wave conditions. The percent occurrence for wave conditions presented above were altered to represent conditions dominated by a single direction as shown in Table 2-1. Figures 2-8 and 2-9 represent results from this redistribution of wave energy. As expected, the higher percent occurrence of the right-directed wave cases (-30° and -15°) increases the influence of these conditions on sediment transport potential (Figure 2-8). Although the longshore location of sediment transport and erosion/accretion peaks remains the same, the magnitude is different. For this case, the higher percent occurrence of right-directed transport creates a greater increase in shoreline erosion potential to the right of the borrow site.

Table 2-1. Redistributed wave energy for idealized borrow site case illustrating the effects of a case dominated by one wave direction.					
	Wave Direction (center of wave spectra)				
	-30°	-15°	0°	15°	30°
% Occurrence	20	35	20	15	10

Because actual wave conditions at a borrow site are dominated by a single direction, the asymmetric distribution of sediment transport potential and associated shoreline change are characteristic of conditions expected at borrow sites along the U.S. East Coast. This asymmetric distribution naturally causes impacts associated with sand mining to be focused along a shoreline area that generally is not directly landward of the borrow site. By performing a wave refraction and longshore sediment transport analysis based on site conditions, the anticipated influence of a specific borrow site on local littoral processes can be determined. In this manner, the numerical modeling process can be used to optimize borrow site excavation strategies, or alternatively, to determine acceptable volume limits of a sand mining operation.

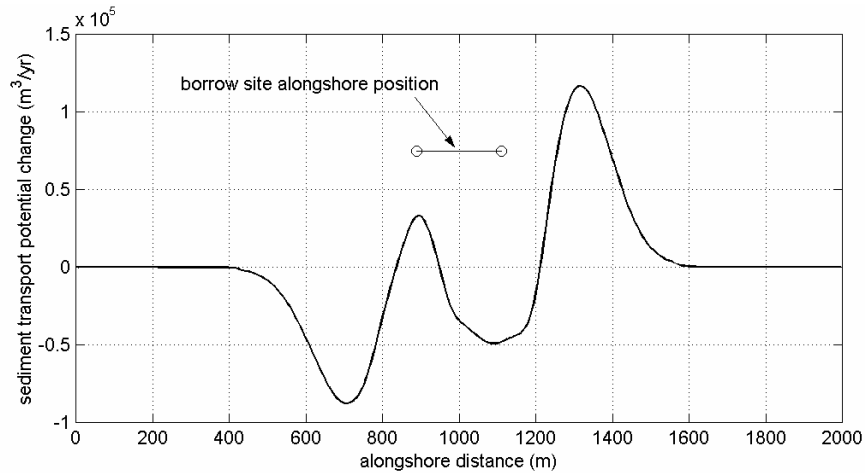


Figure 2-8. Change in computed longshore sediment transport potential based on alternate distribution of wave percent occurrences.

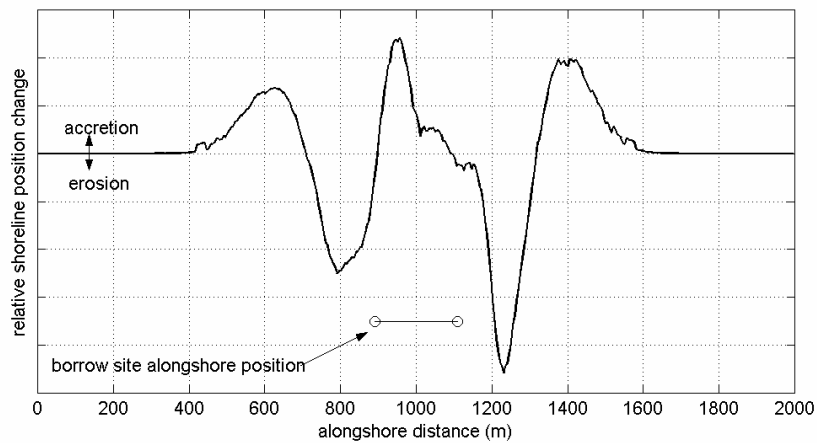


Figure 2-9. Computed cross-shore change in shoreline position based on modifications to longshore sediment transport potential using alternate distribution of wave percent occurrences.

2.4 SIGNIFICANCE OF BORROW SITE IMPACTS

As part of any offshore sand mining effort, the MMS requires an evaluation of potential environmental impacts associated with alterations to nearshore wave patterns. To determine potential impacts associated with borrow site excavation, the influence of borrow site geometry on local wave refraction patterns is evaluated; however, standard methodologies have not been developed to determine the significance of changes associated with these impacts. Because large natural spatial and temporal variability exists within the wave climate at a particular site, determination of physical impacts associated with sand mining must consider the influence of process variability. A method based on historical wave climate variability, as well as local wave climate changes directly attributable to borrow site excavation, has been applied to determine appropriate criteria for assessing impact significance.

Over the past two decades, advances in numerical wave modeling techniques have resulted in more accurate analysis of nearshore wave field transformation. In addition, the availability of long-term wave data and hindcast information has improved the boundary conditions necessary to drive these models. Although future work likely will improve some of the simplifying assumptions inherent in nearshore wave models, as well as the limitations associated with wave model input data (wave and bathymetric information), available spectral wave models can be used to develop reliable estimates of impacts associated with offshore sand mining. As shown in Appendix A, spectral wave models are reliable tools for simulating observed wave conditions affected by rapidly changing nearshore bathymetry (e.g., shoals and/or channels).

2.4.1 Available Methods for Assessing Borrow Site Impacts

One standard method for evaluating borrow site impacts is to perform wave and sediment transport modeling. Information developed from these modeling efforts is used to quantify potential physical environmental impacts associated with dredging activities. Although changes in sediment transport potential and wave energy flux associated with re-direction of wave energy generally are used as impact evaluation criteria, determining acceptable limits for these impacts is not a straightforward process. First, the wave climate in the vicinity of a borrow site exhibits temporal and spatial variations. Therefore, appropriate evaluation criteria must include the temporal and spatial variability of the wave field. Additionally, although past methodologies have described alterations to the wave field at various locations (e.g., immediately landward of the borrow site, at a fixed reference line, at the breaker line), the shoreline or breaker line appears to be most appropriate. In this manner, calculated longshore transport rates (based on wave modeling results) can be validated through evaluation of observed shoreline change.

Over the past few years, the MMS has employed two techniques for determining the significance of borrow site impacts associated with re-direction of nearshore wave energy. In 1999, a statistical approach was developed to evaluate changes in wave climate at a pre-defined offshore reference line, as well as a method for determining the statistical significance of impacts (Basco, 1999). For borrow site studies in Alabama (Byrnes et al., 1999) and New Jersey (Byrnes et al., 2000), the significance of borrow site impacts were evaluated relative to potential error estimates associated with wave height and direction (Rosati and Kraus, 1991). It was concluded that if percent changes in longshore sediment transport caused by offshore sand mining were less than the percent error determined for wave height/direction estimates, the impact was insignificant.

Although the above methodologies provide reasonable quantitative estimates of impact significance associated with offshore sand mining, the present study introduces a new methodology for evaluating borrow site impacts that incorporates temporal and spatial changes in the wave field. All three approaches use site-specific wave analyses as the basis for quantifying potential alterations to nearshore processes; however, the method presented in this study incorporates natural, site-specific variability in wave climate as a basis for determining impact significance. The following sections describe each method in more detail and provide the benefits and shortcomings, associated with each evaluation technique.

2.4.2 Reference Line Statistical Approach

To quantify changes in wave climate associated with sand mining, Basco (1999) applied a linear wave transformation model that incorporated a unit offshore wave height at the model domain boundary. Fifty (50) direction/period band combinations represented the wave climate for the chosen site (Sandbridge Shoal, Virginia), each with appropriate wave height multiplier coefficients. A reference line was defined landward of the borrow area, but seaward of the breaker line for 99% of the incident waves. In this manner, the use of a unit offshore wave height could be justified. The frequency-weighted wave energy variation along the reference line was then calculated to determine the percent change in total wave energy between existing and post-dredging conditions.

Following the development of wave energy changes, basic statistical theory was used to test for the significance of impacts. The method tests the difference in median wave energy between existing and post-dredging conditions at a 95% confidence level for various locations along the reference line. The length of the reference line is chosen to ensure that no wave energy change exists at either end. The evaluation criterion imposed indicates that if more than 50% of the total reference line is negatively impacted under the 95% confidence level, the borrow site should be rejected (Basco, 1999). Figure 2-10 illustrates the application of this significance criterion for Sandbridge Shoal, where borrow site dredging creates significant wave energy change for 12.6 km of the 20-km-long reference line (63% of the reference line length). Therefore, the report concluded “that since over 50 percent of the reference line experiences a wave climate modification, long-term dredging of sand from Sandbridge Shoal will significantly alter the wave climate.” Based on this assumption, it was suggested that the site should be rejected.

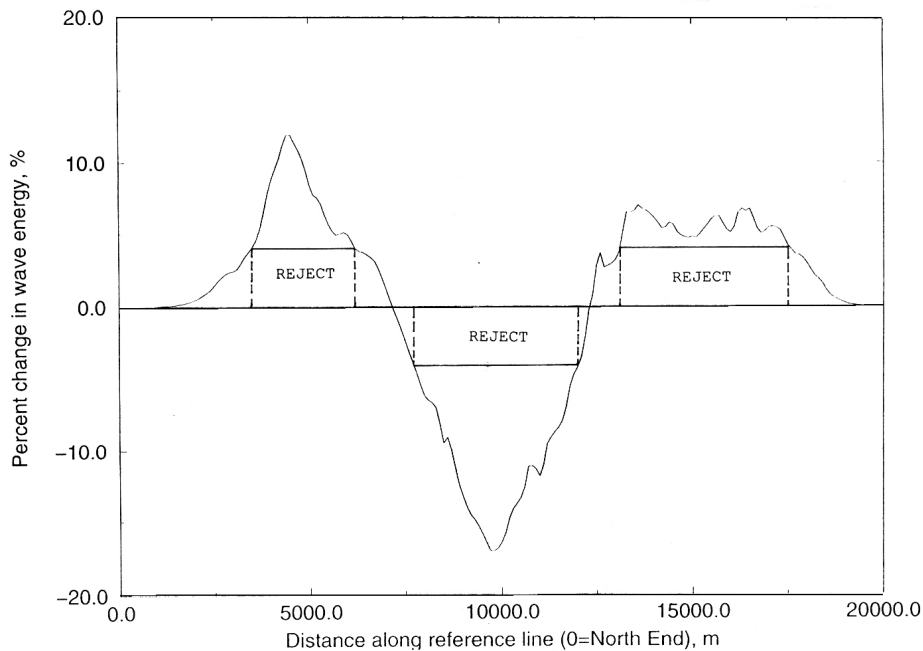


Figure 2-10. Percent change in wave energy showing regions of acceptance and rejection of the null-hypothesis using ≥ 4.0 percent as the cut-off value (from Basco, 1999).

Although the above methodology incorporates a significant numerical wave modeling effort and is statistically rigorous, it requires use of arbitrary limits. For example, rejection of the borrow site was based on greater than 50% of the reference line experiencing significant wave climate modifications. The 50% modification criteria and the length of the reference line are based on the user's judgment rather than scientific principles. Although some type of acceptable limit is required to make the process useful, it should be based on similar statistical arguments as the remainder of the methodology. In addition, waves approach the coast from all directions facing the shoreline. Generally, wave modelers make the decision to limit the angle of wave approach because waves propagating nearly parallel to the shoreline generally occur infrequently and contain little wave energy. However, the selection of reference line length is heavily dependent on the modeler's choice of wave direction limits. For a relatively narrow range of wave directions, the reference line becomes shorter, and the more likely wave impacts will be determined significant for a dredging project (and *vice versa*).

2.4.3 Potential Uncertainties in Wave Information Approach

Rather than focusing on the differences between wave and/or sediment transport processes directly associated with sand mining, borrow site studies offshore Alabama (Byrnes et al., 1999) and New Jersey (Byrnes et al., 2000) determined the significance of borrow site impacts from the error associated with wave height and direction estimates (Rosati and Kraus, 1991). Using conservative estimates for error associated with wave height and wave direction of 10%, sediment transport rates can be predicted to within $\pm 35\%$. These errors can be attributed to the inherent uncertainties in the WIS data set (wave height and directional accuracy) used to develop offshore wave conditions. The $\pm 35\%$ value is significantly higher than the impacts associated with any of the borrow sites evaluated for either Alabama or New Jersey.

Analysis of uncertainties related to longshore sediment transport estimates indicates that variations in transport associated with potential dredging scenarios are an order of magnitude lower than the uncertainty associated with sediment transport calculations. Therefore, the potential effects of offshore sand mining on longshore sand transport rates was determined to be insignificant for the scenarios tested in Alabama and New Jersey. Alternative scenarios were not expected to pose any greater effects unless the quantity of sand dredged from a site was substantially larger than potential dredged volumes selected for these studies.

One advantage of using the above methodology for estimating dredging impact significance is the direct incorporation of sediment transport calculations, rather than the indirect impact associated with changes in wave energy. Impacts to sediment transport patterns can be readily observed, since modifications to longshore transport patterns will alter the shoreline position along a sandy coast. Basco (1999) indicated that calculation of sediment transport quantities and volumes would improve the utility of the reference line statistical approach as a management tool. However, incorporation of shoreline change and sediment transport calculations was left to future work.

Although use of wave information uncertainties offers a simple tool to address borrow site impacts, it also contains inherent shortcomings. The method indicates the potential errors in wave information; however, it does not evaluate any potential errors directly associated with the wave models. If the same offshore wave field is defined for

existing and post-dredging conditions, the error associated with wave measurements (direction and wave height) may not be the best indicator of borrow site impacts.

2.4.4 Spatial and Temporal Variations in Wave Climate Approach

To directly assess the impacts to coastal processes associated with sand mining, a new approach has been developed that considers spatial (longshore) and temporal aspects of the local wave climate. This method uses a similar wave modeling effort as those needed for the previous two methods; however, modeling of waves is performed for the entire 20-year WIS record and five 4-year blocks of the WIS record. In this manner, temporal variations in the wave climate are considered relative to average annual conditions. From these wave model runs, sediment transport potential curves are derived for average annual conditions (based on the full 20-year WIS record) and each 4-year period (based on the five 4-year wave records parsed from the full record). Applying this information, the average and standard deviation in calculated longshore sediment transport potential is determined every 200 m along the shoreline.

Assuming the temporal component of sediment transport potential is normally distributed, the suggested criterion for accepting or rejecting a potential borrow site is based on a range of one standard deviation about the mean. If any portion of the sediment transport potential curve associated with a sand mining project exceeds one standard deviation of the natural temporal variability (which incorporates 2/3 of the variability) in sediment transport potential, the site would be rejected. Although using the standard deviation of each 4-year period is more conservative than using a 1-year period, the methodology provides a useful indication of sediment transport variability relative to the natural system.

An example of this method is shown in Figure 2-11, where the alterations in wave climate caused by dredging of Sandbridge Shoal, Virginia were determined to be insignificant relative to natural variability. The maximum variation in sediment transport potential caused by dredging Sandbridge Shoal was determined to be approximately 25,000 m³ per year, where the standard deviation of the natural sediment transport variability was approximately 100,000 m³/yr. Due to the orientation of the shoreline and the relatively high natural variability in wave climate, an observer on the shoreline is unlikely to notice alterations in shoreline position caused by borrow site dredging. For this reason, sites with large natural variation in wave climate and associated sediment transport potential would be allowed to have larger impacts associated with an offshore sand mining project.

As a management tool for the MMS, this methodology provides several advantages over methods previously employed to assess the significance of borrow site impacts. The primary advantages include:

1. Observed long-term shoreline change is compared with computed longshore change in sediment transport potential. Close comparison between these two curves indicates that longshore sediment transport potential calculations are appropriate for assessing long-term natural change. Therefore, this methodology has a model-independent component (observed shoreline change) used to ground truth the model results.

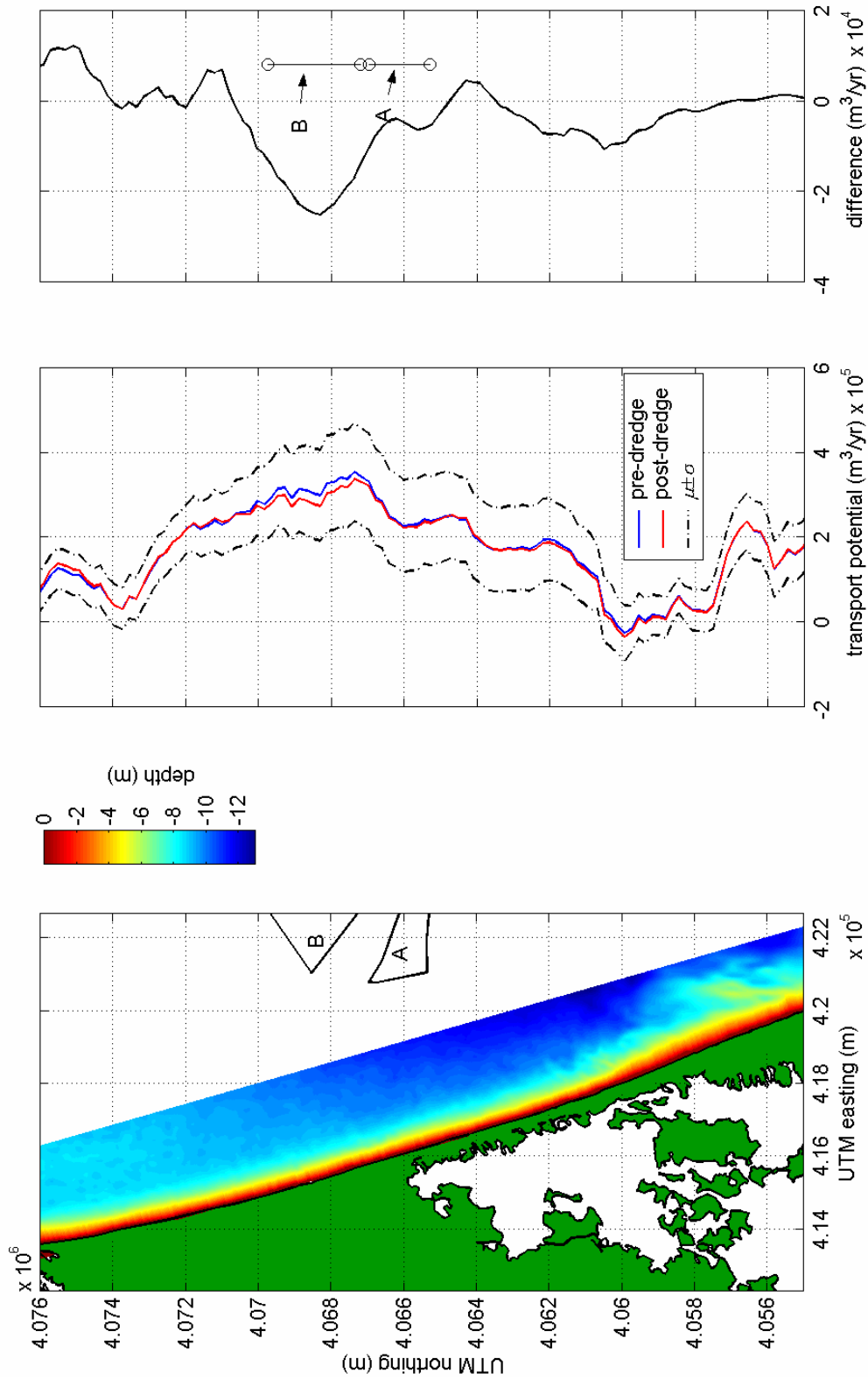


Figure 2-11. Example of results for spatial/temporal variability method for determining significance of borrow site dredging impacts. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore Sandbridge, Virginia. Middle plot shows dredging significance criterion envelope ($\pm\sigma$) determined for this shoreline. The left plot of the shoreline is given for reference.

2. The method is directly related to sediment transport potential and associated shoreline change. Therefore, impacts associated with borrow site excavation can be directly related to their potential influence on observed coastal processes (annualized variability in shoreline position).
3. Site-specific temporal variability in wave climate and sediment transport potential is calculated as part of the methodology. For sites that show little natural variability in inter-annual wave climate, allowable coastal processes impacts associated with borrow site dredging similarly would be limited, and *vice versa*. In this manner, the inter-annual temporal component of the natural wave climate is a major component in the determination of impact significance.
4. Similar to methodologies incorporated in previous MMS studies, the longshore spatial distribution of borrow site impacts is considered. However, the allowable limit of longshore sediment transport variability is computed from the temporal component of the analysis. Therefore, the final results of this analysis provide a spatially-varying envelope of allowable impacts in addition to the modeled impacts directly associated with borrow site excavation. The methodology accounts for spatial and temporal variability in wave climate, as well as providing a defensible means of assessing significance of impacts relative to site-specific conditions.

3.0 MODELING APPROACH AND APPLICATIONS

Excavation of a nearshore borrow site can affect wave heights and the direction of wave propagation. The existence of an offshore trough or trench can cause waves to refract toward the shallower edges of the borrow site. This alteration to the wave field by a borrow area may change local sediment transport rates along the shoreline, where some areas may experience a reduction in longshore transport and other areas may show an increase. In this study, four offshore areas were investigated to determine the potential cumulative physical impacts associated with dredging selected borrow sites to their maximum design limits, including 1) southern New Jersey, in the vicinity of Townsends and Corsons Inlets; 2) southeastern Virginia, in the vicinity of Sandbridge Shoal off Virginia Beach; 3) the North Carolina Outer Banks, between Duck, NC and Oregon Inlet; and 4) Canaveral Shoals, southeast of Cape Canaveral, Florida. Wave transformation modeling and sediment transport potential calculations were performed for existing and post-dredging bathymetric conditions. Comparison of computations for existing and post-dredging conditions are used to illustrate the relative maximum impact of borrow site excavation on wave-induced coastal processes.

3.1 ANALYSIS APPROACH

Sediment transport rates along a coastline are dependent on the wave climate in that area. For this study, nearshore wave heights and directions along the shoreline landward of proposed borrow sites were estimated using the spectral wave model STWAVE to simulate the propagation of offshore waves to the shoreline. Offshore wave conditions used as input for wave modeling were derived from two sources: 1) measured spectral wave data from offshore data buoys, and 2) hindcast simulation time series data, available from the U.S. Army Corps of Engineer's (USACE) Wave Information Study (WIS).

3.1.1 Wave Modeling

Developed by the U.S. Army Engineer Waterways Experiment Station (WES), STWAVE v2.0 is a steady state, spectral wave transformation model (Smith, et al., 1999). Two-dimensional (frequency and direction vs. energy) spectra are used as input to the model. STWAVE is able to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model includes a wave breaking model based on water depth and wave steepness. Model output includes significant wave height (H_s), peak period (T_p), and mean wave direction ($\bar{\theta}$).

STWAVE is an efficient program that requires moderate computing resources to run well. The model is implemented using a finite-difference scheme on a regular Cartesian grid (grid increments in the x and y directions are equal). During a model run, the solution is computed starting from the offshore open boundary and is marched in the onshore direction in a single pass of the model domain. This is why STWAVE can propagate waves only in directions within the $\pm 87.5^\circ$ half plane. A benefit of using this single pass approach is that it uses minimal computer memory, because the only memory-resident spectral data are for two grid columns. As such, the changing wave spectra across each grid column are in turn computed using the information solely from the previous grid column.

STWAVE is based on a form of the wave action balance equation. For this model the wave action density spectrum, which includes the effects of currents, is conserved along wave rays. In the absence of currents, wave rays, correspond to wave orthogonals, and the action density spectrum is equivalent to the wave energy density spectrum. A diagram showing the relationship between wave orthogonal, wave ray and current directions is shown in Figure 3-1. The governing equation of wave transformation, using the action balance spectrum, in tensor notation is written as (Smith et al., 1999)

$$(C_{ga})_i \frac{\partial}{\partial X_i} \frac{C_a C_{ga} \cos(\mu - \alpha) E}{\omega_r} = \sum \frac{S}{\omega_r} \quad (3.1)$$

where

- $E = E(f, \theta)$ wave energy density spectrum,
- S = energy source and sink terms (e.g., whitecapping, breaking, wind input),
- α = wave orthogonal direction,
- μ = wave ray direction (direction of energy propagation),
- ω_r = relative angular frequency ($2\pi f_r$),
- C_a, C_{ga} = absolute wave celerity and group celerity, respectively.

The breaking model in STWAVE is based on a form of the Miche criterion as discussed by Battjes and Janssen (1978). It sets a maximum limit on the zero-moment wave height (H_{mo}), the wave height based on the distribution of energy in the wave spectrum. The formulation of this model is

$$H_{mo(max)} = 0.1L \tanh(kd) \quad (3.2)$$

where L is the wavelength, k is the wave number ($k = 2\pi/L$), and d is the depth at the point where the breaking limit is being evaluated. This equation is used with a simpler

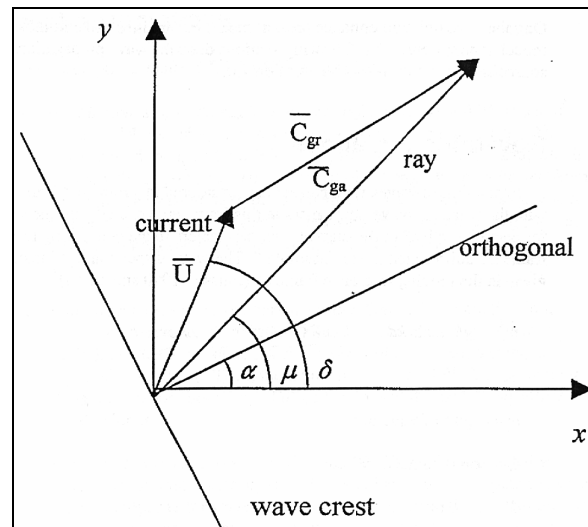


Figure 3-1. Diagram of wave and current vectors used in STWAVE (from Smith et al., 1999). Subscript *a* denotes values in the *absolute* frame of reference, and subscript *r* denotes values in the *relative* frame of reference (with currents).

breaking model, as applied in earlier versions of STWAVE, where the maximum H_{mo} wave height is always expressed as a constant ratio of water depth

$$H_{mo(max)} = 0.64 d . \quad (3.3)$$

An advantage to using Equation 3.2 versus Equation 3.3 is that it accounts for increased wave breaking resulting from wave steepening caused by wave-current interactions. Once model wave heights exceed $H_{mo(max)}$, STWAVE uses a simple method to reduce the energy spectrum, essentially to set the value of $H_{mo} = H_{mo(max)}$. Energy at each frequency and direction is reduced by the same percentage. As a result, non-linear transfers of energy to high frequencies during breaking are not included in STWAVE.

3.1.2 Input Spectra Development

Spectral wave input for STWAVE model runs performed for each of the study areas was developed using WIS hindcast data for borrow sites offshore southern New Jersey, Dam Neck/Sandbridge Beach (Virginia), Dare County North Carolina, and Cape Canaveral (Florida). Alternatively, for the Sandbridge Shoal area offshore southeastern Virginia, a five-year spectral wave data record from an offshore buoy maintained by the National Data Buoy Center (NDBC) was used to develop model input spectra. The NDBC data were used over available WIS data for southeastern Virginia because the buoy record was adequately long and represented actual long-term wave conditions in the area. In general, buoy data are the preferred source of wave information for modeling, because they represent actual offshore measurements rather than hindcast information derived from large-scale models. However, very few sites along the U. S. East Coast have wave measurement records of sufficient length to justify their use as a source of long-term information.

3.1.2.1 Southern New Jersey WIS Data

Wave data for model runs offshore southern New Jersey and Townsends Inlet were developed using WIS station AU2067 (Figure 3-2), located approximately 22 km southeast of Townsends Inlet, NJ. This WIS record covers a 20-year period from January 1976 to December 1995 and includes 58,440 wave events (eight records per day). Two wave roses showing percent occurrence of different wave conditions are shown in Figure 3-3. The first rose shows how wave height distribution varies with direction. The majority of waves (68%) in the WIS record fall within the compass sector between 90° and 180°. The dominant wave direction is east-northeast, from which 28% of waves in the record propagate. The mean height for all waves in the record is 1.2 m, with a standard deviation of 0.7 m. The mean height for waves along the dominant wave direction is 1.1 m, with a standard deviation of 0.8 m. The second rose in Figure 3-3 shows the distribution of peak periods in the record. The mean peak periods for the entire record is 7.7 sec, and 26% of the simulated waves in the record have peak period greater than 9 sec.

3.1.2.2 Southeastern Virginia WIS Data

Wave input conditions for model simulations offshore southern Virginia were developed using WIS hindcast data from station AU2058 (Figure 3-2). The data from this station were used to develop the dredging significance envelope discussed in the following sections. Station AU2058 is located approximately 17 km offshore Sandbridge, VA. The hindcast data for this site cover the same 20-year period as the New Jersey

record from WIS station AU2067. The two wave roses showing wave height and wave period distributions for station AU2058 are presented in Figure 3-4. Most waves in this record (68%) are from the 60 degree compass sector around due east. The prevailing wave direction is east-northeast, where 38% of the wave of the WIS record propagate. The mean wave height for all waves in the record is 1.2 m, with a standard deviation of 0.7 m. From the prevailing east-northeast compass sector, the mean wave height is 1.3 m, with a standard deviation of 0.9 m. The second plot of Figure 3-4 shows the distribution of wave periods in the WIS record. The mean period for the entire hindcast record is 8.7 sec.

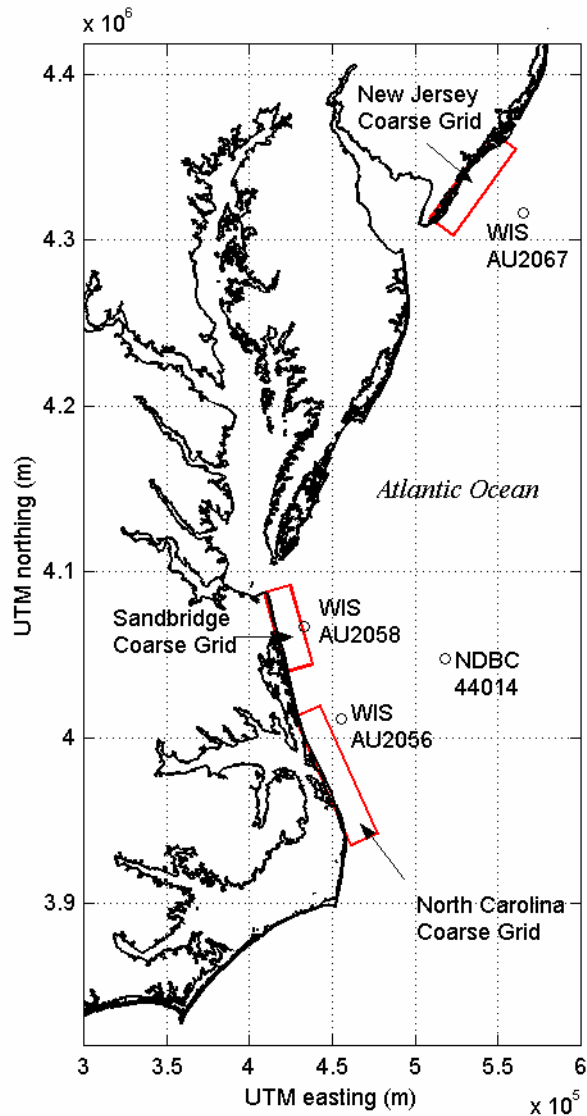


Figure 3-2. Shoreline from New Jersey to North Carolina with coarse grid limits and wave input data stations used to determine dredging impacts from offshore sand mining.

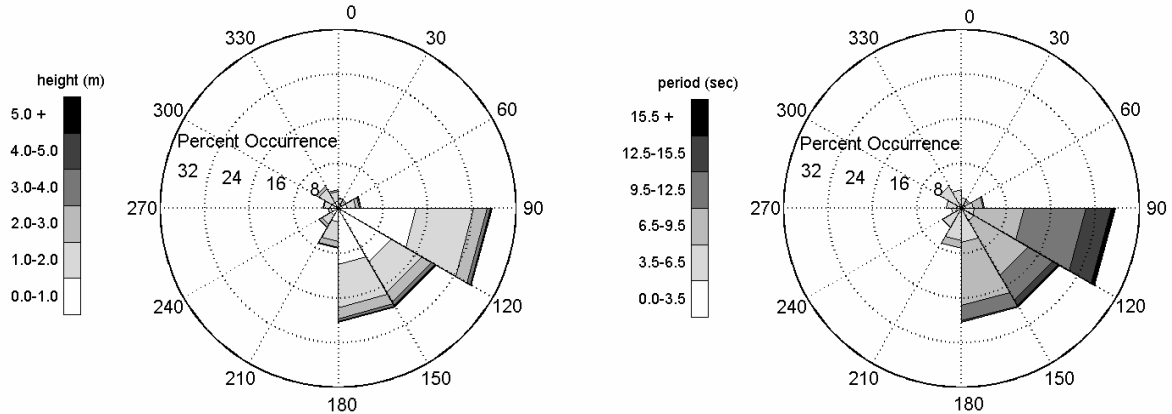


Figure 3-3. Wave height and period for hindcast data from WIS station AU2067 (offshore New Jersey) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction.

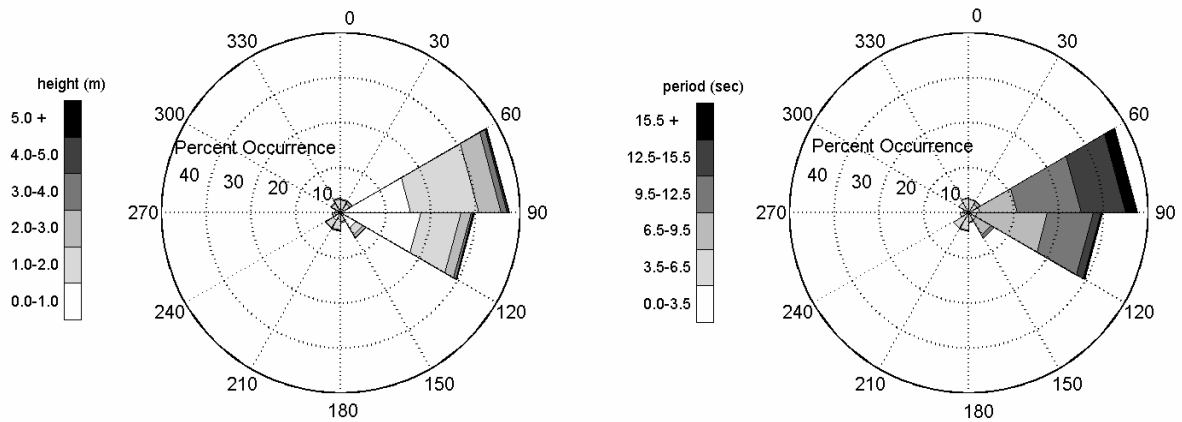


Figure 3-4. Wave height and period for hindcast data from WIS station AU2058 (offshore southern Virginia) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction.

3.1.2.3 North Carolina WIS Data

Wave input conditions for simulations offshore North Carolina were developed using hindcast data from WIS station AU2056 (Figure 3-2), which is located approximately 33 km northeast of Bodie Island, NC. This WIS record covers a 20-year period from January 1976 to December 1995. Two wave roses showing percent occurrence of different wave conditions are shown in Figure 3-5. The first rose shows how wave height distribution varies with direction. The majority of waves (52%) in the WIS record fall within the compass sector between 60° and 120°. The dominant wave direction is east-northeast, from which 32% of waves in the record propagate. The mean height for all waves in the record is 1.5 m, with a standard deviation of 0.9 m. The mean height for waves along the dominant wave direction is 1.2 m, with a standard

deviation of 0.8 m. The second rose in Figure 3-5 shows the distribution of peak periods in the record. A significant number of wave events (32%) have peak periods greater than 9 sec, and the mean peak period for the entire record is 8.3 sec.

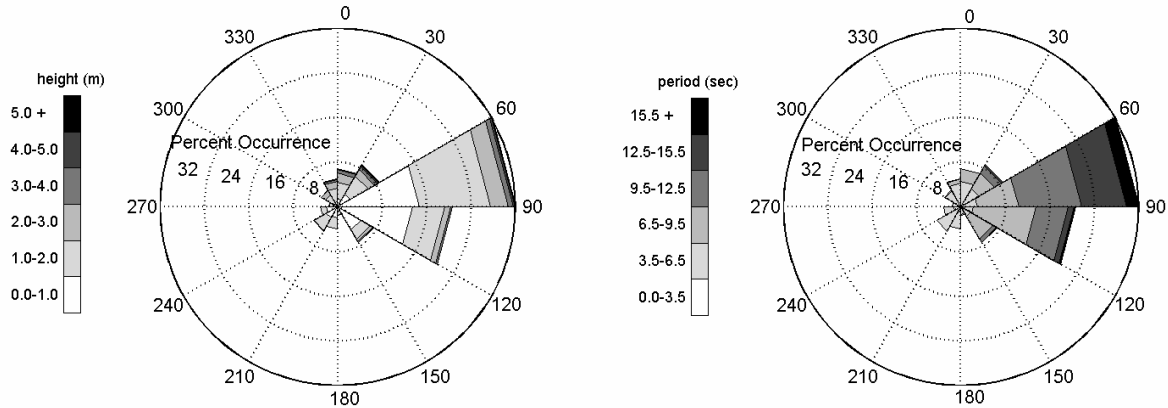


Figure 3-5. Wave height and period for hindcast data from WIS station AU2056 (offshore North Carolina) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction.

3.1.2.4 Cape Canaveral WIS Data

Wave data for model runs offshore Cape Canaveral were developed using WIS station AU2019 (Figure 3-6), which is located approximately 29 km east-northeast of Cape Canaveral, FL. Two wave roses showing percent occurrence of different wave conditions are shown in Figure 3-7. The first rose shows how wave height distribution varies with direction. Most waves (90%) in the record fall within the compass sector between 30° and 120°, and the greatest percentage of waves (43%) are from the east-northeast sector. The mean height for all waves in the record is 1.3 m, with a standard deviation of 0.7 m. The mean height for waves along the dominant wave direction is 1.4 m, with a standard deviation of 0.7 m. The second rose in Figure 3-7 shows the distribution of peak periods in the record. The mean peak period for the entire record is 9.3 sec, and 38% of simulated waves in the record have peak periods greater than 9 sec.

3.1.2.5 Development of Model Spectra from WIS Data

In order to reduce the offshore extent of the computational grid used by STWAVE, the program WAVETRAN was used to propagate WIS waves closer to shore. For the New Jersey WIS data, waves were propagated from a depth of 18 m at the station to a depth of 17 m, the mean depth along the offshore open boundary of the coarse model grid. For the North Carolina data, waves were propagated from a 37-m water depth to a 24-m water depth approximately 17 km offshore (the seaward limit of the STWAVE grid). For the Cape Canaveral model grid, WIS data were propagated from a depth of 27 m to 24-m water depth at the offshore boundary of the coarse model grid. WAVETRAN is part of the Shoreline Modeling System (SMS) developed by WES (Jensen, 1983).

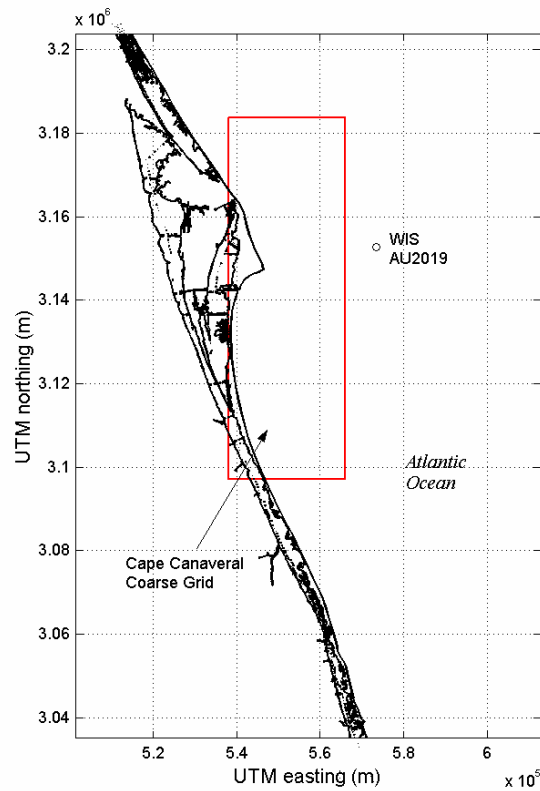


Figure 3-6. East Florida shoreline at Cape Canaveral with coarse grid limits and wave input data station used to determine dredging impacts from offshore sand mining.

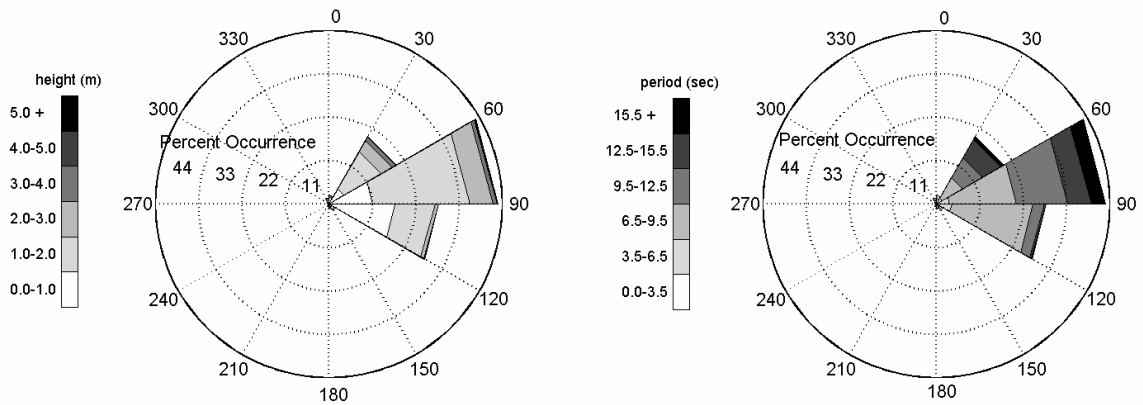


Figure 3-7. Wave height and period for hindcast data from WIS station AU2019 (Cape Canaveral) for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction.

STWAVE input spectra were developed using a second numerical routine which re-creates a two dimensional spectrum for each individual wave condition in the transformed WIS record. This program computes the frequency and directional spread of a wave energy spectrum based on significant wave parameters (i.e., wave height, peak period, and peak direction), as well as wind speed. This method is described by Goda (1985). The frequency spectrum $S(f)$ is computed using the relationship

$$S(f) = 0.257 H_{1/3}^2 T_{1/3} (T_{1/3} f)^{-5} \exp[-1.03(T_{1/3} f)^{-4}] \quad (3.4)$$

known as the Bretschneider-Mitsuyasu spectrum, where $H_{1/3}$ is the significant wave height, f is the discrete frequency where $S(f)$ is evaluated, and $T_{1/3}$ is the significant period, estimated from the peak wave frequency (f_p) by

$$T_{1/3} = 1/(1.05f_p). \quad (3.5)$$

To compute the two-dimensional energy spectrum, a directional spreading function $G(f, \theta)$ must be applied to the frequency spectrum such that

$$S(f, \theta) = S(f)G(f, \theta). \quad (3.6)$$

In this method, the directional spreading function is computed using the relationship

$$G(f, \theta) = G_o \cos^{2s} \left(\frac{\theta}{2} \right) \quad (3.7)$$

where s is a spreading parameter related to wind speed and frequency, θ is the azimuth angle relative to the principle direction of wave travel, and G_o is a constant dependent upon θ and s . The spreading parameter s is evaluated using the expression

$$s = \begin{cases} s_{\max} \cdot (f/f_p)^5 & : f \leq f_p \\ s_{\max} \cdot (f/f_p)^{-2.5} & : f \geq f_p \end{cases} \quad (3.8)$$

where $s_{\max} = 11.5(2\pi f_p U/g)^{-2.5}$. Wind speed U is therefore used to control the directional spread of the spectrum by increasing the directional spread with increasing wind speed. Finally, the constant G_o is computed by evaluating the integral

$$G_o = \left[\int_{\theta_{\min}}^{\theta_{\max}} \cos^{2s} \left(\frac{\theta}{2} \right) d\theta \right]^{-1}. \quad (3.9)$$

The result is a wave energy spectrum that is based on parameters from the WIS record, where spectral energy is distributed based on wave peak frequency and wind speed. An example of a two-dimensional spectrum generated by this method is presented in Figure 3-8.

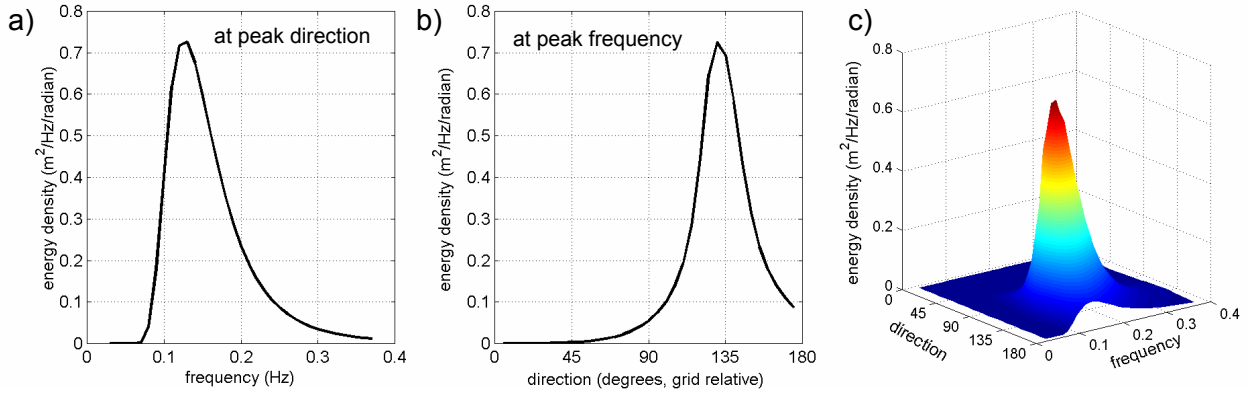


Figure 3-8. Example of STWAVE input spectrum developed using WIS 20-year hindcast data and Goda method of computing frequency and direction spectrum. Plots show a) frequency distribution of energy at peak direction, b) directional distribution of energy at peak frequency, and c) surface plot of two-dimensional energy spectrum. Example is model case 5 ($H_{mo} = 0.9$ m, $\theta_{mean} = 130^\circ$ grid relative).

After re-creating a two-dimensional spectrum from the parameters given in the WIS record, each individual spectrum is sorted (or binned) by peak direction and peak period. Wave spectra computed from wave parameters that fall within the limits of individual direction and period bins are added together, and a mean spectrum for all waves in each bin is computed based on the total number of wave events in the bin. In total, six direction bins and two period bins were used to characterize wave data. From the 12 total bins, conditions used in the model runs of STWAVE were selected based on the percent occurrence and percent energy for conditions in each bin. Selected conditions have a percent occurrence greater than two percent and contain more than 2.5 percent of the energy of the entire wave record. For the four modeled regions conditions selected for model runs are shown in Tables 3-1 through 3-4, with significant parameters for each input spectrum.

Table 3-1. Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for New Jersey model grid.

	STWAVE model input condition	% occurrence	H _{mo}	Mean wave	Peak wave	Peak wave	Direction
			wave height	period, T _p	direction, θ _p	direction, θ _p	bin
			m	sec	deg. true north	grid relative	grid relative
Period Band 1	1	6.4	1.4	7.7	61	25	0-30
	2	14.1	1.1	8.3	86	50	30-60
	3	14.1	1.2	7.7	111	75	60-90
	4	17.7	1.2	7.1	131	95	90-120
	5	6.6	0.8	5.0	161	125	120-150
Period Band 2	6	5.1	1.3	11.1	61	25	0-30
	7	14.5	1.6	11.1	81	45	30-60
	8	5.8	2.0	10.0	96	60	60-90

Table 3-2. Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for Virginia model grid.

	STWAVE model input condition	% occurrence	H _{mo}	Mean wave	Peak wave	Peak wave	Direction
			wave height	period, T _p	direction, θ _p	direction, θ _p	bin
			m	sec	deg. true north	grid relative	grid relative
Period Band 1	1	5.4	0.5	4.4	14	30	0-30
	2	9.1	1.3	5.3	34	50	30-60
	3	8.2	1.4	6.7	64	80	60-90
	4	10.4	1.1	7.3	89	105	90-120
	5	14.2	0.9	7.6	114	130	120-150
	6	3.4	1.0	4.8	139	155	150-180
Period Band 2	7	9.7	1.5	11.8	74	90	60-90
	8	18.8	1.5	12.9	79	95	90-120
	9	6.1	1.3	11.2	109	125	120-150

Table 3-3. Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for North Carolina model grid.

	STWAVE model input condition	% occurrence	H _{mo}	Mean wave	Peak wave	Peak wave	Direction
			wave height	period, T _p	direction, θ _p	direction, θ _p	bin
			m	sec	deg. true north	grid relative	grid relative
Period Band 1	1	9.4	1.1	5.1	1	25	0-30
	2	8.1	1.9	6.0	21	45	30-60
	3	8.7	1.5	6.7	56	80	60-90
	4	10.1	1.2	7.4	86	110	90-120
	5	16.3	0.9	7.6	106	130	120-150
	6	8.1	0.6	4.6	131	155	150-180
Period Band 2	7	6.0	1.9	11.5	66	90	60-90
	8	19.2	1.5	12.8	71	95	90-120
	9	6.3	1.3	11.3	101	125	120-150

Table 3-4. Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs for Florida model grid.

	STWAVE model input condition	% occurrence	H _{mo}	Mean wave	Peak wave	Peak wave	Direction
			wave height	period, T _p	direction, θ _p	direction, θ _p	bin
			m	sec	deg. true north	grid relative	grid relative
Period Band 1	1	8.2	1.7	7.7	55	55	30-60
	2	20.8	1.4	7.7	80	80	60-90
	3	24.6	1.0	7.7	100	100	90-120
	4	2.3	1.5	6.3	130	130	120-150
Period Band 2	5	6.5	1.7	12.5	60	60	30-60
	6	28.5	1.6	14.3	65	65	60-90
	7	3.4	1.5	11.1	100	100	90-120

3.1.2.6 Spectral Development from Wave Buoy Data

An alternate method was used to develop wave spectra for the southeastern Virginia region model. In addition to the WIS record, which was used in model runs to determine the dredging significance envelope, spectral input for the Sandbridge Shoal STWAVE model was developed using NDBC spectral wave buoy data (NDBC buoy 44014), which is located approximately 95 km east of False Cape, VA. The buoy record was used for model runs executed to determine post-dredging impacts caused by the two sites offshore Sandbridge, VA. This buoy record covers a 5-year period from January 1996 to December 2000. Wave roses showing the percent occurrence of different wave conditions is illustrated in Figure 3-9.

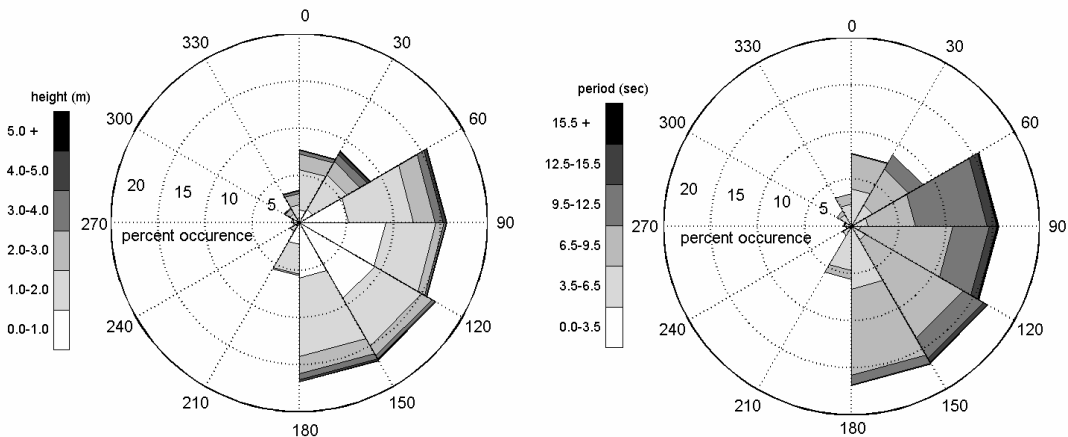


Figure 3-9. Wave height and wave period roses for data recorded by NDBC buoy 44014 (offshore Virginia Beach) for the 5-year period between January 1996 and December 2000. Direction indicates the direction waves were propagating from relative to true north. Radial length of gray tone segments indicates percent occurrence of each range of wave condition (height or period). Combined length of segments in each sector indicates percent occurrence of all waves from that direction.

The first rose shows how wave height distribution varies with direction. The majority of waves (69%) in the buoy record fall within the broad compass sector between

60° and 180°. The dominant wave direction is south-southeast, where 18% of waves in the record propagate. The mean significant wave height for all conditions in the record is 1.4 m, with a standard deviation of 0.9 m. The second rose in Figure 3-8 shows the distribution of peak periods in the record. A significant number of wave events (22%) have peak period greater than 10 sec, and the mean dominant periods for the entire record is 7.9 sec.

In order to reduce the offshore extent of the computational grid used by STWAVE, a computer program was developed to propagate buoy spectra, from 47.5-m water depth at the buoy to 16.6-m water depth approximately 15 km offshore (the seaward limit of the coarse STWAVE grid). The method employed to refract buoy spectra also was used in WIS Phase III (Jensen, 1983). This method is based on the conservation of energy along wave rays and Snell's law. For monochromatic waves, assuming straight and parallel bottom contours, shallow water wave height after shoaling and refraction is expressed as the product of the offshore wave height H_0 with the shoaling and refraction coefficients (K_s and K_r respectively):

$$H = H_0 K_s K_r \quad (3.10)$$

where the shoaling coefficient is determined using the group velocity of offshore (C_{g0}) and shallow water (C_g) wave conditions, expressed as $K_s = (C_{g0}/C_g)^{0.5}$, and the refraction coefficient is determined using the approach angle of the incident offshore wave θ_0 and the angle of the refracted shallow water wave θ , expressed as $K_r = (\cos \theta_0 / \cos \theta)^{0.5}$. In terms of energy for a wave spectrum, the total energy of the refracted spectrum can be expressed in terms of the initial two-dimensional (f frequency, and θ direction) energy spectrum $E(f, \theta)$ (Jensen, 1983),

$$E_t = \int_0^\infty \int_0^{2\pi} E(f, \theta) \frac{(C_{g0})_0}{(C_g)} \left| \frac{\partial \theta}{\partial \theta_0} \right| d\theta df \quad (3.11)$$

where the term

$$\frac{(C_{g0})_0}{(C_g)} \left| \frac{\partial \theta}{\partial \theta_0} \right| \quad (3.12)$$

is essentially the combined refraction and shoaling coefficients. Therefore, Equation 3.11 is applied to individual spectral components, using Snell's law to determine $\partial \theta / \partial \theta_0$ for each direction bin in the spectrum. Finally, the shallow water wave angle of the refracted component is determined using Snell's law directly, $\theta(f, d, \theta_0) = \sin^{-1}(c/c_0 \sin \theta_0)$.

Before transforming buoy spectra to the offshore limit of the computational grid, an additional numerical routine was used to sort the spectral data for each individual wave record in the transformed buoy data. Each wave record was sorted by peak direction and peak period. Wave spectral components computed from wave parameters that fall within the limits of individual direction and period bins are summed, and a two-dimensional (frequency and direction) mean spectrum for all waves in each bin is computed based on the total number of wave events in the bin. In total, a matrix of six direction bins *versus* two period bins were used to characterize the wave data. From the 12 total bins, conditions used in the STWAVE model runs were selected based on

percent occurrence and energy content of conditions in each bin. The 11 conditions selected for model runs are shown in Table 3-5, with significant parameters for each input spectrum.

Table 3-5. Significant parameters for input wave spectra used for existing and post-dredging STWAVE model runs for offshore southeastern Virginia sites.

	STWAVE model input condition	% occurrence	H_{mo}	Peak wave	Peak wave	Peak wave	Direction
			wave height	period, T_p	direction, θ_p	direction, θ_p	bin
			m	sec	deg. true north	grid relative	grid relative
Period Band 1	1	7.2	1.6	7.7	359	15	0-30
	2	7.7	1.6	8.3	34	50	30-60
	3	8.1	1.4	9.1	54	70	60-90
	4	10.1	1.1	8.3	104	120	90-120
	5	13.2	1.1	8.3	119	135	120-150
	6	15.2	1.2	8.3	149	165	150-180
Period Band 2	7	2.0	2.8	11.1	39	55	30-60
	8	7.5	2.0	11.1	64	80	60-90
	9	5.2	1.6	11.1	79	95	90-120
	10	3.4	1.8	10.0	134	150	120-150
	11	1.2	2.4	10.0	144	160	150-180

3.1.3 Grid Development

Along with input spectra, bathymetry grids were developed for existing and post-dredging scenarios. Plots of coarse and fine-nested grids for modeled regions are shown in Figures 3-10 through 3-17. For each of the four modeled areas, two coarse grids were developed that have the same geographical coverage and differ only by modifications to bathymetry in the borrow area. The maximum cumulative dredged volumes and mean depths for the modeled borrow sites for each region are shown in Table 3-6. The National Ocean Service (NOS) was the primary source of bathymetric data used to create the grids (NOS, 1998). However, these data were supplemented by other sources of data when needed (i.e., digitized NOAA chart bathymetry for areas along the North Carolina shoreline), or when more recent survey data were available (i.e., recent USACE surveys of the nearshore region along Cape Canaveral, FL). Depths at the offshore open boundary of the coarse grids vary between 9.2 and 21.4 m for the southern New Jersey coarse grid, 10.5 and 24.6 m for the southeastern Virginia coarse grid, 19.0 and 31.0 m for the North Carolina grid, and 19.3 and 29.7 m for the Cape Canaveral grid.

The spatial extent of each model coarse grid is given in Table 3-7. The geographical limits of the grids were chosen based on wave conditions available for model runs. Wave conditions with relatively small angles to the shoreline require a large grid in the longshore direction so the site of interest (i.e., the borrow site and affected shoreline) does not fall within the “shadow” of lateral grid boundaries. The grids all have a node spacing of 200 m. Grid axes are rotated to match the orientation of the shoreline in the modeled area.

Fine grids also were developed for each region in order to obtain greater resolution of waves in the nearshore behind the borrow site (Figure 3-11, 3-13, 3-15, and 3-17),

particularly in the surf zone. For each region, the same fine grid was used for existing and post-dredging conditions. Alongshore and cross-shore node spacing for fine grids is 20 m for all four regions. Boundary conditions (wave spectra) at the offshore and lateral boundaries of the fine grids were extracted from coarse-grid model runs. Therefore, boundary conditions vary along the length of the open boundary of the fine grid (nested into the coarse grid model solution).

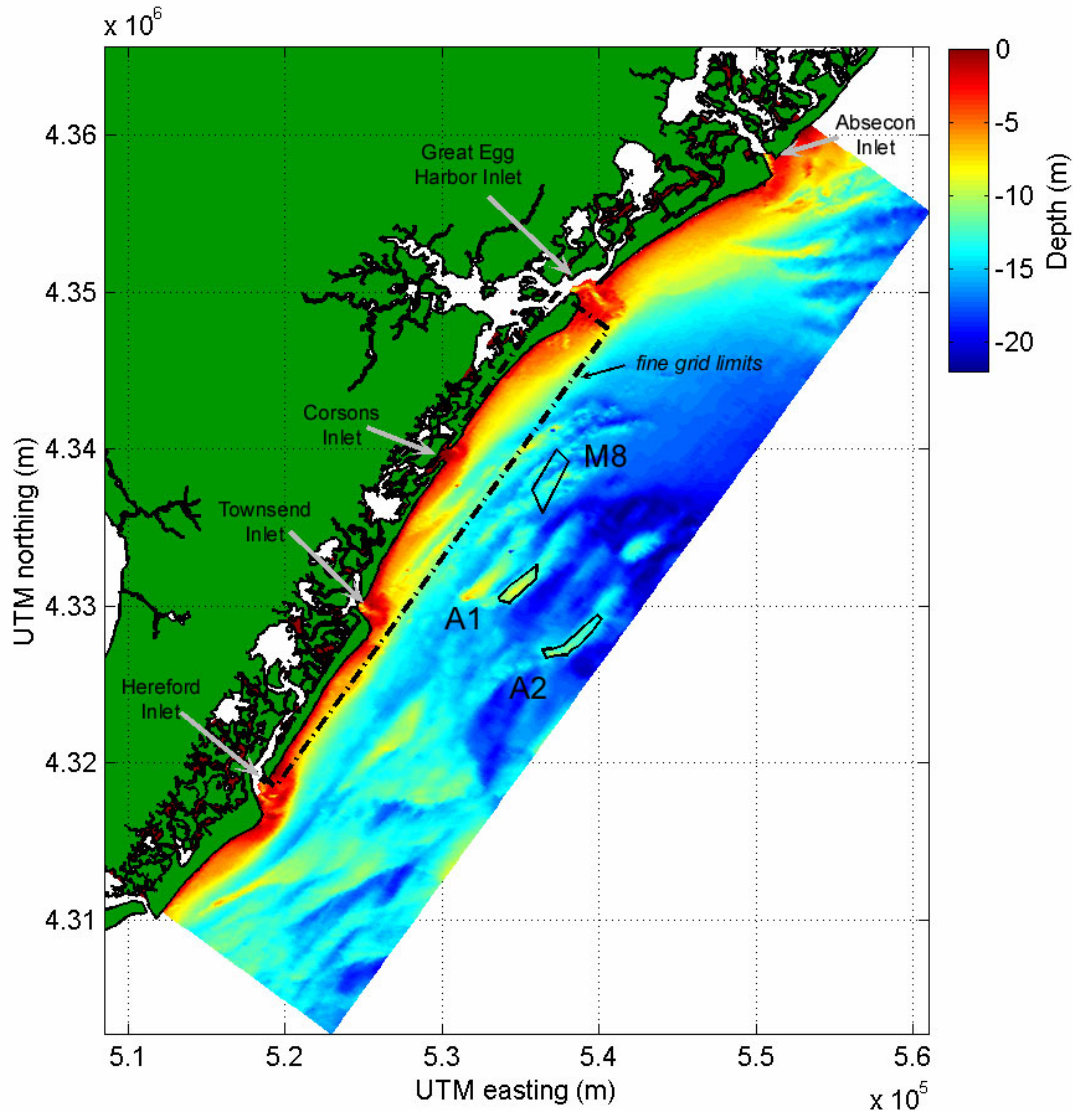


Figure 3-10. Color contour plot of coarse model grid (200 m x 200 m grid spacing) of offshore New Jersey. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line.

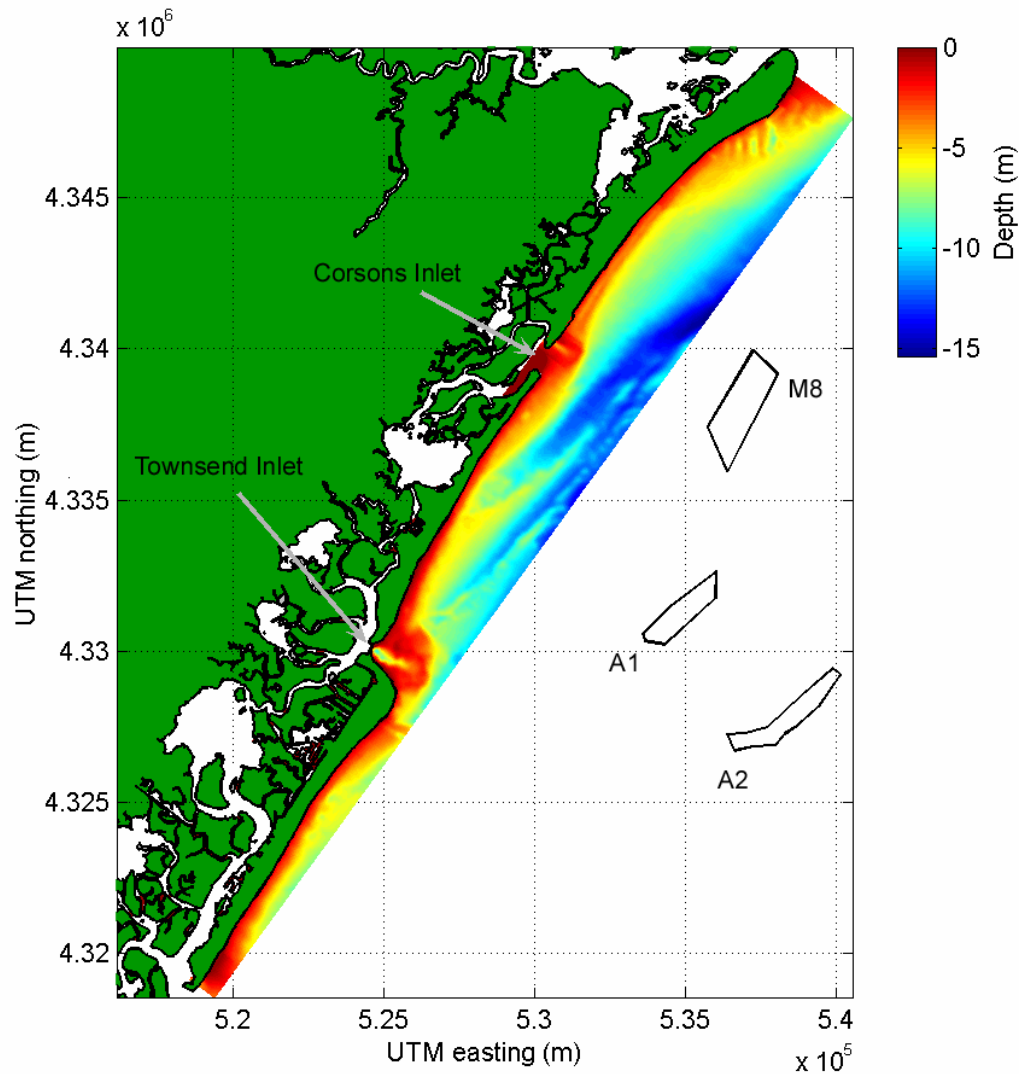


Figure 3-11. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) used with STWAVE for offshore New Jersey. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line.

Region	Site Designation	Volume (10 ⁶ m ³)	Area (10 ⁶ m ²)	Excavation Mean Depth (m)
New Jersey	A1	8.8	2.2	4.0
	A2	7.8	2.6	3.0
	M8	8.0	4.0	2.0
Virginia	A	5.3	1.8	3.0
	B	6.9	2.3	3.0
North Carolina	3 east	1.4	0.7	2.0
	3 west	2.5	0.8	3.0
Florida	2	26.0	5.0	5.2

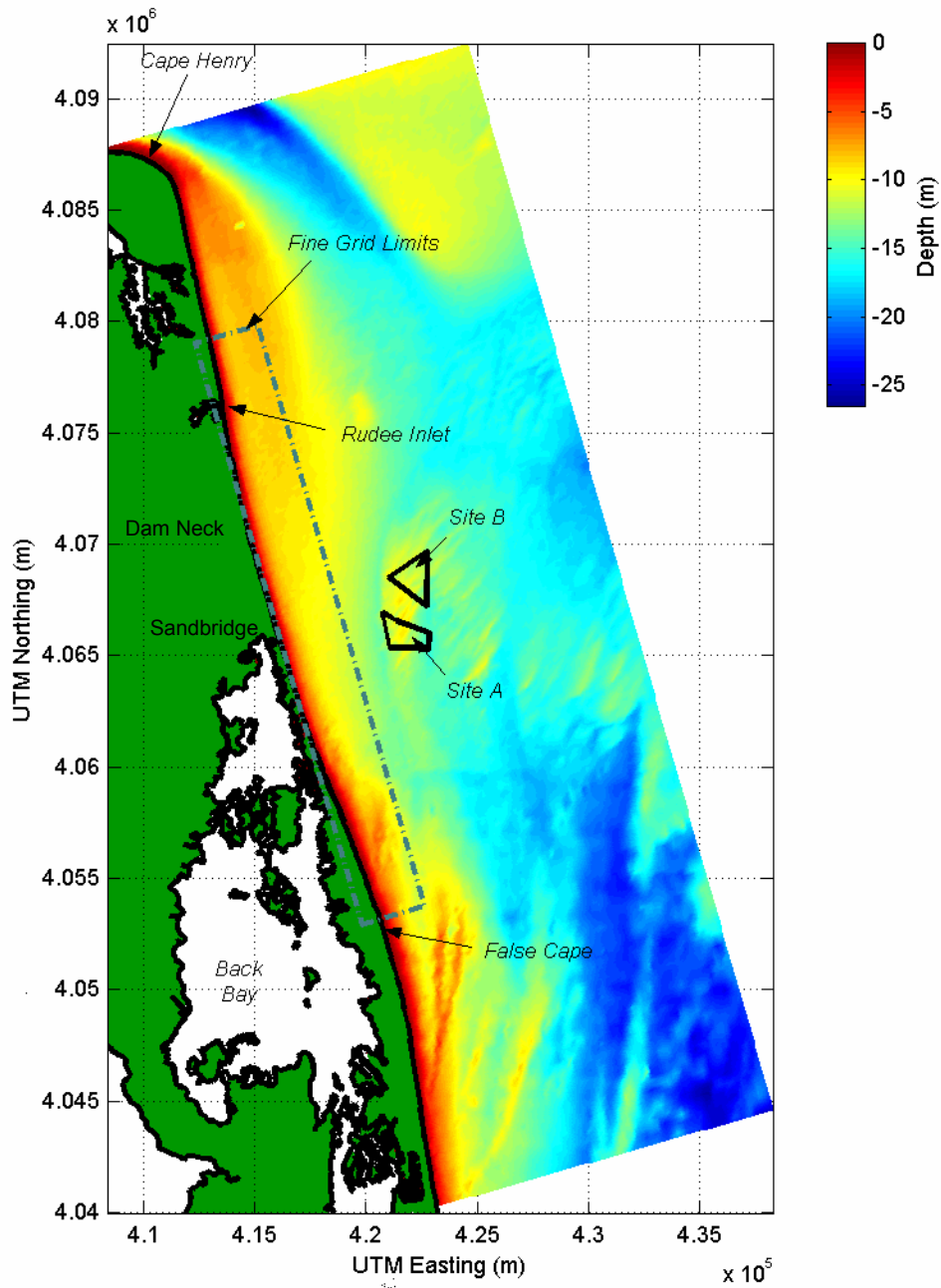


Figure 3-12. Color contour plot of coarse model grid (200 m x 200 m grid spacing) of offshore southeastern Virginia. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line.

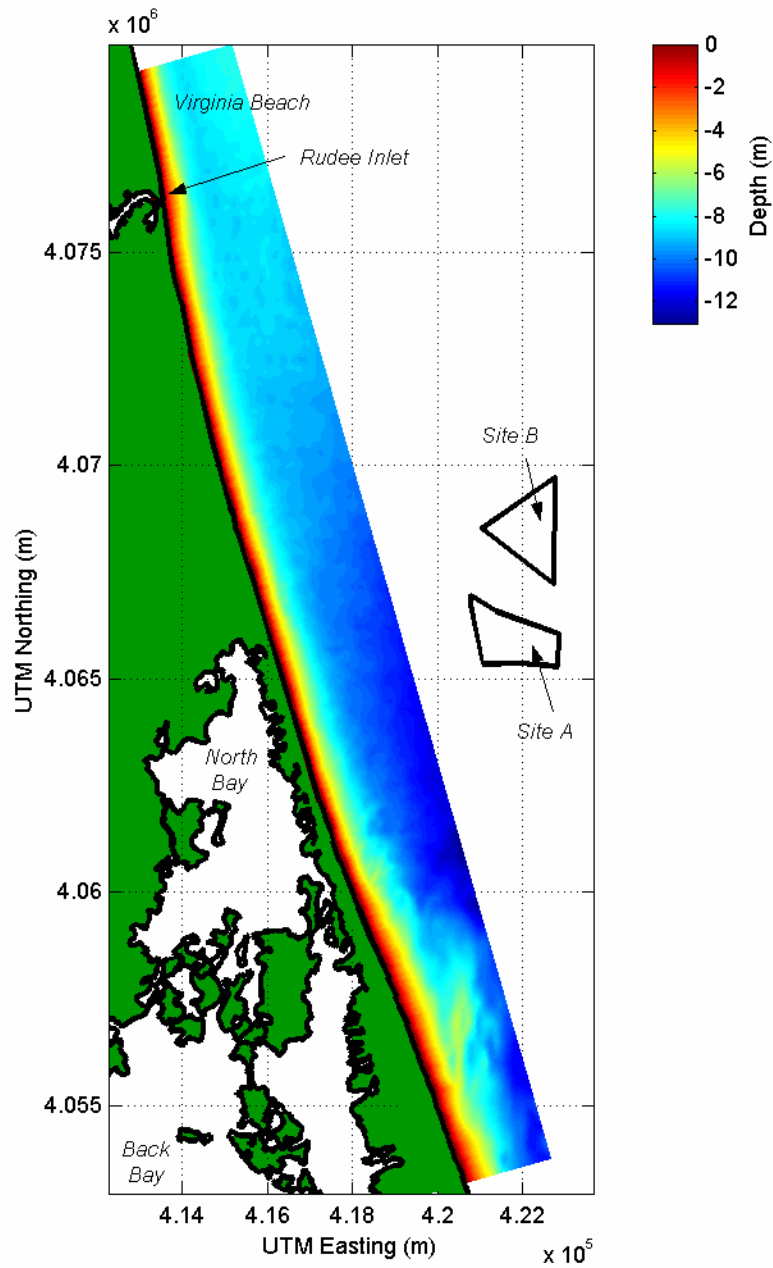


Figure 3-13. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) of offshore southern Virginia used with STWAVE. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line.

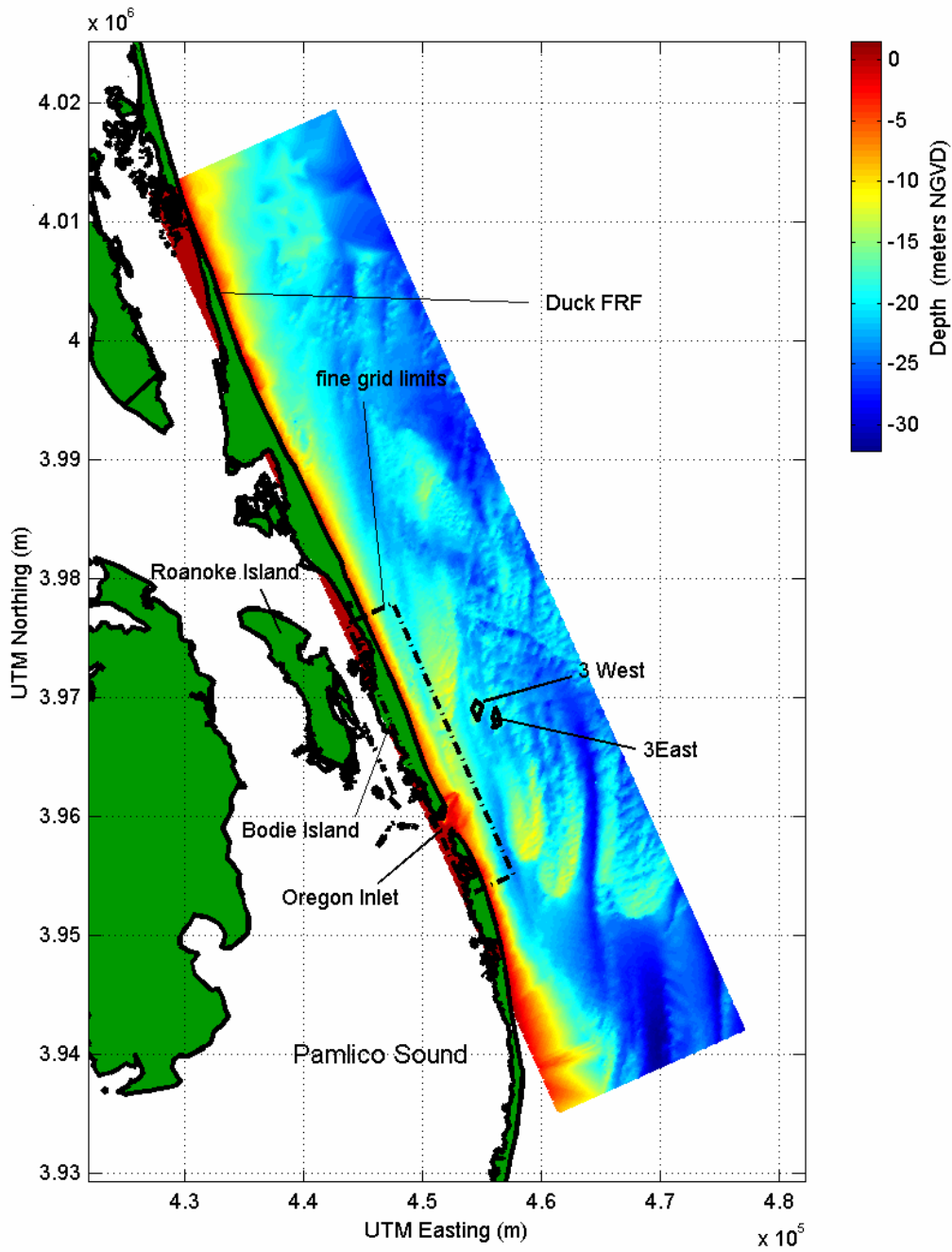


Figure 3-14. Color contour plot of coarse model grid (200 m x 200 m grid spacing) for offshore North Carolina. Depths are relative to NVGD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line.

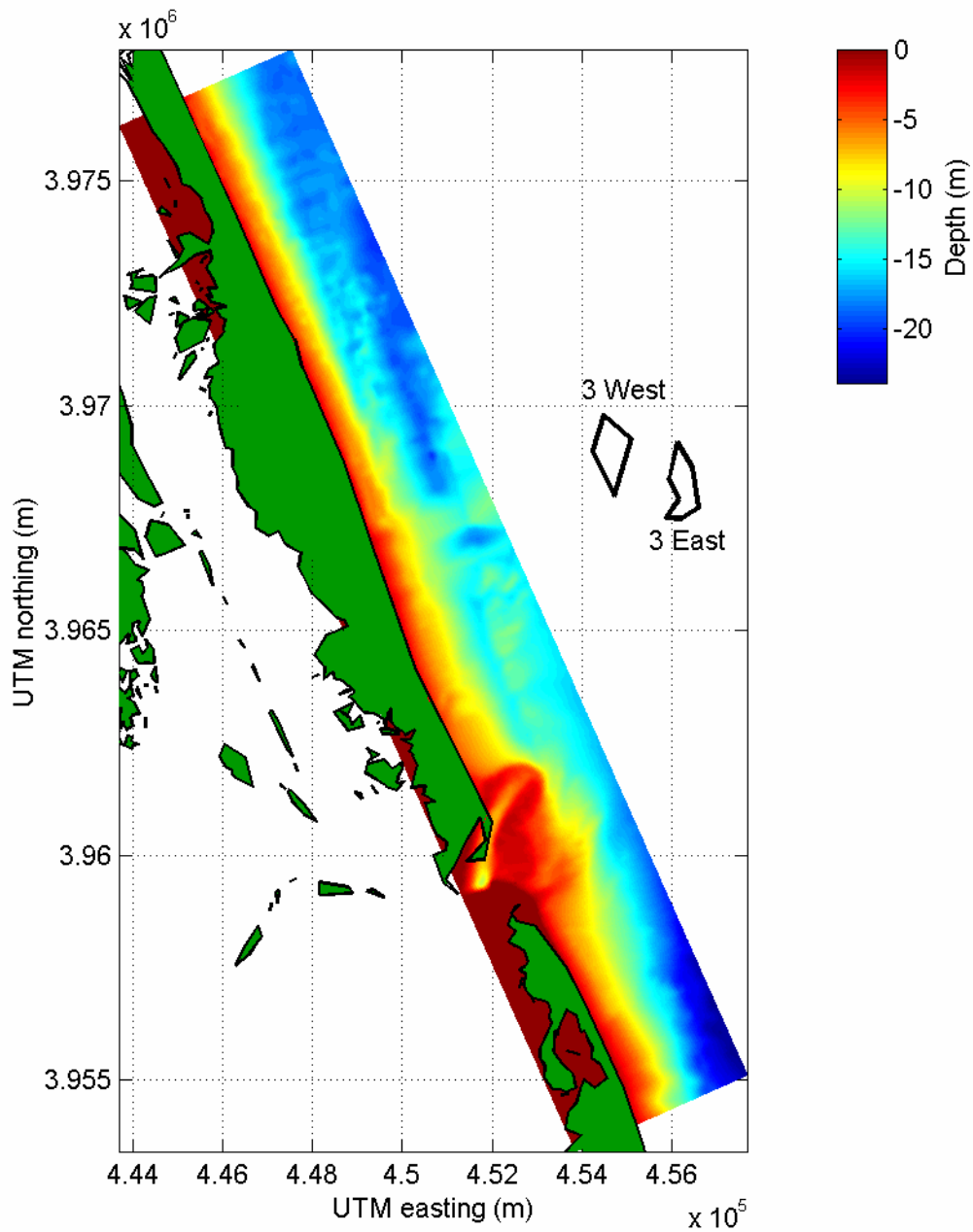


Figure 3-15. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) for offshore North Carolina. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line.

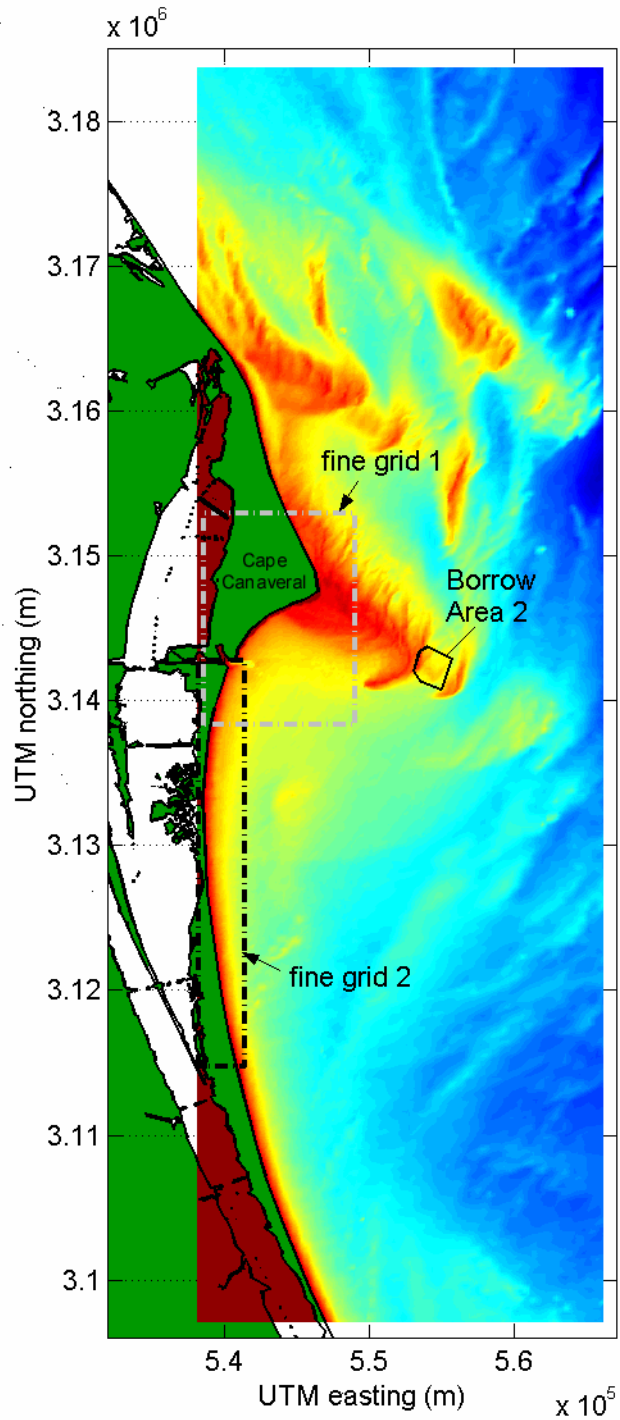


Figure 3-16. Color contour plot of coarse model grid (200 m x 200 m grid spacing) for offshore Cape Canaveral, FL. Depths are relative to NAVD83. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line.

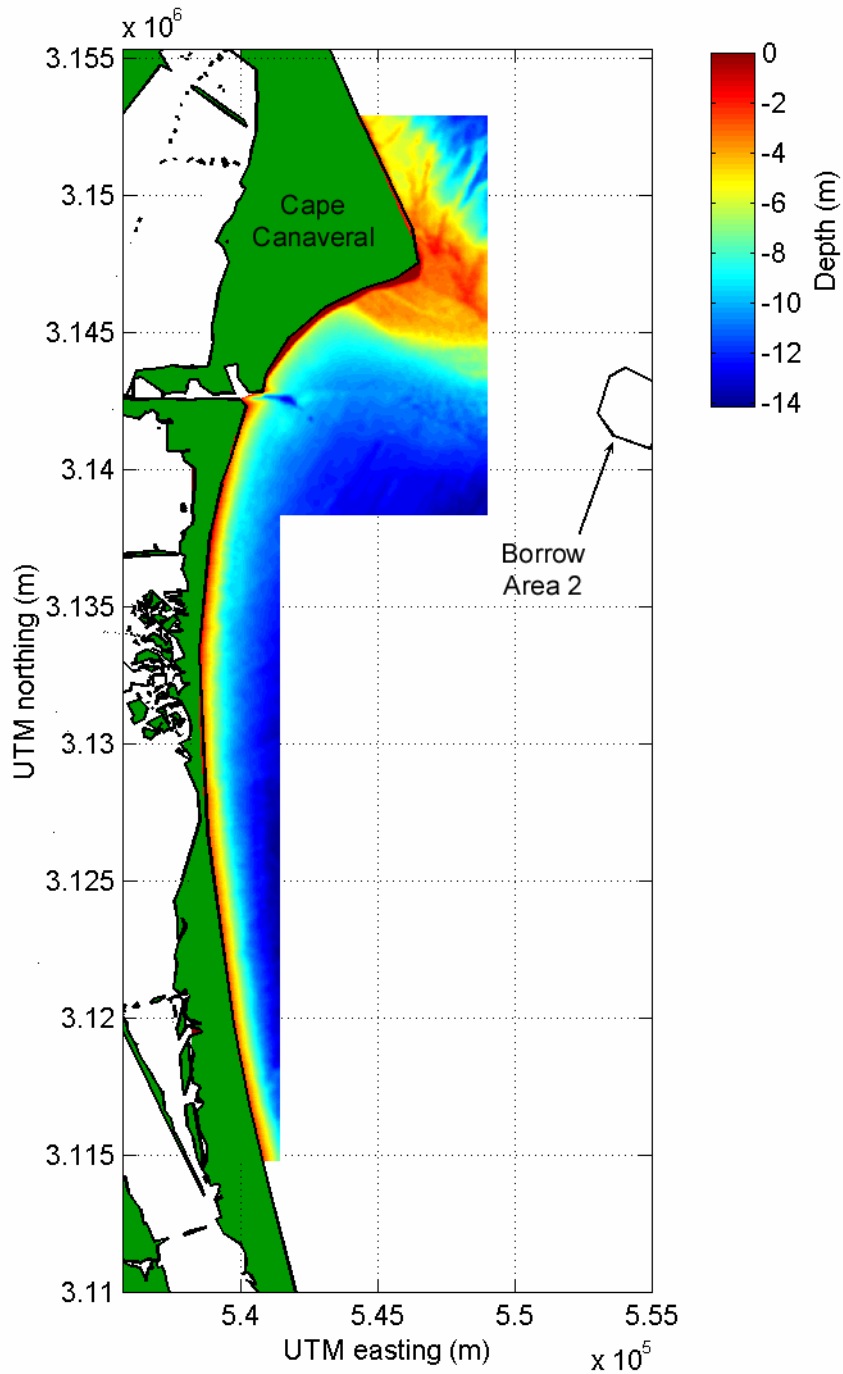


Figure 3-17. Color contour plot of the nested fine model grid (20 m x 20 m grid spacing) for offshore Cape Canaveral, FL. Depths are relative to NVGD. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line.

Table 3-7. Numerical grid dimensions for offshore (coarse) and nearshore (fine) grids. Dimensions are given as (cross-shore x alongshore).

Region	Coarse Grid (200 m spacing)		Fine Grid (20 m spacing)		grid angle (deg CW from north)
	nodes	distance (km)	nodes	distance (km)	
New Jersey	90 x 325	18 x 65	200 x 1800	4 x 36	36
Virginia	85 x 250	17 x 50	150 x 1360	3 x 27	-16
North Carolina	87 x 425	17 x 85	210 x 1250	4 x 25	-24
Florida	141 x 434	28 x 87	520 x 730	10 x 15	0
			160 x 1400	3 x 28	

3.1.4 Sediment Transport Potential

Initially, calculations of sediment transport potential were performed to indicate the maximum quantity of transport possible based on a sediment-rich environment. Results from spectral wave modeling formed the basis for evaluating changes in sediment transport rates along the beach. Longshore transport depends on long-term fluctuations in incident wave energy and the resulting longshore current. Therefore, annual transport rates were calculated from long-term wave statistics.

The longshore sediment transport equation employed in this study is based on the formulation presented by the U.S. Army Corps of Engineers (USACE, 1984). In general, the longshore sediment transport rate is assumed to be proportional to the longshore wave energy flux at the breaker line, which is dependent on wave height and direction. Because the transport equation was developed using data from sediment-rich environments (no hardened structures), it typically over-predicts sediment transport rates along many coasts. However, the formula provides a useful technique for comparing erosion/accretion trends along a shoreline of interest.

The volumetric longshore transport, Q , past a point on a shoreline is computed using the relationship:

$$Q = \frac{I}{(s - 1)\rho g a'} \quad (3.13)$$

where I is the immersed weight longshore sediment transport rate, s is the specific gravity of sediment, a' is the void ratio of the sediment, and ρ is the density of seawater.

The immersed weight longshore sediment transport, I , can be computed using the CERC formula (USACE, 1984),

$$I = KP_{ls} \quad (3.14)$$

where K is a dimensionless coefficient and P_{ls} is the longshore energy flux factor computed using the following relationship:

$$P_{ls} = \frac{\rho g^{3/2}}{16\sqrt{\gamma}} H_{sb}^{5/2} \sin 2\alpha_b \quad (3.15)$$

where H_{sb} is the significant wave height at breaking, γ is the coefficient for the inception of wave breaking ($\gamma=H_b/h_b$), and α_b is the breaking wave angle. Generally, a value of $K=0.4$ is used with significant wave heights (as computed by STWAVE), or the more familiar value $K=0.77$ is used with RMS wave height.

For this study, an alternate method was used to compute immersed weight longshore sediment transport, as described by Kamphuis (1990). This method is a modification to the original CERC formula that adds a dependency on the median grain diameter of beach sediment and incorporates the surf similarity parameter, ξ_b , expressed as

$$\xi_b = \frac{m}{(H_b / L_0)^{0.5}} \quad (3.16)$$

where m is the bottom slope and L_0 is the deep water wavelength. The complete expression of Kamphuis is given by

$$I = K^* \rho g \left(\frac{g}{2\pi} \right)^{0.75} \xi_b T^{0.5} (md_{50})^{-0.25} H_s^{2.5} \sin^{0.6}(2\theta_b) \quad (3.17)$$

where the coefficient $K^* = 0.0013$.

Sediment transport computations were based on wave information at breaking for each grid cell along the modeled coastline. The shoreline segment incorporates the influence of all changes to nearshore wave climate associated with proposed dredging activities. Computations of sediment transport rates for each wave condition were performed and then weighted by the annual percent occurrence. Sediment transport potential was computed for existing and post-dredging conditions.

3.2 MODEL RESULTS

Due to the redistribution of wave energy and alteration of wave directions resulting from offshore sand excavation, changes to longshore sediment transport patterns will occur. Depending on the net direction of local sediment transport, the influence of borrow site conditions can either increase or decrease net littoral drift. Example model cases for each of the four sites are discussed in the following subsections. Complete wave model output for the four modeled regions, showing wave heights and wave height difference plots between existing and post-dredging conditions for all modeled wave cases, are given in Appendices B through E.

3.2.1 Wave Modeling

Overall, post-dredging wave model output for the four study sites illustrates reduced wave heights landward of borrow sites and increased wave heights at the longshore limits of the borrow site. This effect is more pronounced for cases with larger wave heights and longer periods. As waves propagate across a borrow site (deeper water than the surrounding area), wave refraction bends waves away from the center of the borrow site and toward the shallower edges. The net effect is to create a shadow zone of reduced wave energy immediately landward of the borrow site and a zone of increased wave energy updrift and downdrift of the borrow site.

This shadowing effect is apparent in model results presented in Figure 3-18 for offshore southern New Jersey. In this figure, color contours represent coarse grid wave height differences between model results computed for existing and post-dredging conditions. In the immediate vicinity of the borrow site, wave heights increased by a maximum of 0.20 m at the northern and southern edges of the borrow site and decreased by a maximum of 0.19 m behind the borrow site. In Figure 3-19, fine grid model results for the same wave condition (case 7) show how waves propagate toward shore landward of proposed borrow sites. The wave shadow generated by Site M8 is most prominent. For this wave case, the maximum wave height difference between existing and post-dredging conditions is 0.27 m at the borrow site, but closer to shore within the fine grid, the maximum wave height difference is reduced to 0.06 m.

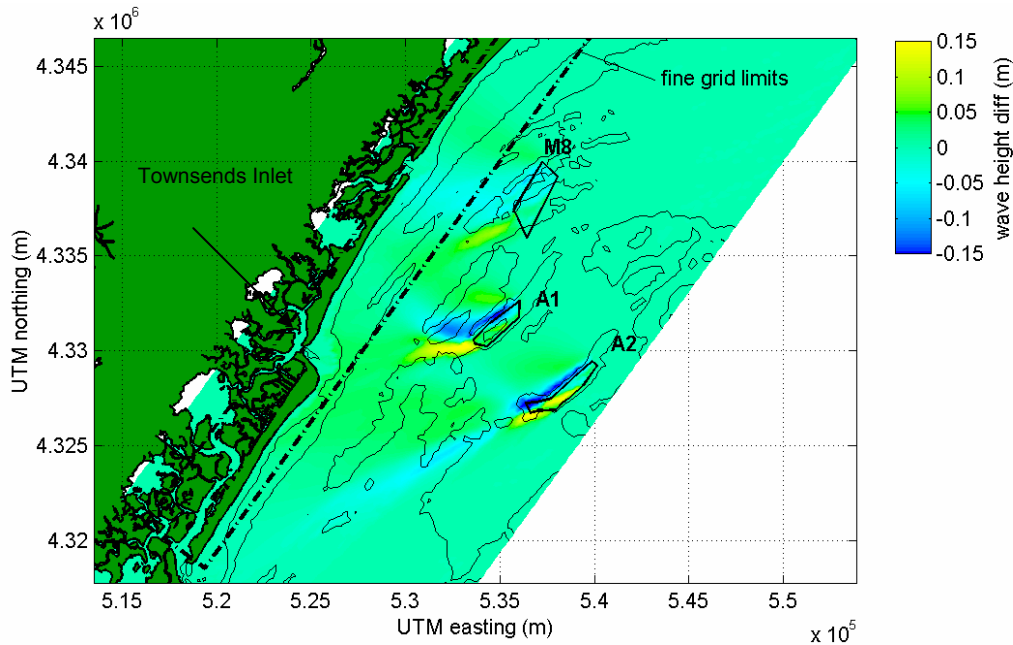


Figure 3-18. Example of coarse grid wave height difference plot between existing and post-dredging bathymetry conditions offshore Townsends Inlet, NJ. This result is for NJ wave case 7; 1.6 m wave height and 11.1 sec period.

Because these are spectral wave model results, and because different frequencies in the spectrum are refracted by varying degrees at the borrow area, the areas of increased and reduced wave height gradually diffuse as the wave field approaches shore. As a result, the extent of this energy diffusion can be considerably longer than the borrow area. For this particular example, the length of shoreline affected by Site M8 is approximately three times greater than the alongshore dimension of the borrow site.

Although borrow sites that are further offshore impact a longer length of shoreline, the actual magnitude of impact is lower because the affected wave field has had a greater distance over which to diffuse energy. This is illustrated in a comparison of wave transformation impacts for borrow sites M8 and A1 in Figure 3-18. Borrow Site A1 causes a greater local difference in wave heights primarily because it has a greater excavated depth. However, because the borrow site is further offshore, wave height change from existing to post-dredging conditions at the shoreline is less than the changes that are caused by borrow Site M8, as seen in Figure 3-19.

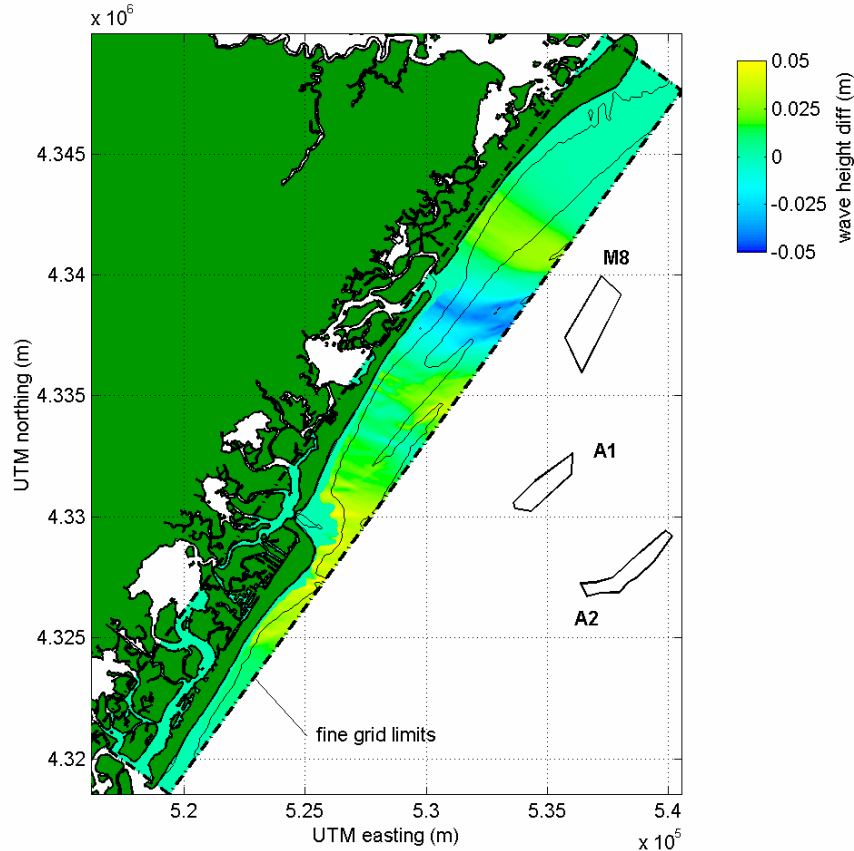


Figure 3-19. Example of fine grid wave height difference plot between existing and post-dredging bathymetry conditions offshore Townsends Inlet, NJ. This result is for NJ wave case 7; 1.6 m wave height and 11.1 sec period.

In addition to wave impacts resulting from borrow site excavation, wave heights and directions are modified by natural offshore bottom features as well. From the existing conditions model results for offshore North Carolina, it is seen how bottom features offshore the Outer Banks modify the wave field as it propagates shoreward. Model output presented in Figure 3-20 shows how waves respond to offshore shoals, even in relatively deep water (>15 m). For example, an area of reduced wave heights starting in the vicinity of 450,000 E, 3,985,000 N is caused by shallower areas immediately north and south. The shoal areas refract the wave field, causing a slight focusing of wave energy behind each feature. Because energy is conserved, the focusing of wave energy behind the shoal causes a reduction in energy at the northern and southern edges of the shoal, which is apparent by reduced wave heights in these areas. Another example of energy focusing caused by offshore features is shown in Figure 3-21, for Sandbridge Shoal offshore Virginia Beach. The focusing effect of shoals is clear in this southeast wave condition. As wave energy is focused on the shoreline in the vicinity of Rudee Inlet in this example, there is a concurrent decrease in wave energy to the southwest of the shoals.

In addition to the effects of bottom features far offshore, waves are refracted by the straight and parallel bottom contours in the nearshore. In Figure 3-22, fine grid results show how wave directions change as the wave field propagates shoreward. For this SE wave condition (as in Figure 3-21) waves refract and the mean direction of wave

propagation becomes more shore-normal (perpendicular to the shoreline). In addition to the change in wave direction, wave heights are also modified by nearshore bathymetry. Waves begin to shoal (increase in height) about 440 m offshore, and increase in height by 0.1 m before breaking begins. Wave heights are reduced as energy is dissipated in the surf zone, which is about 120 m wide in this example.

The following discussion summarizes wave modeling results for the most common wave approach conditions at each potential sand resource area. Existing and post-dredging model results are described with reference to natural offshore bottom features and bathymetry changes resulting from proposed sand dredging.

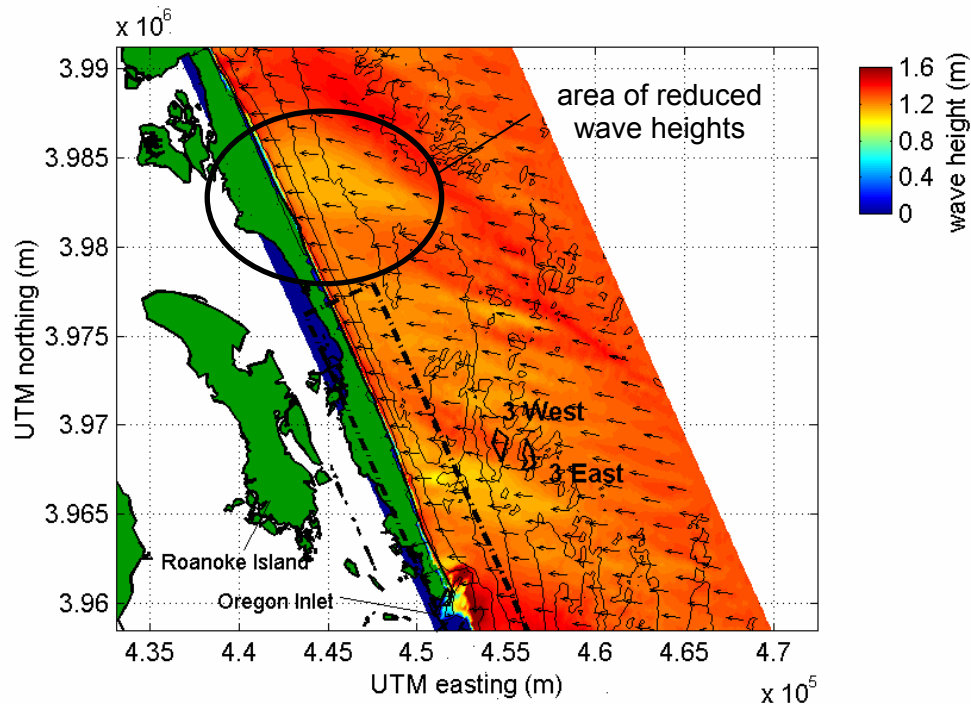


Figure 3-20. Coarse grid model results for offshore North Carolina (wave case 9; 1.3 m wave height, 11.3 sec period) illustrating area of reduced wave heights resulting from refraction of wave energy due to bottom bathymetry.

3.2.1.1 Offshore New Jersey

Examples of wave model output for existing conditions offshore southern New Jersey are shown in Figures 3-23 and 3-24 (wave cases 4 and 7 of Table 3-1). Case 4 has 1.2 m waves with a 7.1 sec peak period propagating from the southeast. The coarse grid results presented in Figure 3-23 illustrate that the direction of wave propagation is directly onshore; therefore, the effects of wave refraction are not discernable until waves are well within a kilometer of the shoreline. Waves increase in height and break on the shoals present in the vicinity of each of the modeled inlets. The highest refracted wave height for this case is about 1.5 m, which occurs in the shoals near Great Egg Harbor Inlet. Immediately offshore the coastline between Townsends and Great Egg Harbor Inlet, wave height reductions are observed that result from wave energy spreading by refraction along the gently crescent-shaped bottom contours of this area.

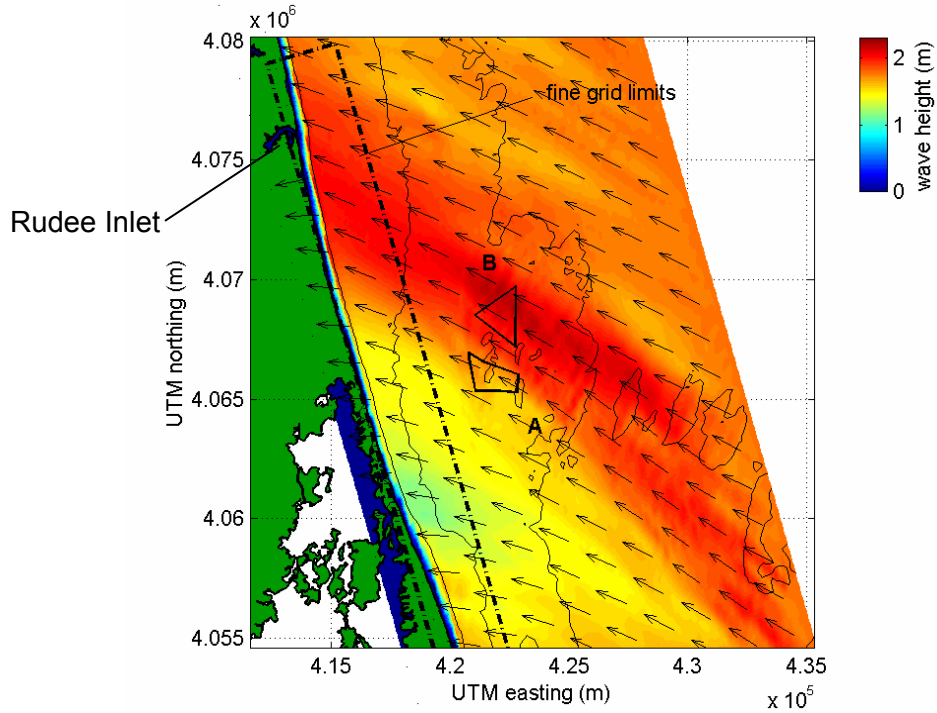


Figure 3-21. Coarse grid model results for Sandbridge Shoal, Virginia for wave case 10 (1.8 m wave height, 10.0 sec wave period) showing wave focusing effect of natural shoal deposits and area of reduced wave heights to the southwest of the shoals.

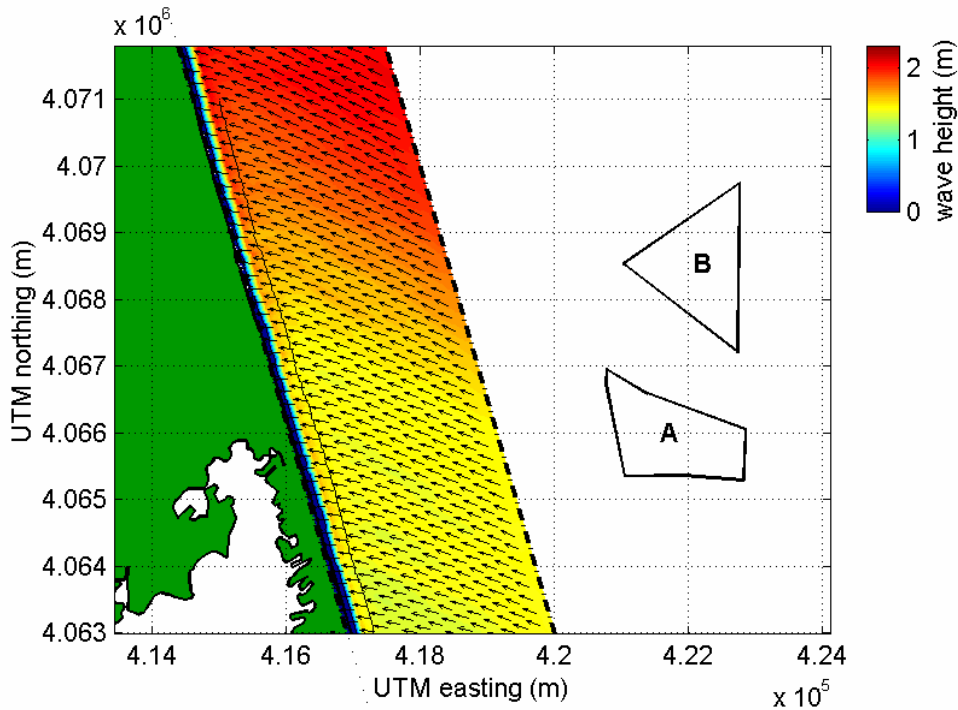


Figure 3-22. Fine grid model results for Sandbridge Shoal, Virginia for the same wave case presented in Figure 3-21. Detailed analysis illustrates nearshore refraction of waves and wave height reductions through the width of the surf zone.

In Figure 3-24, the results of wave Case 7 illustrate how 1.6 m, 11.1 sec waves propagating from the east are transformed as they approach the coast. The effects of wave refraction are more pronounced in this example as wave rays are seen to gradually arc toward shore-normal about 4 km offshore. Offshore wave height differences are more dramatic than the previous example due to the combination of the higher wave height, longer wavelength, and a more oblique offshore approach angle. In several offshore regions, wave heights have been reduced by approximately 0.25 m due to spreading of wave energy by refraction. In contrast to Case 4, where highest wave heights in the model grid occur are associated with inlet ebb shoals, the highest wave heights for Case 7 occur on the offshore shoal in the vicinity of borrow site A2. At this shoal, wave heights reach 2.1 m, a half-meter increase over the offshore boundary condition.

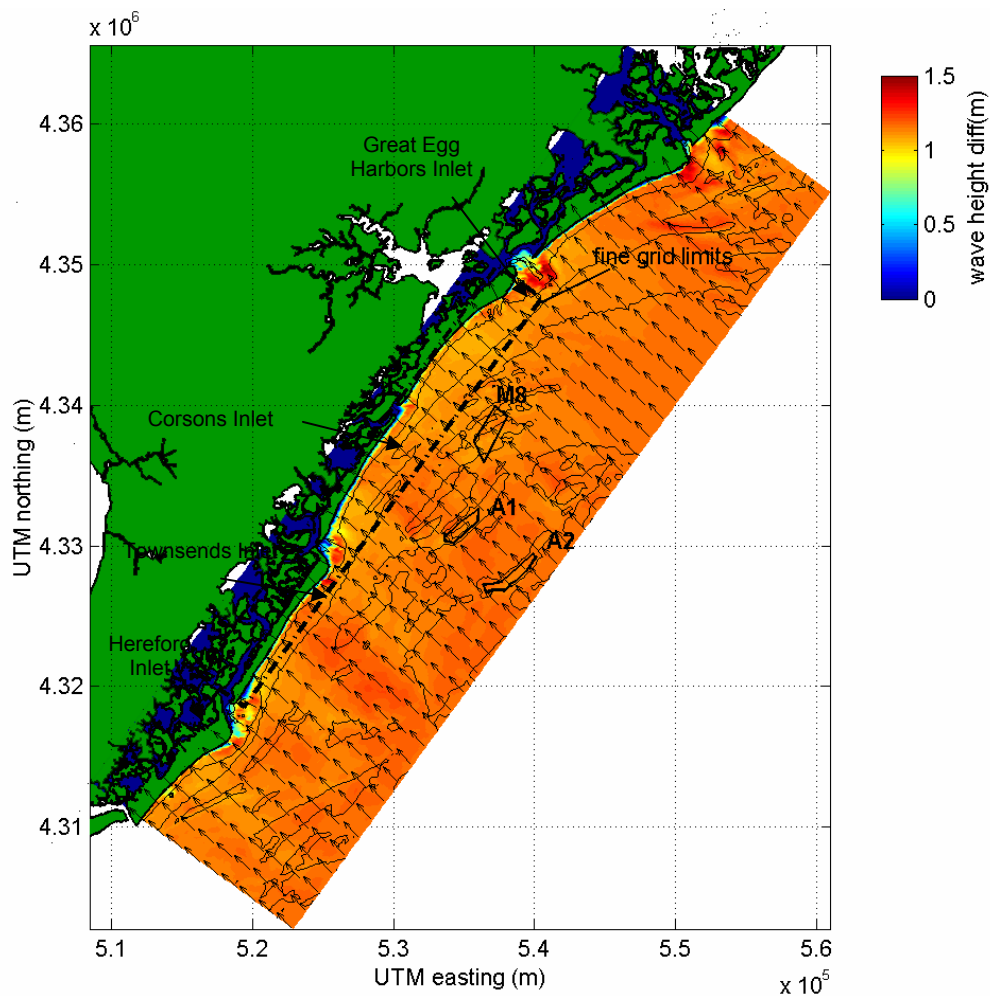


Figure 3-23. Plot of STWAVE model output for southern New Jersey wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.1$ sec, $\theta_{peak}=131$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

Plots of wave height difference between existing and post-dredging conditions for Cases 4 and 7 are presented in Figures 3-25 and 3-26. For Case 4, the maximum change in wave heights is ± 0.05 m. Borrow Site A1 has a greater influence on wave

heights than other sites, where wave heights increase at the northeast and southwest edges due to wave refraction, and a corresponding decrease in wave heights is present between these margins. For wave Case 4, the length of shoreline impacted by the combination of the three borrow sites is approximately 20 km between Townsends and Great Egg Harbor Inlets.

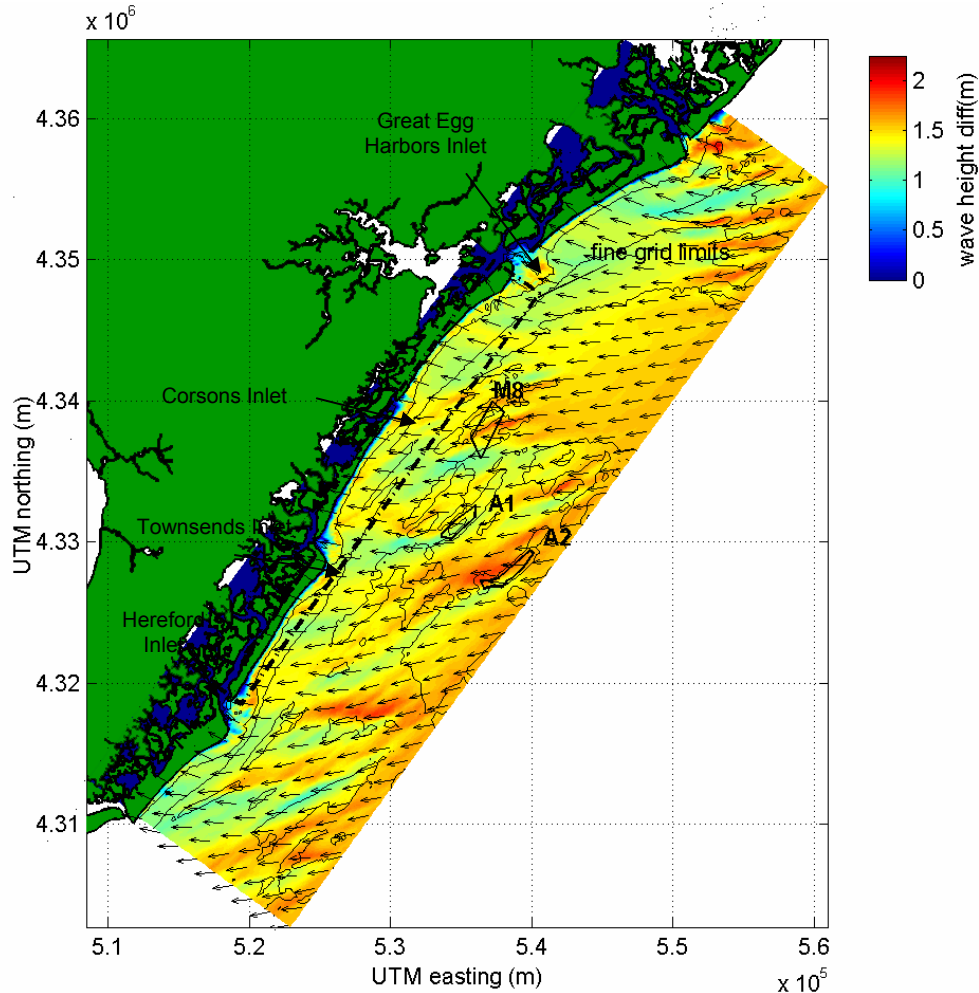


Figure 3-24. Plot of STWAVE model output for southern New Jersey wave Case 7 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=81$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

The wave difference plot for Case 7 in Figure 3-26 again shows that site A1 has the greatest influence on wave heights. Maximum wave height changes are ± 0.25 m, near Site A1. The greatest increase in wave heights occurs long the southwestern margin of Site A1. For Site A2, the resulting wave shadow from the borrow site is much more focused than what is indicated for Case 4. This results from the geometry of the site, which is long and narrow, because waves are propagating along the major axis of the site in this case. Because offshore waves propagate from a more oblique angle relative to the shoreline than in Case 4, the area of shoreline influence for the three sites is considerably longer. For this case, approximately 30 km of shoreline between Hereford and Great Egg Harbor Inlets is in the zone of influence of the three sites.

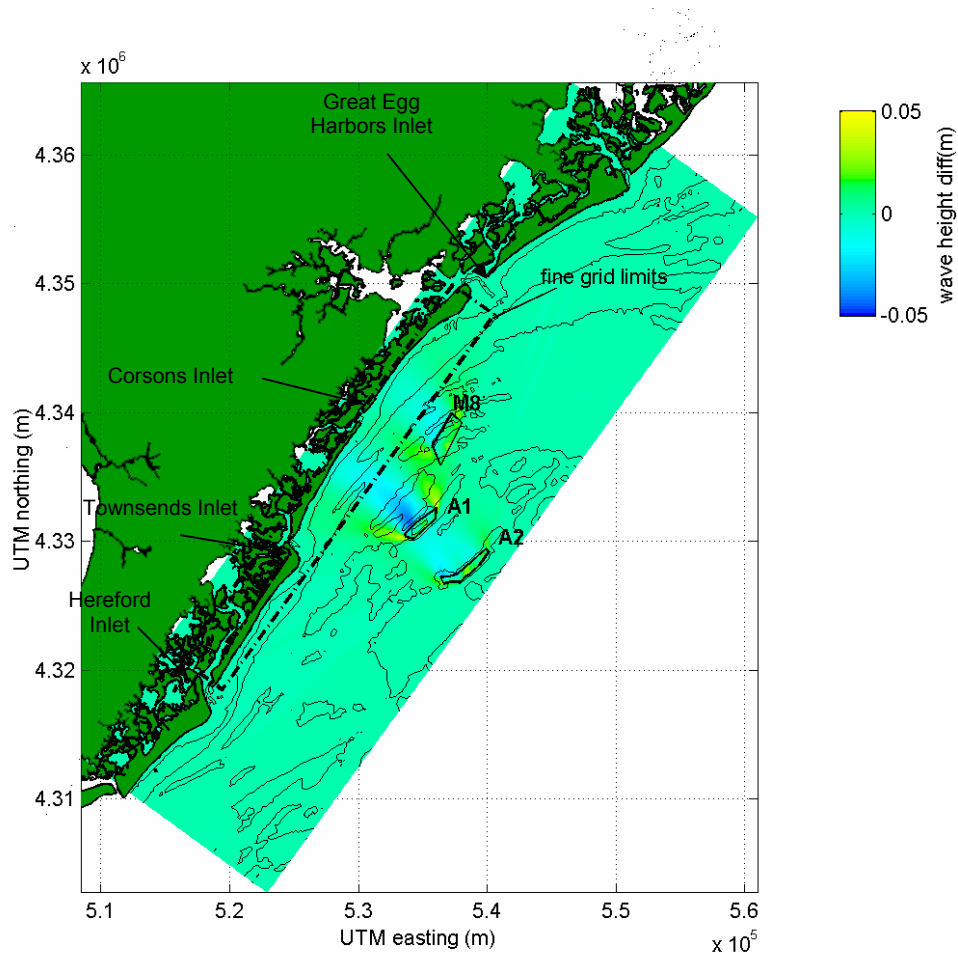


Figure 3-25. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites for STWAVE model output of southern New Jersey wave Case 4 ($H_s=1.2$ m, $T_{peak}=7.1$ sec, $\theta_{peak}=131$ deg).

3.2.1.2 Offshore Southeastern Virginia

Wave model output for wave Cases 7 and 10 (see Table 3-5) for southern Virginia are presented in Figures 3-27 and 3-28. The results of Case 7 are for a 2.8 m wave with a peak period of 11.1 sec, propagating from the northeast. Because these waves basically are moving directly onshore and nearshore bathymetric contours are generally parallel to the shoreline, wave directions do not change significantly until they are very close to shore. The maximum refracted wave height in the model grid is 3.3 m, which is 0.5 m greater than the boundary condition. These maximum wave heights occur just outside the seaward extent of the surf zone, prior to the inception of wave breaking. Aside from wave height reductions seen near the top lateral boundary of the model grid (at the entrance to Chesapeake Bay), significant differences in offshore wave heights are not present due to the limited effect of refraction in this onshore wave condition.

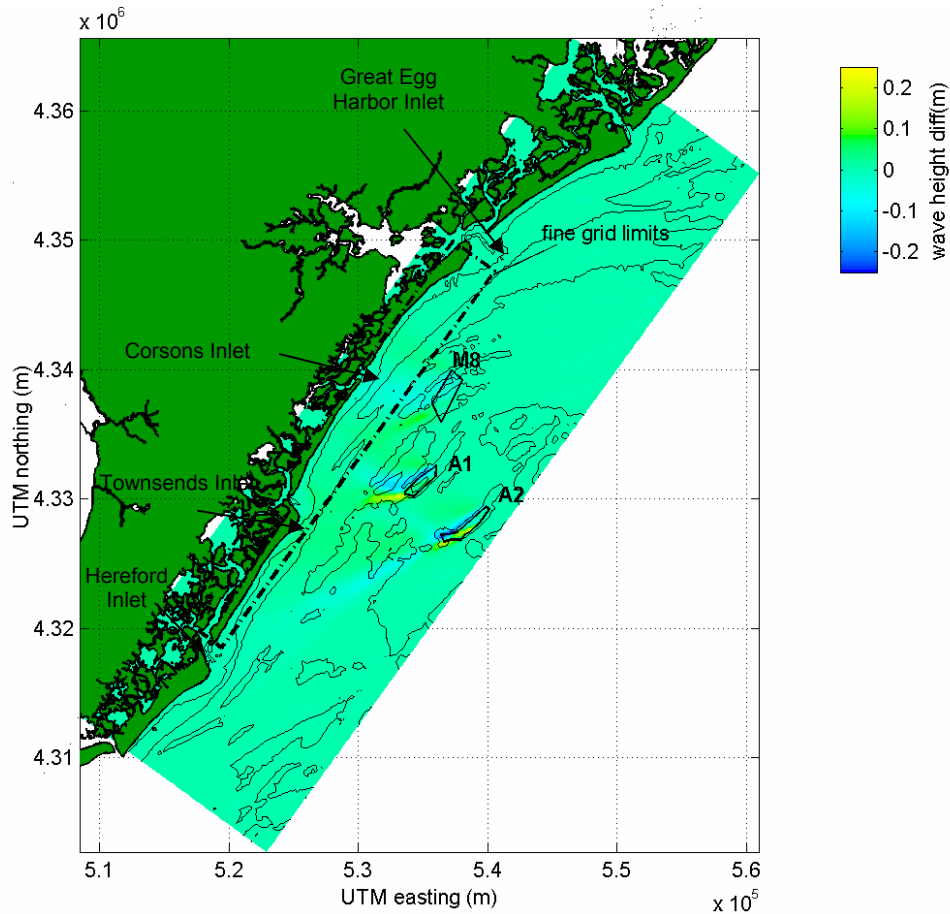


Figure 3-26. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at indicated borrow sites for STWAVE model output of southern New Jersey wave Case 7 ($H_s=1.6$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=81$ deg).

A second example of model output for southeastern Virginia is shown in Figure 3-28, for Case 10 (see Table 3-5). The offshore wave condition used for this model run was a 1.8 m high, 10 sec peak period wave that propagates from the southeast. The plot of this wave condition shows significant modifications to the offshore wave field that result from complex bathymetric features present at Sandbridge Shoal. Wave energy in this case is focused by the shoals, which results in an area of increased wave heights in the vicinity of Rudee Inlet. Maximum increased wave heights in this zone are 0.5 m above the offshore condition, or 2.3 m. This zone of increased wave heights extends approximately 10 km on either side of Rudee Inlet. As a result of the wave focusing by the shoals, there is a corresponding decrease in wave heights south of the shoals, shoreward to Sandbridge. An area of maximum decrease in wave height is indicated just seaward of Sandbridge, where wave heights are approximately 0.8 m less than at the offshore boundary. The full extent of the area of reduced wave heights is approximately 15 km.

Additional plots showing wave height changes that result from dredging the full design volumes at sites A and B for Cases 7 and 10 are shown in Figures 3-29 and 3-30. For waves modeled in Case 7, a case where waves are propagating almost directly onshore, maximum wave height changes are ± 0.35 m. The largest decreases in wave heights after dredging are illustrated near Site B, at the western vertex of the triangle

that defines this site. The region of maximum wave height increase is found in the area between the two sites, resulting from the combined influence of Sites A and B. Wave energy is refracted by Site B to the south, where it combines with wave energy that has been refracted to the northwest by Site A, resulting in the observed increased wave heights. The shoreline potentially impacted by the presence of the two sites for wave model case 7 extends approximately 10 km alongshore in the vicinity of Sandbridge.

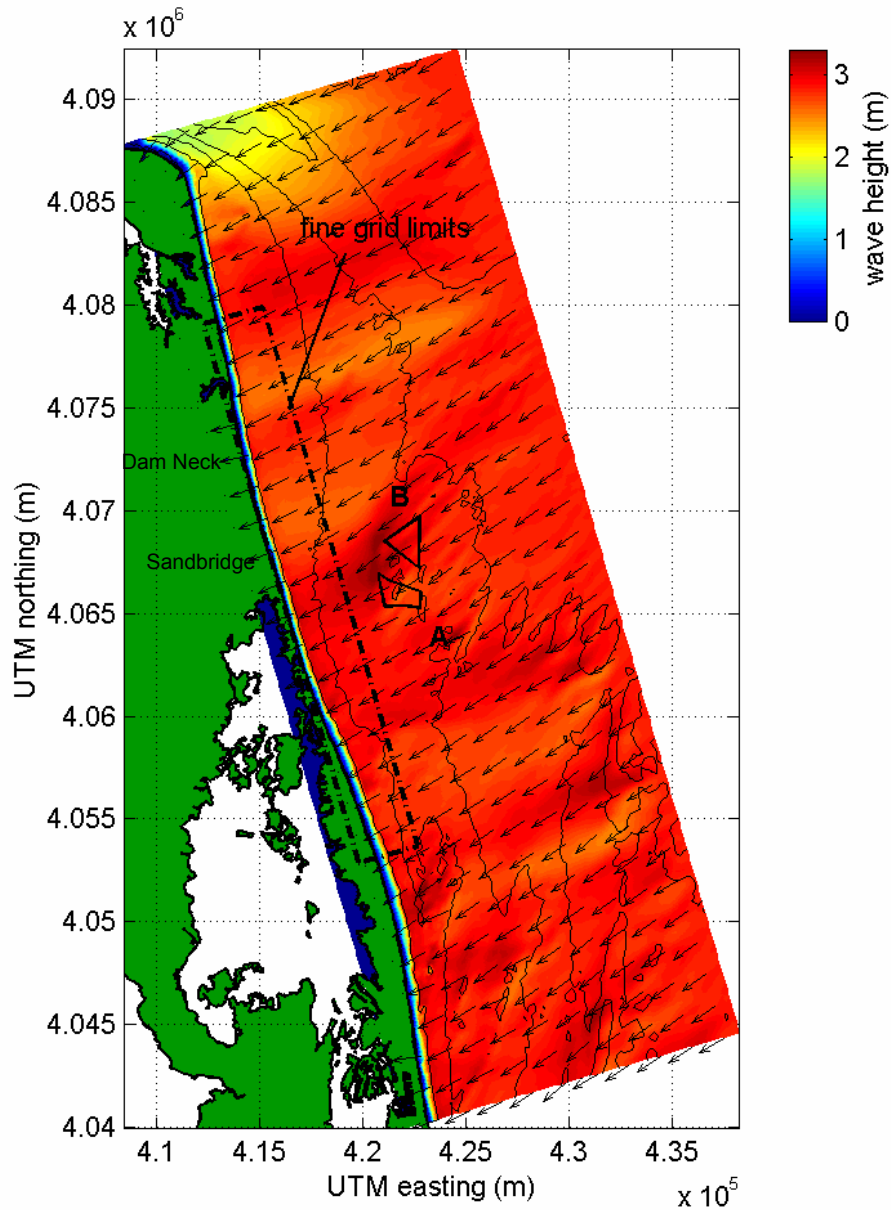


Figure 3-27. Plot of STWAVE model output for southeastern Virginia wave Case 7 ($H_s=2.8$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=39$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

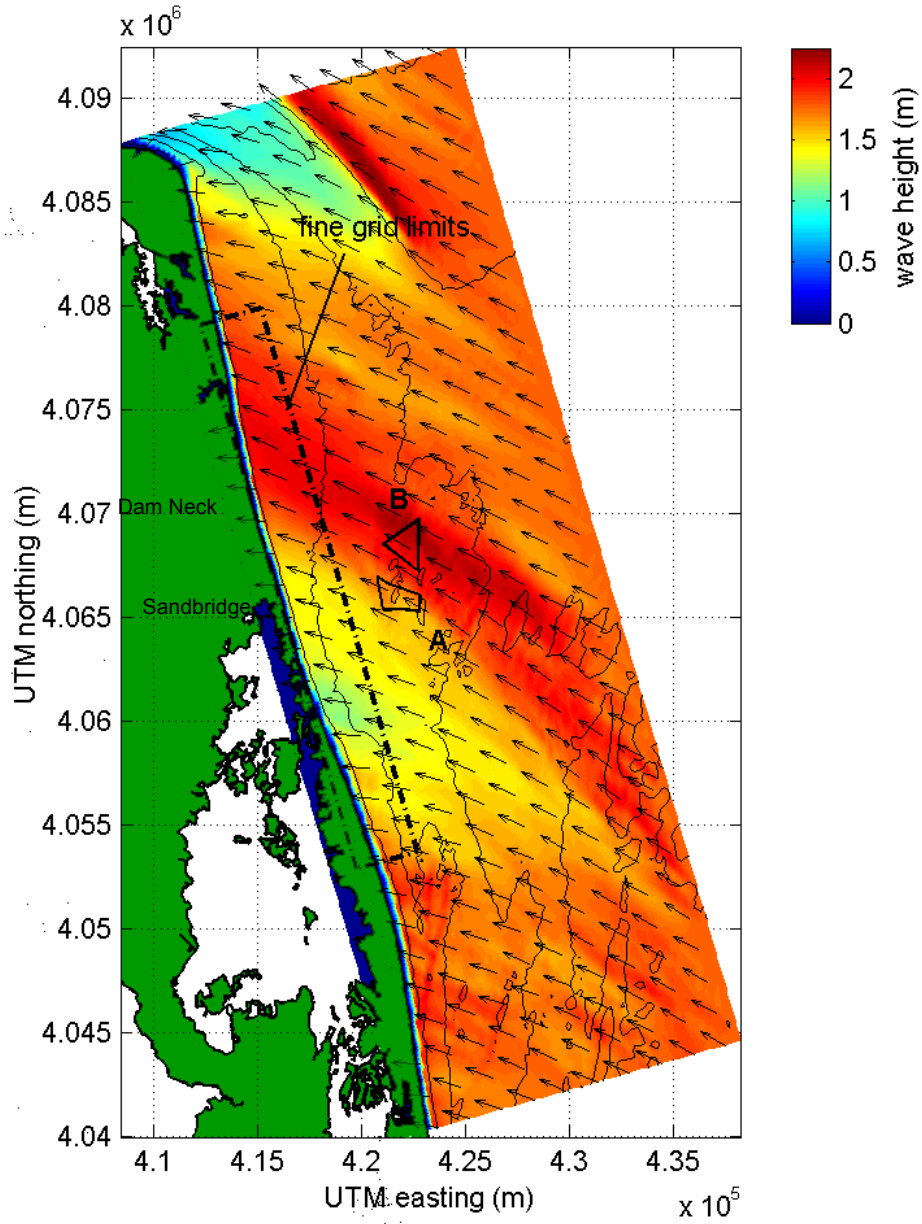


Figure 3-28. Plot of STWAVE model output for southeastern Virginia wave Case 10 ($H_s=1.8$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=134$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

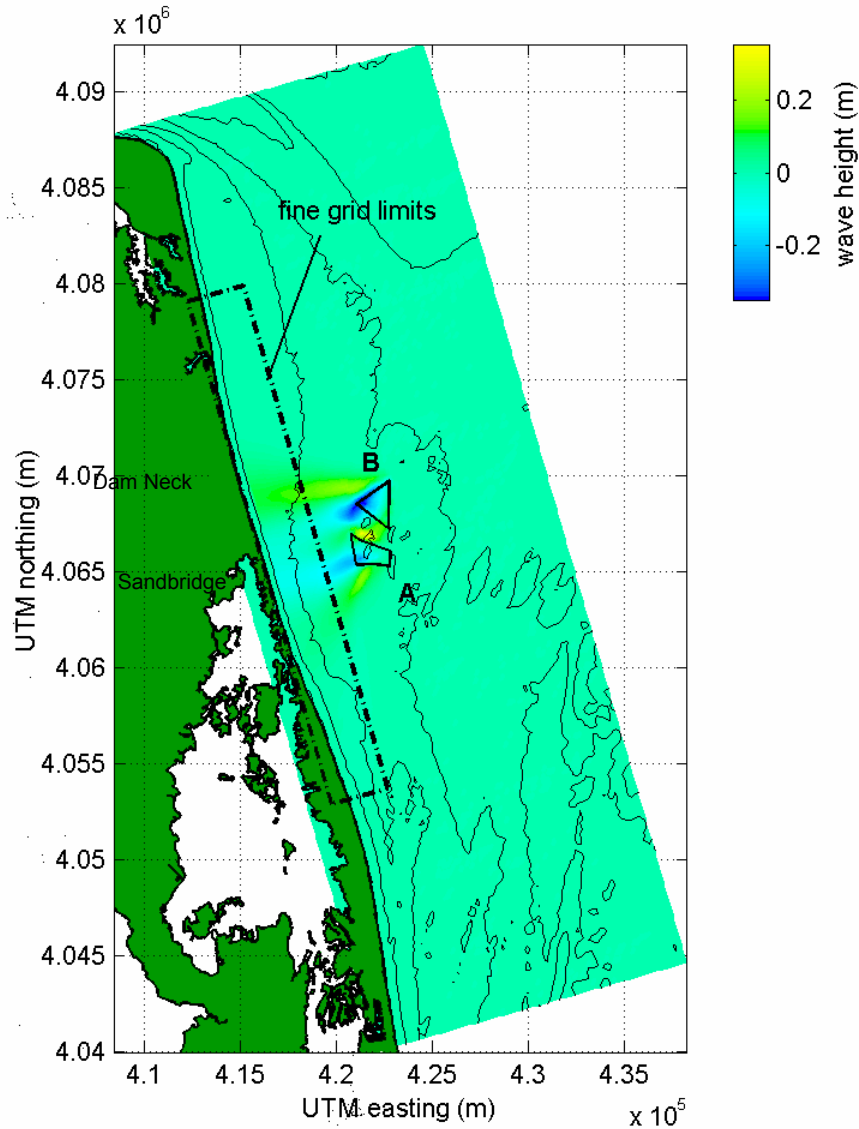


Figure 3-29. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites A and B for STWAVE model output for southeastern Virginia wave Case 7 ($H_s=2.8$ m, $T_{peak}=11.1$ sec, $\theta_{peak}=39$ deg).

A plot of wave height changes for Case 10 between existing and post-dredging model conditions is shown in Figure 3-30. Modeled wave height changes range between 0.2 and -0.35 m. The zone of influence along the shoreline for the two sites extends approximately 12 km, from just north of Rudee inlet to Sandbridge. Maximum wave height reductions occur near Site A for this case, and the greatest increased wave heights occur in the area between the two sites. The shadow zones (areas of reduced wave height) from each borrow site merge to form a single shadow zone at about 3 km offshore.

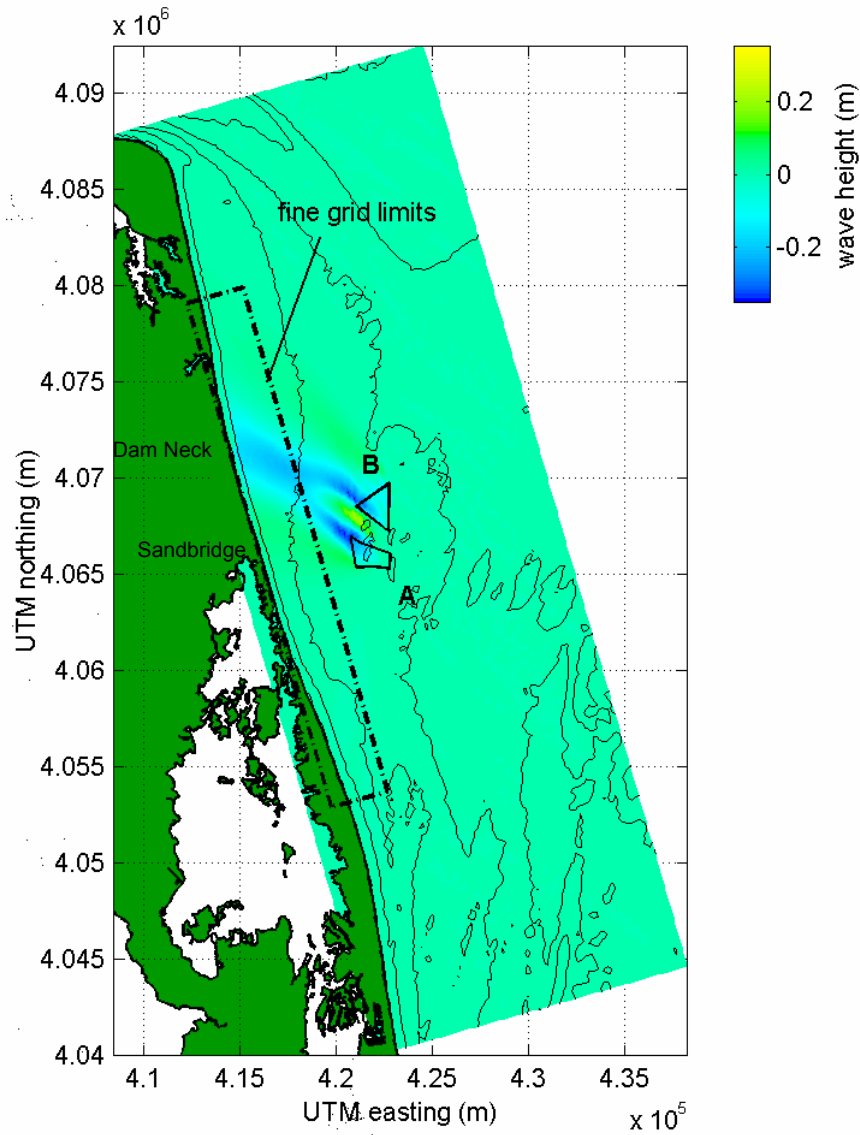


Figure 3-30. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites A and B for STWAVE model output for southeastern Virginia wave Case 10 ($H_s=1.8$ m, $T_{peak}=10.0$ sec, $\theta_{peak}=134$ deg).

3.2.1.3 Offshore North Carolina

Examples of wave model output for offshore North Carolina are illustrated in Figures 3-31 (Case 2) and 3-32 (Case 8). For Case 2, shoals offshore Oregon Inlet produce a small increase in wave heights landward of the shoals, with a corresponding small decrease in wave heights seaward of the shoals. Otherwise, no significant shoaling or refraction is observed in this relatively short period wave case.

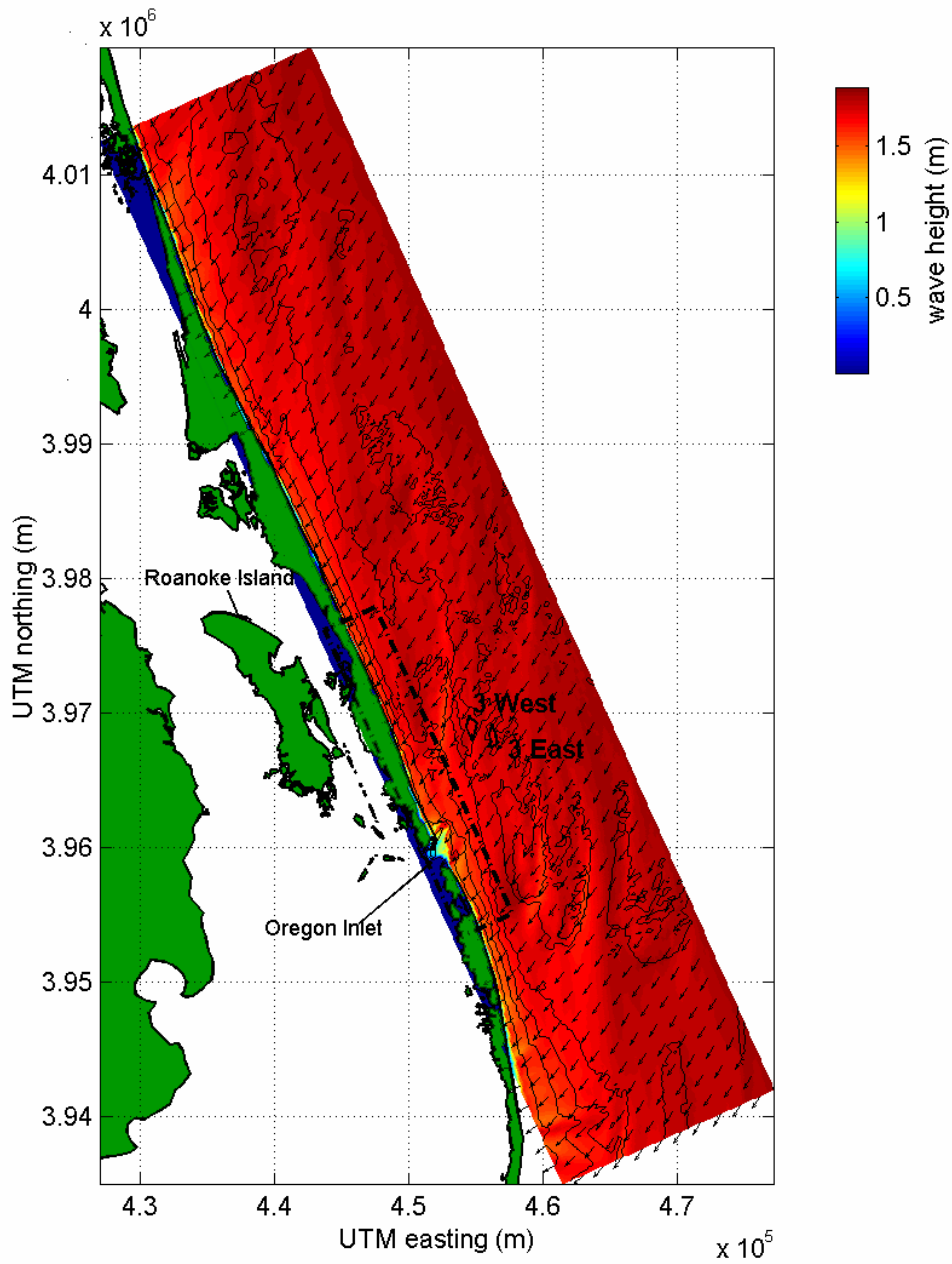


Figure 3-31. Plot of STWAVE model output for offshore North Carolina wave Case 2 ($H_s=1.9$ m, $T_{peak}=6.0$ sec, $\theta_{peak}=21$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

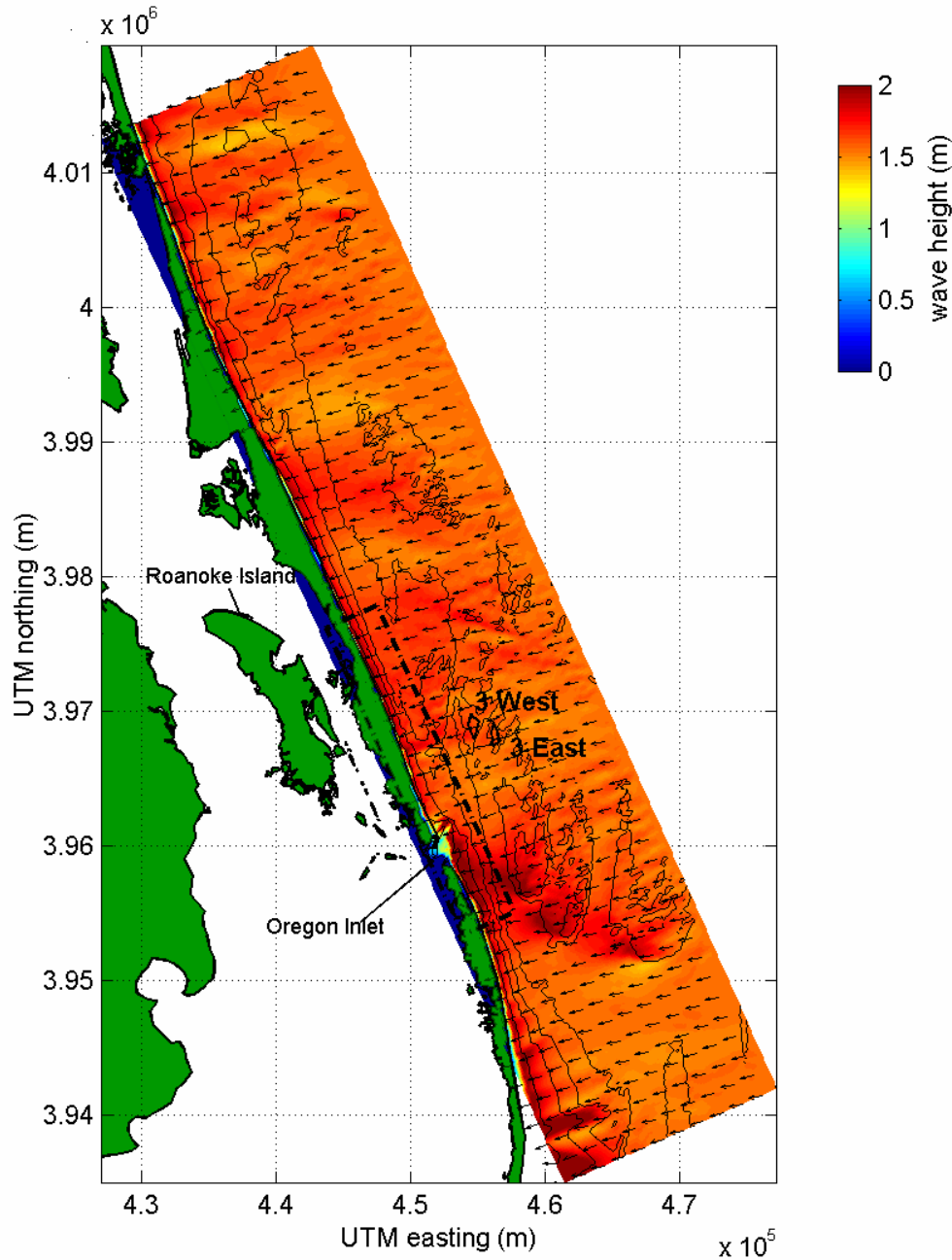


Figure 3-32. Plot of STWAVE model output for offshore North Carolina wave Case 8 ($H_s=1.5$ m, $T_{peak}=12.8$ sec, $\theta_{peak}=71$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

Model output for wave Case 8 (see Table 3-5) is shown in Figure 3-32. This wave condition has a significantly longer period than the previous example, and as a result, waves are much more affected by offshore bathymetry gradients. Although the direction of wave propagation is not modified as much as was indicated in previous examples,

wave heights have changed significantly (e.g., a maximum height of 2.4 m at the southern side of Oregon Inlet) relative to offshore conditions. At the offshore shoals directly east of the inlet, wave heights increase approximately 0.7 m over the offshore boundary condition. Several shoal areas along the modeled coastline show similar impacts on wave heights, including the area encompassing the two modeled borrow sites.

Plots of wave height change from existing and post-dredging conditions at the two borrow sites are shown in Figures 3-33 and 3-34 for wave Cases 2 and 8. For Case 2 results (Figure 3-33), the area of influence for sites 3 East and 3 West extends approximately 20 km around Oregon Inlet. The extent of influence is the result of the approach angle for offshore waves. The greatest increase in wave heights resulting from the potential dredging was south of the western borrow site, where wave heights increased 0.04 m over existing conditions. The area of greatest wave height reduction also is located near the western borrow site, where wave heights decreased 0.07 m from existing conditions.

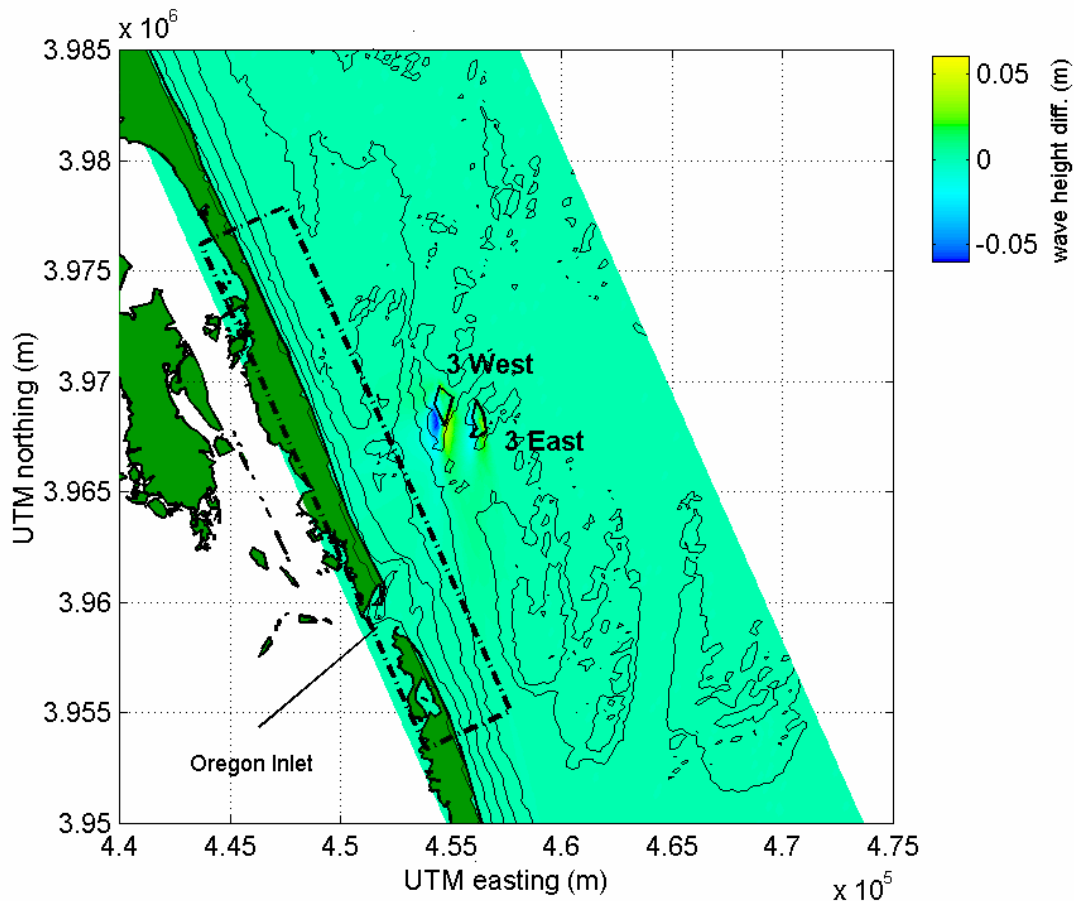


Figure 3-33. Plot of wave height change between existing and post-dredging ($\Delta H = H_{post} - H_{pre}$) conditions at borrow sites 3 East and 3 West for STWAVE model output for offshore North Carolina wave Case 2 ($H_s = 1.9$ m, $T_{peak} = 6.0$ sec, $\theta_{peak} = 21$ deg).

Figure 3-34 presents the wave height difference plot for Case 8 (see Table 3-5). The two borrow sites have an overlapping region of influence, as site 3 West is located directly landward of the site 3 East along the direction of wave propagation. The area of maximum increased wave heights for post-dredging conditions is located at the northern corner site 3 West, where wave heights increase 0.06 m over existing conditions. Similar to the southeastern Virginia examples, wave height increase is the result of the combined influence of the two sites. The area of maximum wave height decrease is located landward of site 3 West, where wave heights are reduced by 0.07 m from existing conditions. Again, this maximum wave height reduction results from the combined impacts of the two sites. In a later section of this report (Section 4), it is determined that the cumulative impact of changes at each site are simply additive.

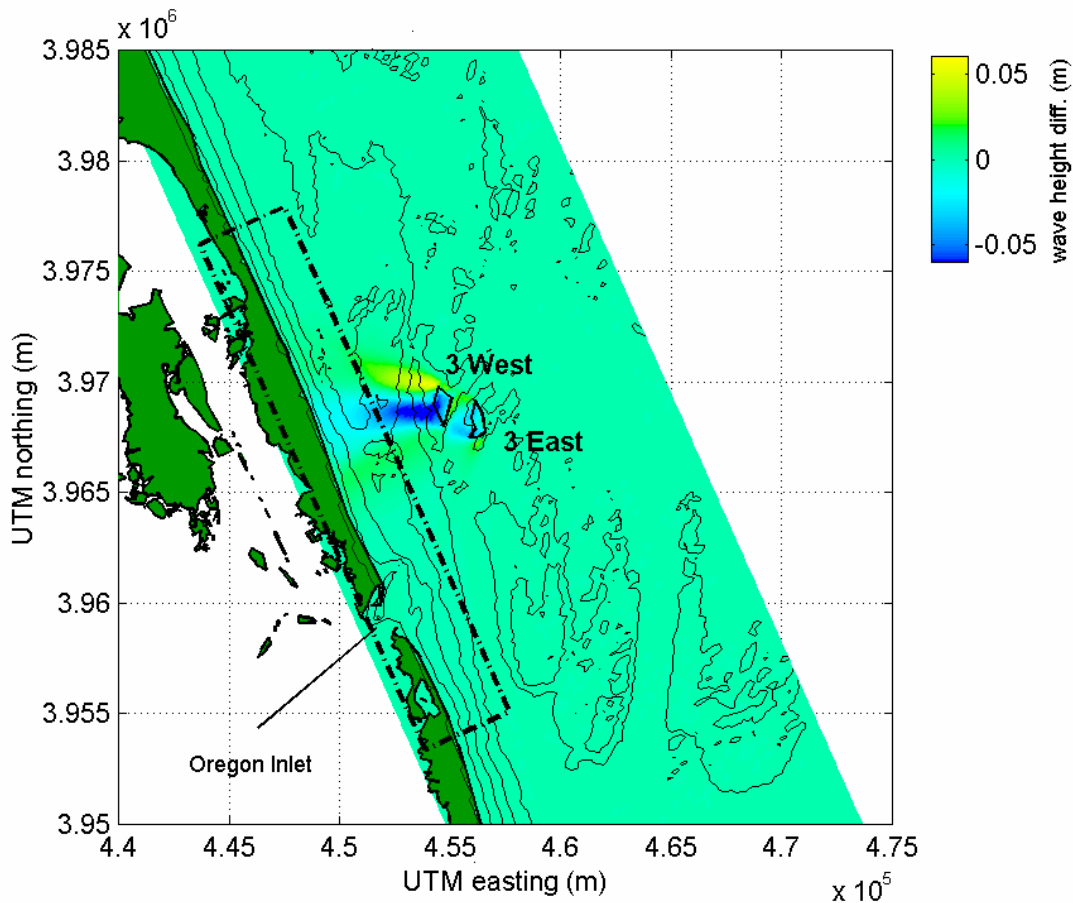


Figure 3-34. Plot of wave height change between existing and post-dredging ($\Delta=H_{post}-H_{pre}$) conditions at borrow sites 3 East and 3 West for STWAVE model output for offshore North Carolina wave Case 8 ($H_s=1.5$ m, $T_{peak}=12.8$ sec, $\theta_{peak}=71$ deg).

3.2.1.4 Offshore Cape Canaveral

The results of two example wave cases are presented for offshore Florida in Figures 3-35 and 3-36. Output for existing conditions offshore Cape Canaveral for wave Case 3 (Table 3-4) is presented in Figure 3-35. Canaveral Shoals, the complex of

ridges and troughs that extend southeast from Cape Canaveral, cause significant increases in wave heights as waves propagate over this area. As waves refract over the shoals, wave heights increase by 0.5 m over the offshore boundary condition. In the

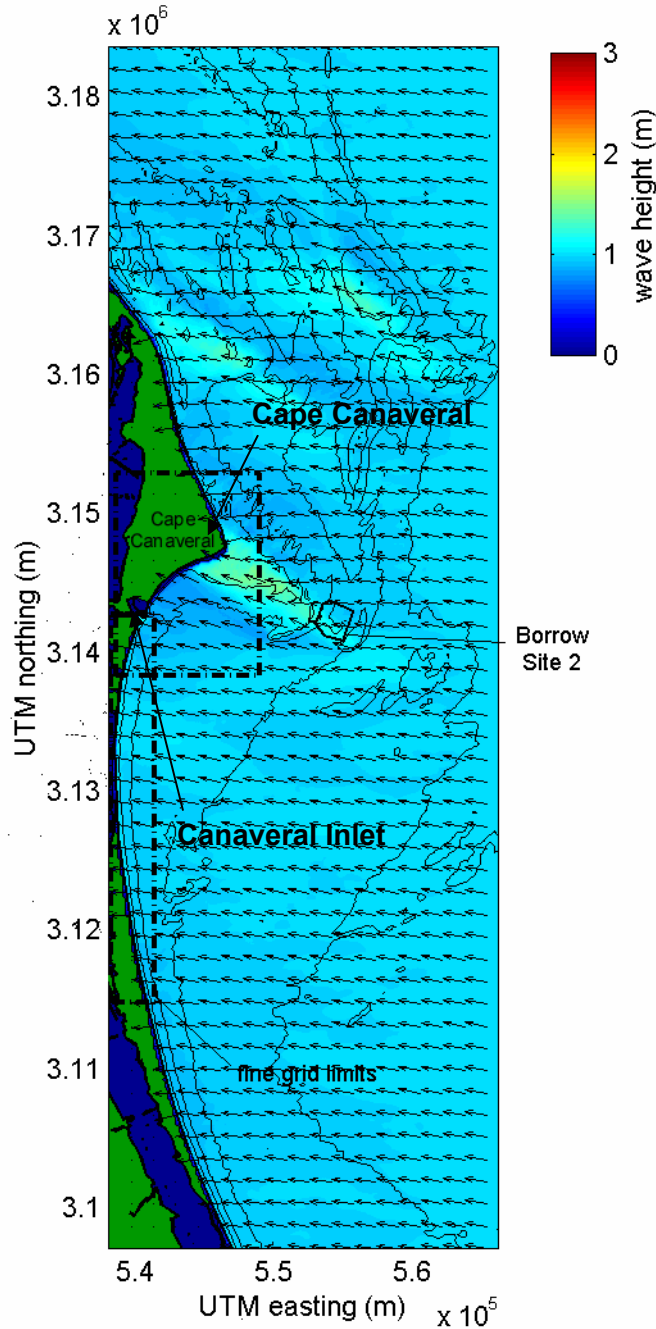


Figure 3-35. Plot of STWAVE model output for Cape Canaveral, Florida wave Case 3 ($H_s=1.0$ m, $T_{peak}=7.7$ sec, $\theta_{peak}=100$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

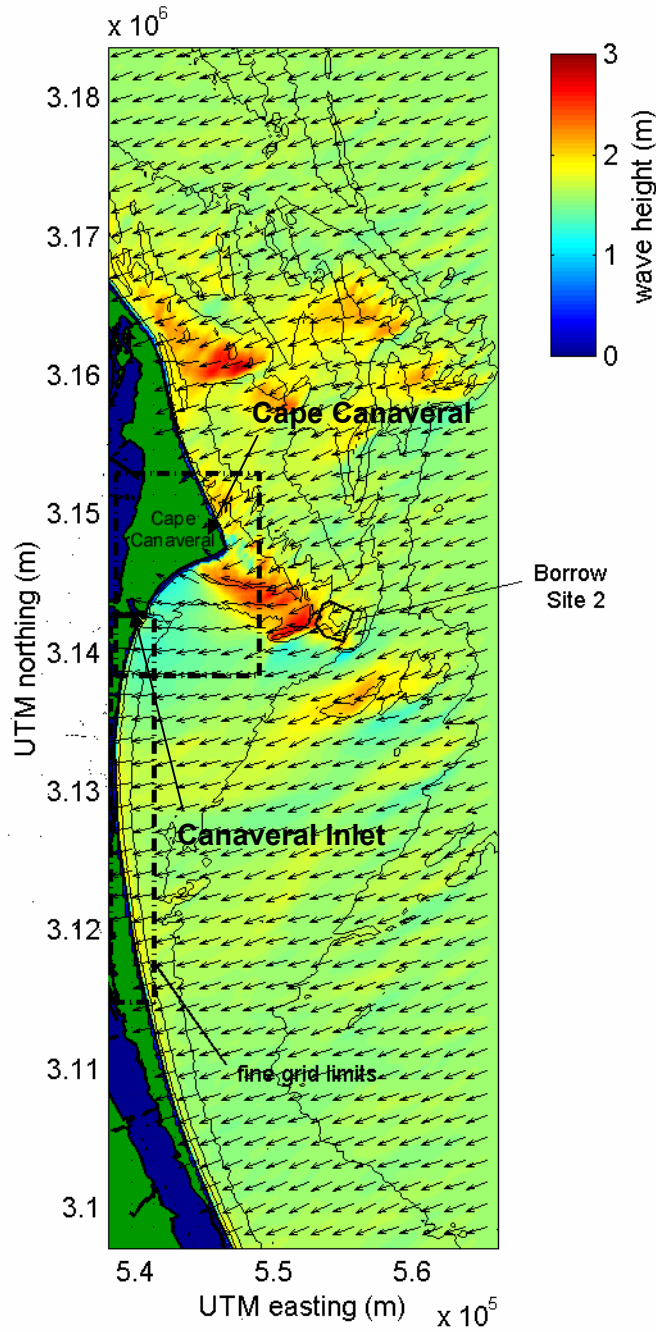


Figure 3-36. Plot of STWAVE model output for Cape Canaveral, Florida wave Case 6 ($H_s=1.6$ m, $T_{peak}=14.3$ sec, $\theta_{peak}=65$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

shoal areas located northeast of the Cape, wave heights increase by about 0.3 m above offshore wave heights. Wave direction changes also are observed at the shoals.

A greater degree of direction change is seen in the model output for Case 6 (Figure 3-36). The offshore wave boundary condition is a 1.6 m, 14.3 sec wave propagating from the east-northeast. Vectors indicating wave direction illustrate that for some nearshore regions adjacent to the Cape, the direction of wave propagation changes more than 45 degrees, following the gradient in bathymetric contours. The largest waves in the model domain occur at the shoals north of Cape Canaveral, and are 1.3 m higher than offshore waves. At shoals in the vicinity of the borrow site, wave heights increase to a maximum of 2.8 m, 1.2 m above offshore conditions. Shoals tend to refract wave energy and focus it near the cusp of the Cape. Wave energy is focused away from the coast south of Cape Canaveral, and an area of reduced wave heights is created.

Wave height change plots are shown in Figures 3-37 and 3-38 for Cases 3 and 6, respectively. For Case 3, maximum wave height increase resulting from dredging the borrow site is 0.2 m, and the maximum decrease in the shadow zone of the site is 0.3 m. The overall area of influence of this borrow site extends approximately 14 km north of the Cape to about 4 km south of Port Canaveral.

Similar wave difference results are illustrated for Case 6 (Figure 3-38). Maximum changes in post-dredging wave heights were ± 0.7 m, which are substantially greater than changes observed at previous sites. The area of greatest wave height increase occurs at the northwest corner of the site. Wave heights do not increase by the same amount at the southwest corner, likely due to the geometry and bathymetry of the site. Deeper excavation depths at the northwest corner cause a greater degree of wave refraction. The alongshore extent of influence is similar to that of Case 3, but it is shifted slightly southward due to the different direction of wave propagation.

3.2.2 Sediment Transport Potential

Comparisons of average annual sediment transport potential were performed for existing and post-dredging conditions to indicate the relative impact of dredging to longshore sediment transport processes. Sediment transport potential is a useful indicator of shoreline impacts caused by offshore borrow sites because the computations include the borrow site influence on wave height and direction. For each study area, the net sediment transport potential associated with average annual conditions was computed. Post-dredging model conditions in each study area are listed in Table 3-7. These values represent the recommended maximum excavation depths for each individual site, whether dredged during the course of one project or over the course of several projects.

3.2.2.1 Model Comparison with Historical Shoreline Change

To ensure that the spectral wave modeling and the associated longshore sediment transport potential could be utilized effectively to evaluate long-term alterations to the littoral system, a comparison of model predictions with observed shoreline change was performed. This analysis provides a semi-quantitative method for determining whether a) longshore wave-induced transport is responsible for observed shoreline change, and b) the long-term shoreline change trends are consistent with the shorter time-period (20-year) sediment transport potential analyses. For the four potential sand resource areas,

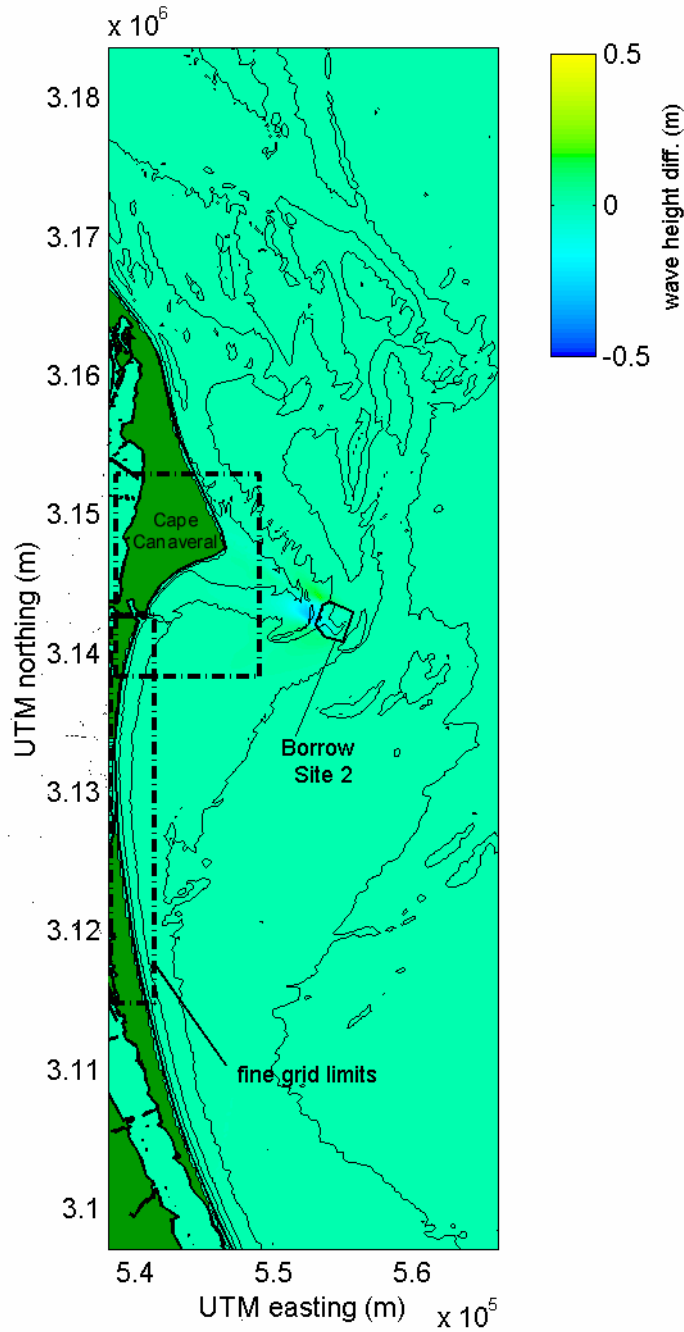


Figure 3-37. Plot of wave height change between existing and post-dredging ($\Delta H = H_{post} - H_{pre}$) conditions at Borrow Site 2 for STWAVE model output for Cape Canaveral, Florida wave Case 3 ($H_s = 1.0$ m, $T_{peak} = 7.7$ sec, $\theta_{peak} = 100$ deg).

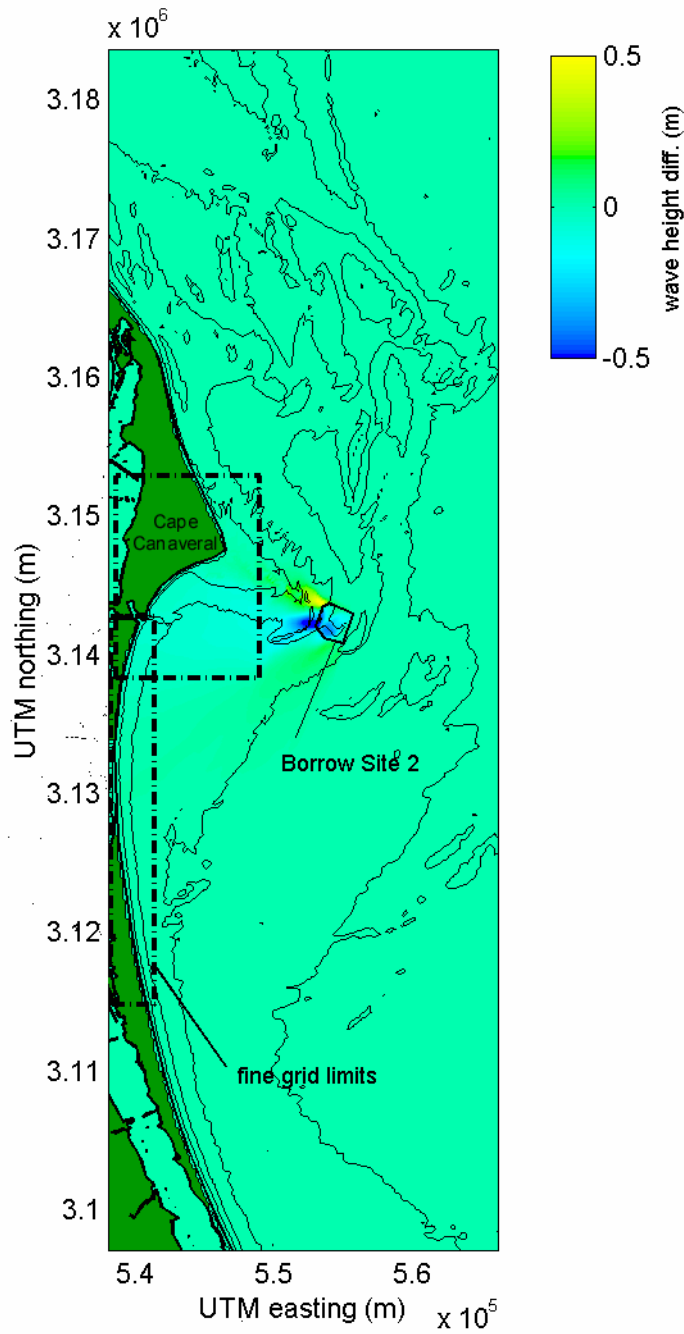


Figure 3-38. Plot of wave height change between existing and post-dredging ($\Delta H = H_{post} - H_{pre}$) conditions at Borrow Site 2 for STWAVE model output for Cape Canaveral, Florida wave Case 6 ($H_s = 1.6$ m, $T_{peak} = 14.3$ sec, $\theta_{peak} = 65$ deg).

an evaluation of model output was performed using a comparison of computed gradients in sediment transport to historical shoreline change data. The basis for this comparison is the relationship between shoreline movement and the longshore gradient of sediment transport. Simply expressed, this relationship is

$$\frac{\partial Q}{\partial y} \propto \frac{\partial x}{\partial t} \quad (3.17)$$

where Q is sediment transport, y is alongshore distance, x is the cross-shore position of the shoreline, and t is time. A comparison of results should illustrate similar trends in long-term shoreline change and transport potential computed using wave conditions that represent long-term average conditions. Good general agreement between these two quantities would suggest that the transport potential model reasonably represents long-term coastal processes for a given area, and thus, the model's ability to predict the likely impacts that would result from offshore dredging.

The time variation in shoreline position was determined from an analysis of historical shoreline data for each of the study areas. Regional change analysis provides a without-project assessment of shoreline response for comparison with predicted changes in wave-energy focusing at the shoreline resulting from potential offshore sand dredging activities. Because continuous measurements of historical shoreline change are available at 50-m alongshore intervals, model results (wave and sediment transport) at discreet intervals along the coast can be compared with historical data to develop process/response relationships for evaluating potential impacts. In this study, shoreline data covering the periods 1842 to 1977 for southern New Jersey (Byrnes et al., 2000); 1859 to 1980 for Sandbridge, southeastern Virginia (completed as part of this study); 1849 to 1980 for Dare County, North Carolina (Byrnes et al., 2001); and 1877 to 1996 for the shoreline south of Cape Canaveral, Florida (Byrnes and Kraus, 1999; Kraus et al., 1999) was used to quantify trends. Methods used for compiling and analyzing historical data sets are described in Byrnes and Hiland (1994). Alongshore variations in sediment transport were determined using the computed values of transport potential for each shoreline for modeled existing conditions. Comparisons of shoreline change to the modeled transport gradient are shown in Figures 3-39 to 3-42.

Southern New Jersey. For the modeled New Jersey shoreline shown in Figure 3-39, there is general agreement between shoreline change and transport gradient. Shoreline change data from Great Egg Harbor Inlet to Corsons Inlet show a trend from stable to erosional at the northeast side of Corsons Inlet. This trend is indicated in the transport gradient as well. From Corsons to Townsends Inlets, the shoreline change trend is from slightly erosional to slightly accretional, which is also the general trend documented in the gradient of transport potential. At the southwestern side of Townsends Inlet, a highly erosional area followed by an area of accretion is illustrated in shoreline change data and the modeled transport gradient. However, south of this area, agreement between modeled shoreline change trends and measured shoreline change do not appear to match well. Although the modeling predicts an area of significant accretion centered at approximately UTM Northing 4,325,000 meters, measurements indicate a stable shoreline in this region. Other than this one portion of the grid, which is not influenced by proposed borrow sites, agreement between the modeled gradient in transport potential and measured shoreline change is good. Even erosion and accretion trends

are predicted well in the vicinity of tidal inlets, where tidal current processes often dominate nearshore sediment transport patterns.

Southeastern Virginia. For the modeled shoreline of southeastern Virginia, the comparison of modeled transport gradient and measured shoreline change is shown in Figure 3-40. Shoreline change data and model results indicate a fairly stable shoreline between Rudee Inlet (north end of the plot) and Sandbridge (immediately landward of Borrow Sites A and B). South of Sandbridge, both analyses show a change to an erosional shoreline. Farther south from the maximum negative gradient in transport potential, the gradient changes to an accretional trend where shoreline change data indicate a change to a stable shoreline. Overall, the agreement between trends in longshore sediment transport potential gradient and observed shoreline change was good for the Virginia coast. This suggests that the 5-year offshore wave record used for calculating sediment transport potential represented long-term wave conditions responsible for regional shoreline change.

North Carolina. Trends in shoreline change generally agree with modeled transport gradients for the North Carolina coast north of Oregon Inlet (Figure 3-41). Results of both analyses illustrate a stable to erosional shoreline, with an area of maximum erosion between 5 and 7 km north of Oregon Inlet. For the modeled transport gradient, there is an area of accretion approximately 3 km north of the point of maximum erosion that is not indicated in the shoreline change analysis. This may be due to a lack of detailed nearshore bathymetry data for a 2 km section of coastline at this location. Bathymetry data used for developing the model grid was digitized from a NOAA navigational chart and does not have a high level of detail as is available in the data used for adjacent sections of coast. In addition, severe erosion observed immediately north of Oregon Inlet may have created an erosion hot-spot that has propagated to the north as shoreline orientation changed over the past century. The gradient in sediment transport potential was not expected to simulate this process that likely occurs over a time period spanning several decades. Significant migration of Oregon Inlet also may be responsible for some of the differences between observed and modeled shoreline change trends, where the peak in erosion likely has migrated south with the inlet. Therefore, the peak erosion area determined from the gradient of modeled transport potential, based on 20 years of recent wave information, may be more representative of present conditions than the long-term shoreline change (based on more than 100 years of shoreline data). Overall, good agreement exists between observed shoreline change and longshore gradient in modeled transport potential. Minor differences between the two methods, especially in the region of maximum erosion, likely are due to long-term alterations (spanning several decades) in shoreline position and the historical migration of Oregon Inlet.

Cape Canaveral. Model results and shoreline change data for the Cape Canaveral area are shown in Figure 3-42. Both analyses show that the shoreline is stable about 6 km south of Canaveral Inlet. In the shoreline change results, the trend from the Cape headland south to Port Canaveral is highly accretional to accretional. This trend is not duplicated in the modeled transport gradient, which shows an area of high accretion at the cusp of the Cape, followed by an area of significant erosion between the Cape and the Inlet. The model likely has difficulty in this area due to complex offshore bathymetric features associated with Canaveral Shoals and limitations related to wave modeling (wave diffraction presently not included in STWAVE). In addition, STWAVE propagates wave energy within a ± 90 degree sector from the cross-shore axis of the grid, which is important in areas where the shoreline angle is steeply inclined from the axis of the grid

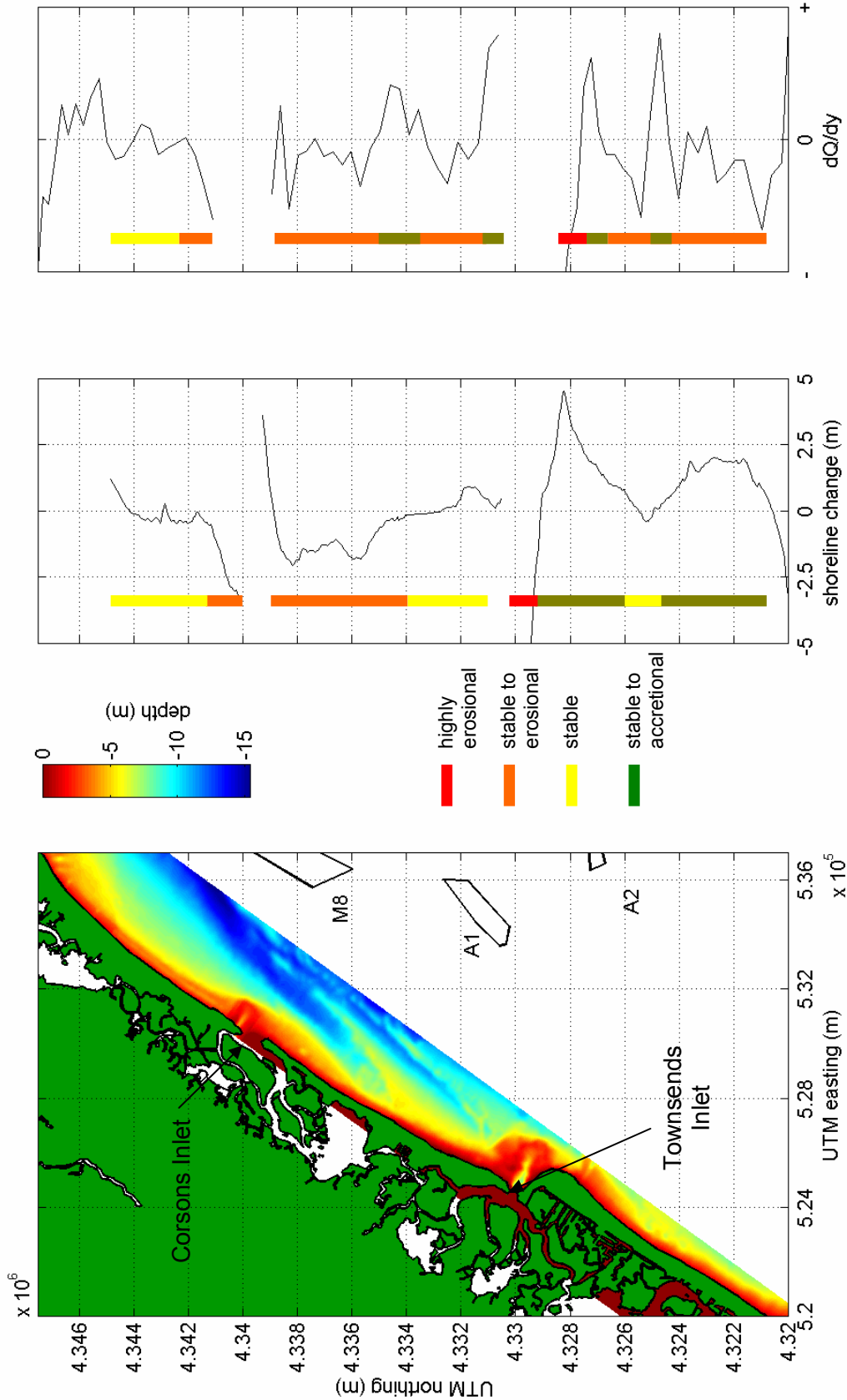


Figure 3-39. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the southern New Jersey shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional.

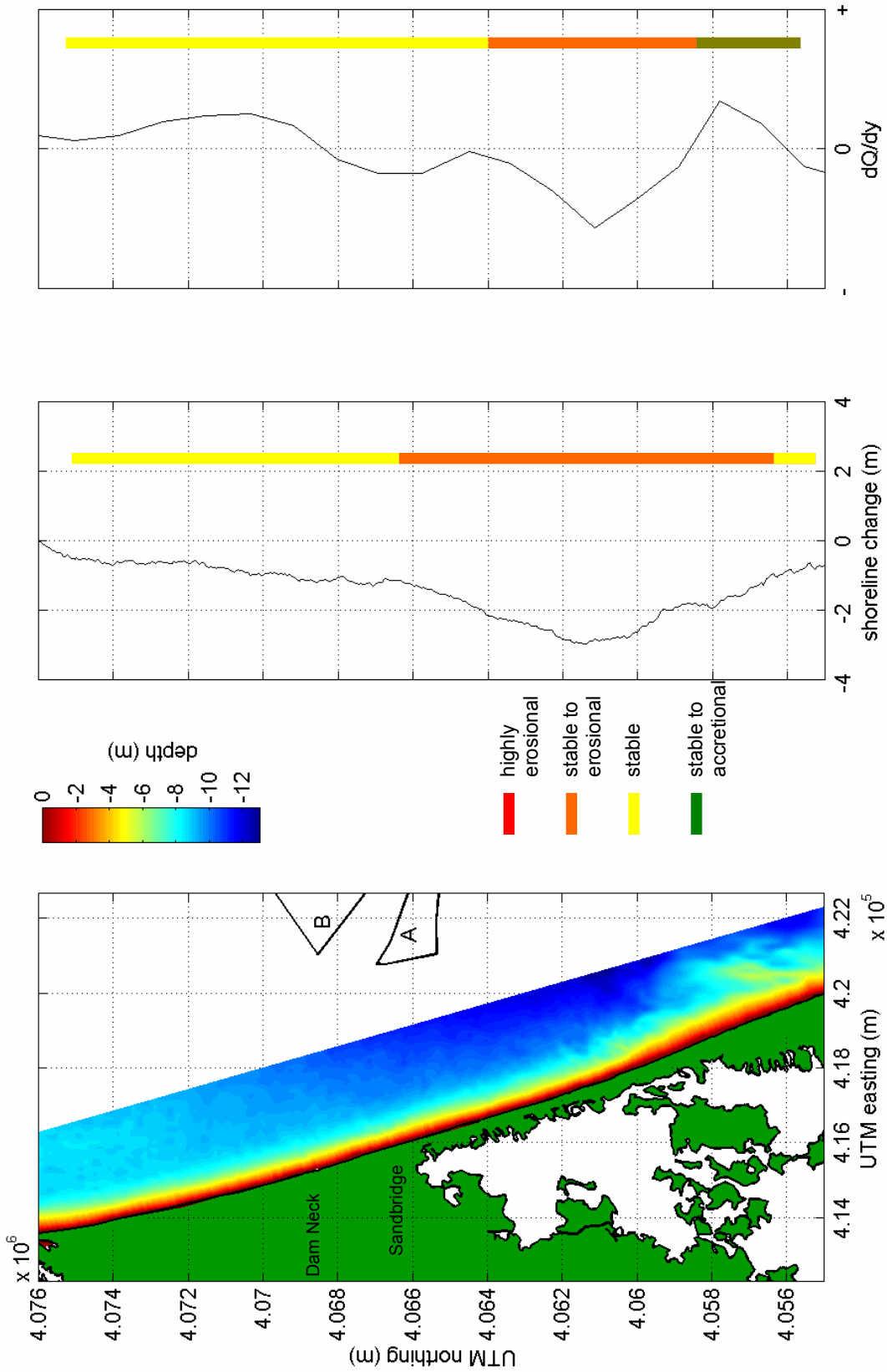


Figure 3-40. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the southeastern Virginia shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional.

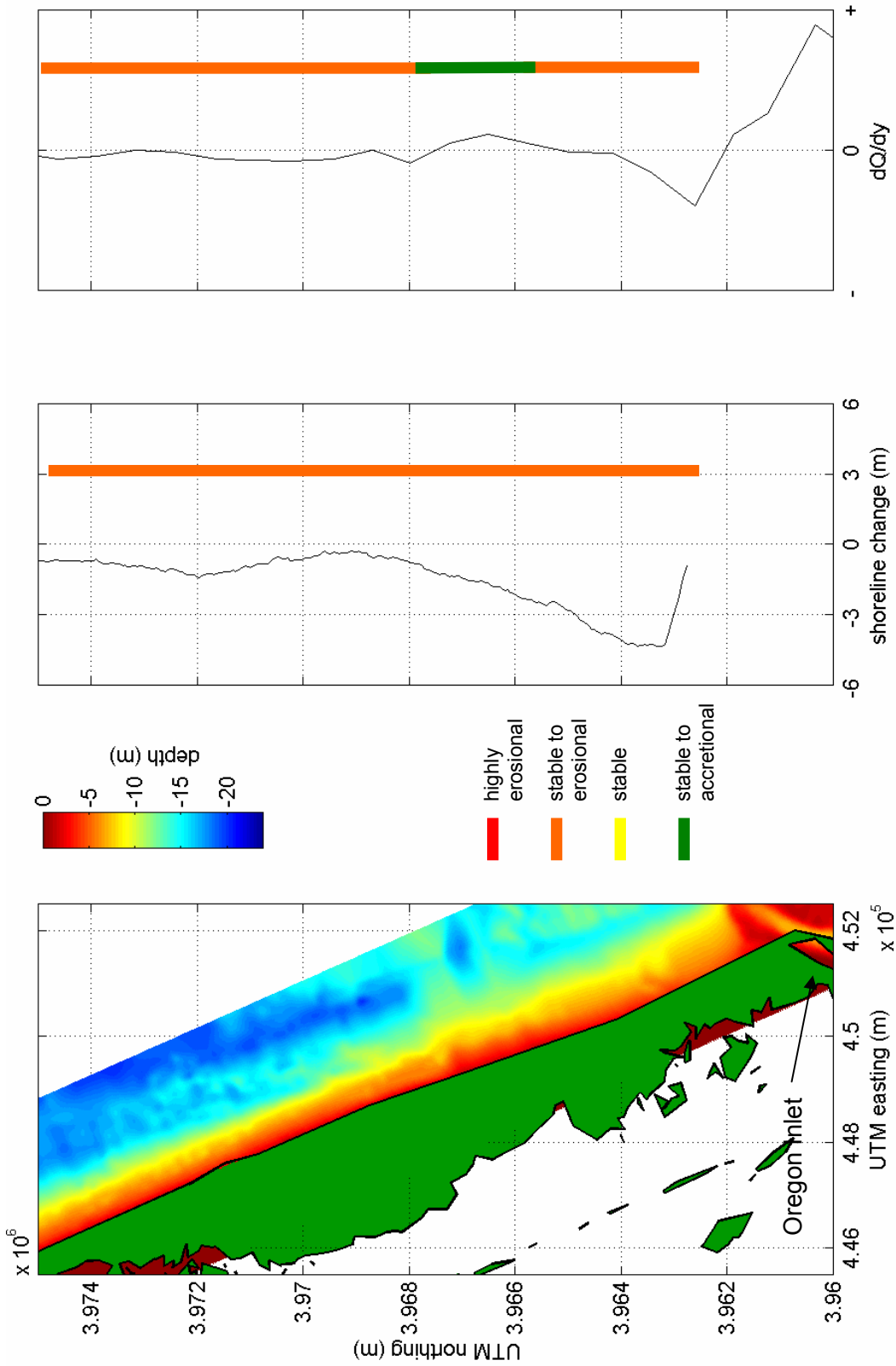


Figure 3-41. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the North Carolina shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional.

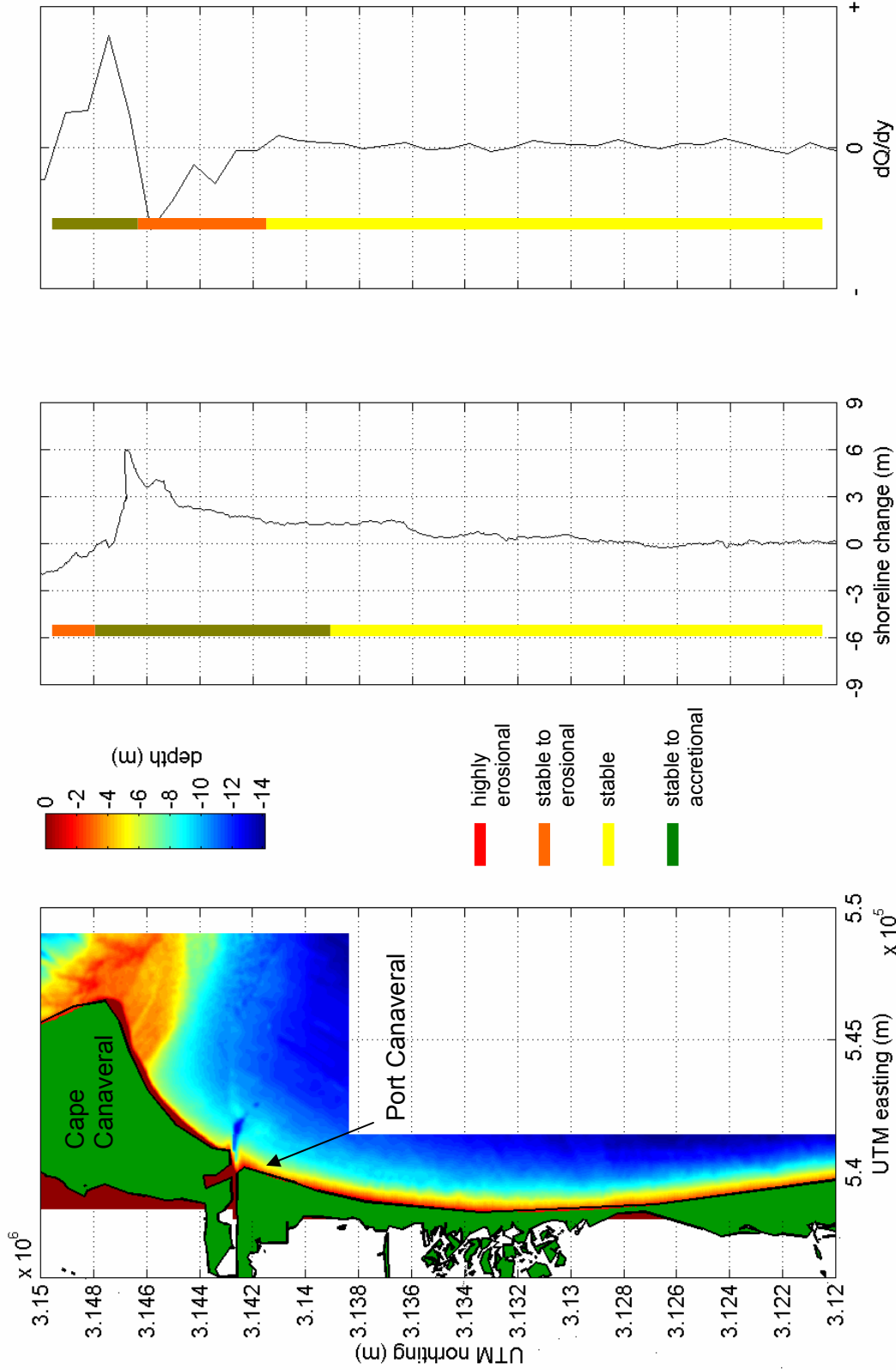


Figure 3-42. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the Cape Canaveral shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional.

(e.g., just south of the cusp of the Cape). Based on the curvature of the shoreline north of Port Canaveral, significant erosion is anticipated immediately south of the cusp of Cape Canaveral (as indicated by the modeled gradient of transport potential). However, shoreline change data indicate substantial accretion in this area. The primary reason for this accretion likely is due to the shoal serving as a sediment source for beaches to the south. This cross-shore transport mechanism is not considered in longshore sediment transport analyses. For shorelines where nearshore shoals exhibit significant diffraction and potentially serve as a sediment source to the beach system, modeled sediment transport potential cannot match observed trends in shoreline change. South of Port Canaveral, away from the influence of the Cape's topographic and bathymetric features, the trends predicted by the sediment transport potential model match well with historical shoreline change.

3.2.2.2 Modeled Transport and Dredging Impacts

To quantitatively assess impacts to coastal processes associated with sand mining, a new approach was developed that considers the spatial (longshore) and temporal variability of local wave climate. This methodology uses similar wave modeling results as those required for two previous analyses (Basco, 1999 and Byrnes, et al., 1999); however, wave modeling is performed for the entire 20-year WIS record as well as five 4-year blocks of the WIS record. In this manner, temporal variations in wave climate are considered relative to average annual conditions. From these wave model runs, sediment transport potential curves are derived for average annual conditions (using the full 20-year WIS record) and each 4-year period (using five 4-year wave records parsed from the full record). Based on this information, the average and standard deviation in calculated longshore sediment transport potential is determined every 200 m along the shoreline. Results of each of the four investigated areas are shown in Figures 3-43 through 3-46.

The purpose of segmenting the wave time series into five 4-year segments was to reduce the number of wave model runs without sacrificing information and to compute a more conservative estimate of wave variability (smaller range) for determining the significance of predicted impacts. Because the evaluation of sediment transport potential was performed to indicate long-term trends and not seasonal variations, the minimum length of wave record needed is one complete year. By grouping the 20-year wave record into 4-year blocks rather than into individual years, a more conservative standard deviation (smaller range) about the mean transport rate was derived. By definition, the standard deviation of a normally distributed variable would be reduced if the number of variables were reduced by grouping the original data.

Assuming the temporal component of sediment transport potential is normally distributed, the suggested criterion for accepting or rejecting a potential borrow site is based on one standard deviation about the mean. If any portion of the sediment transport potential curve associated with a sand mining project exceeds one standard deviation of the natural temporal variability (which incorporates 2/3 of the variability) in sediment transport potential, the site would be rejected. Because the standard deviation of each 4-year period is more realistic for documenting long-term variability than using a 1-year period, the methodology provides a useful indication of sediment transport variability relative to the natural system.

The methodology used to determine impact significance depended on a region's site-specific wave characteristics by considering temporal (inter-annual) and spatial variability in wave conditions. For this reason, the statistical envelope defining the limits of acceptable borrow site impacts varies along a given shoreline. A shoreline that experiences a wide variety of wave conditions (in direction, peak period, and significant wave height) from year to year naturally experiences large variability in sediment transport rates; therefore, the level of acceptable borrow site impacts would be relatively high. Conversely, a shoreline that experiences a limited range of wave conditions cannot accept a high level of borrow site impacts. An offshore site that is dominated by swell conditions from a single narrow direction band would be a good example of this latter case. Because the natural variability in inter-annual shoreline migration changes along the coast, certain portions of the shoreline will be more tolerant of alterations to the wave climate and associated sediment transport patterns. The methodology used to evaluate borrow site impacts provides a reliable quantitative technique for developing acceptable site-specific limits associated with changes in sediment transport potential.

Offshore Southern New Jersey. An illustration of sediment transport potential for existing and post-dredging conditions for the southern New Jersey coastline is plotted with the acceptable limits for post-dredging based on the dredging significance criterion (Figure 3-43). Typically, net transport potential values are around 300,000 m³/yr to the south, with minimum values occurring in the vicinity of Townsends and Corsons Inlets. Post-dredging changes fall within the limits of the dredging significance criterion envelope, and therefore, the proposed excavation depths would be acceptable in terms of impact on transport patterns in the modeled area. For this section of modeled coastline, the significance criterion envelope is ± 10 to 15% of the modeled annualized net transport potential, with values of about $\pm 30\%$ close to Great Egg Harbor Inlet, north of Corsons Inlet. Overall, the significance criterion envelope (representing plus or minus one standard deviation about the mean) for southern New Jersey was relatively narrow compared with the other three modeled areas. This results from the limited variability in inter-annual wave climate along this portion of the New Jersey coast.

Figure 3-43 includes the difference between existing and post-dredging conditions for all borrow sites (cumulative impacts). Generally, the greatest impact is indicated between Townsends and Corsons Inlets, with maximum changes in net transport potential of about -22,000 m³/yr. In this case, negative transport changes mean that there has been an *increase* in southerly-directed transport. Based on the model results, nearly all of the borrow sites cause an increase in southerly-directed transport with the exception of regions immediately south of Townsends and Corsons Inlets. Because the magnitude of impacts north and south of Corsons Inlet appears to be significantly larger than the impacts south of Townsends Inlet, borrow sites A1 and M8 appear to have greatest influence on transport rates. The impact of offshore site A2 likely is distributed over a longer stretch of shoreline; however, the magnitude is reduced.

Offshore Southeastern Virginia. The results from wave model runs encompassing Sandbridge Shoal are presented in Figure 3-44. Sediment transport potential is directed to the north, with a maximum value of around 300,000 m³/yr. A nodal point exists in the model output near False Cape. The significance criterion envelope is typically ± 20 to 35% of the modeled annualized net transport potential, which is larger than that for the modeled New Jersey shoreline. This means that borrow sites in this area would be able to impact sediment transport by a greater percentage than in the New Jersey simulations, because the sediment transport potential is more variable than it is in New

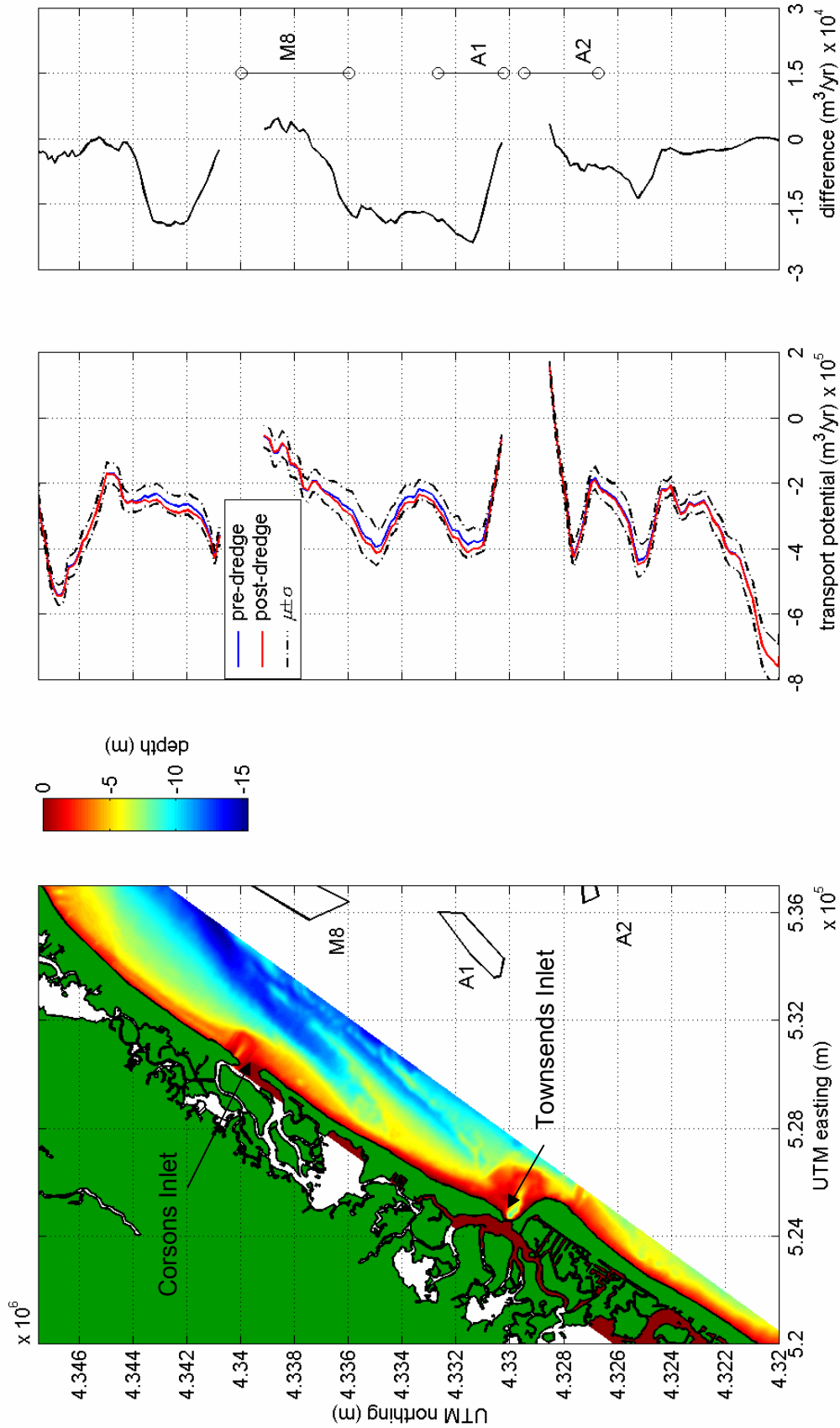


Figure 3-43. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore southern New Jersey. The middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference.

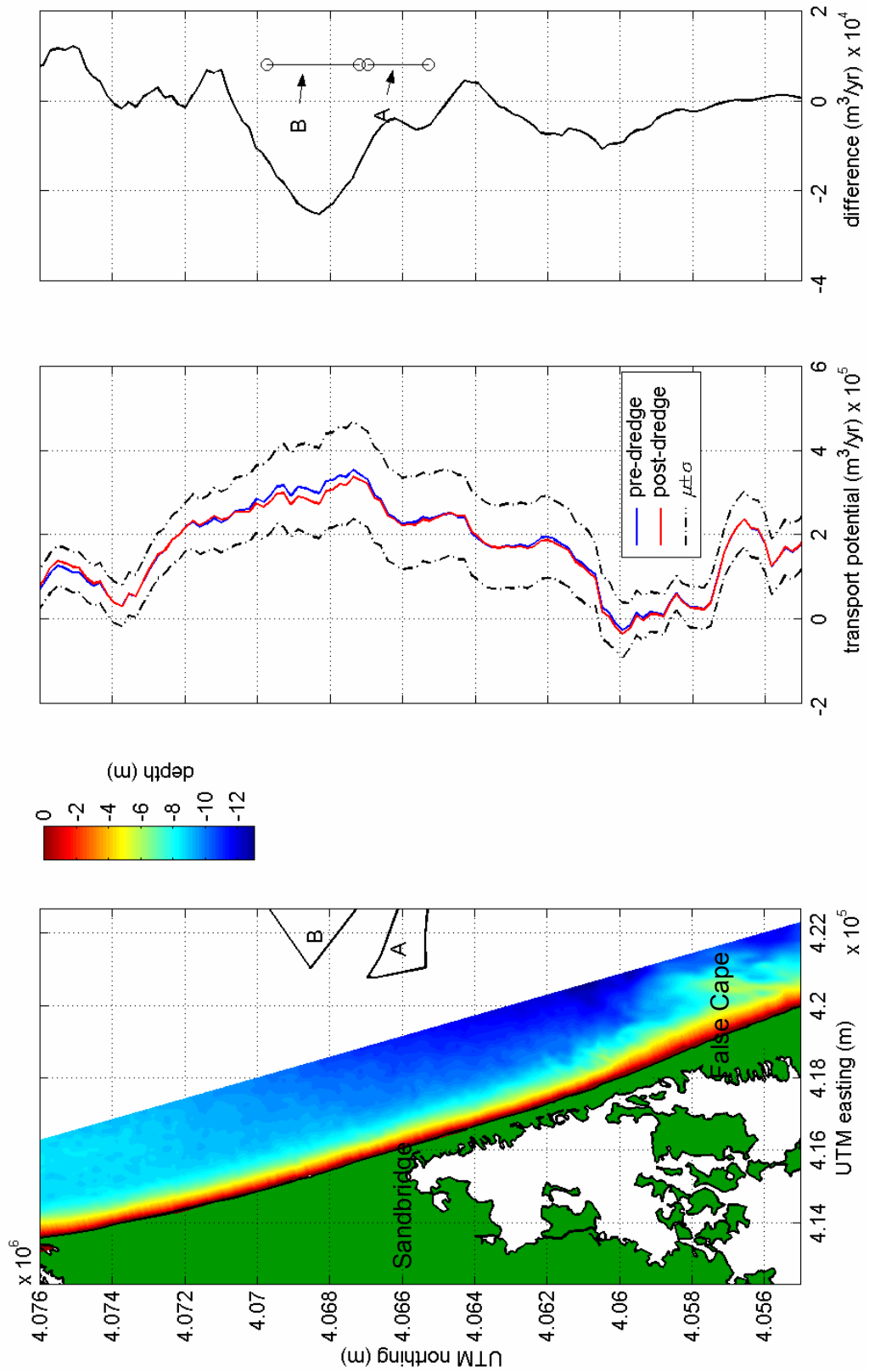


Figure 3-44. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore southeastern Virginia, the middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference.

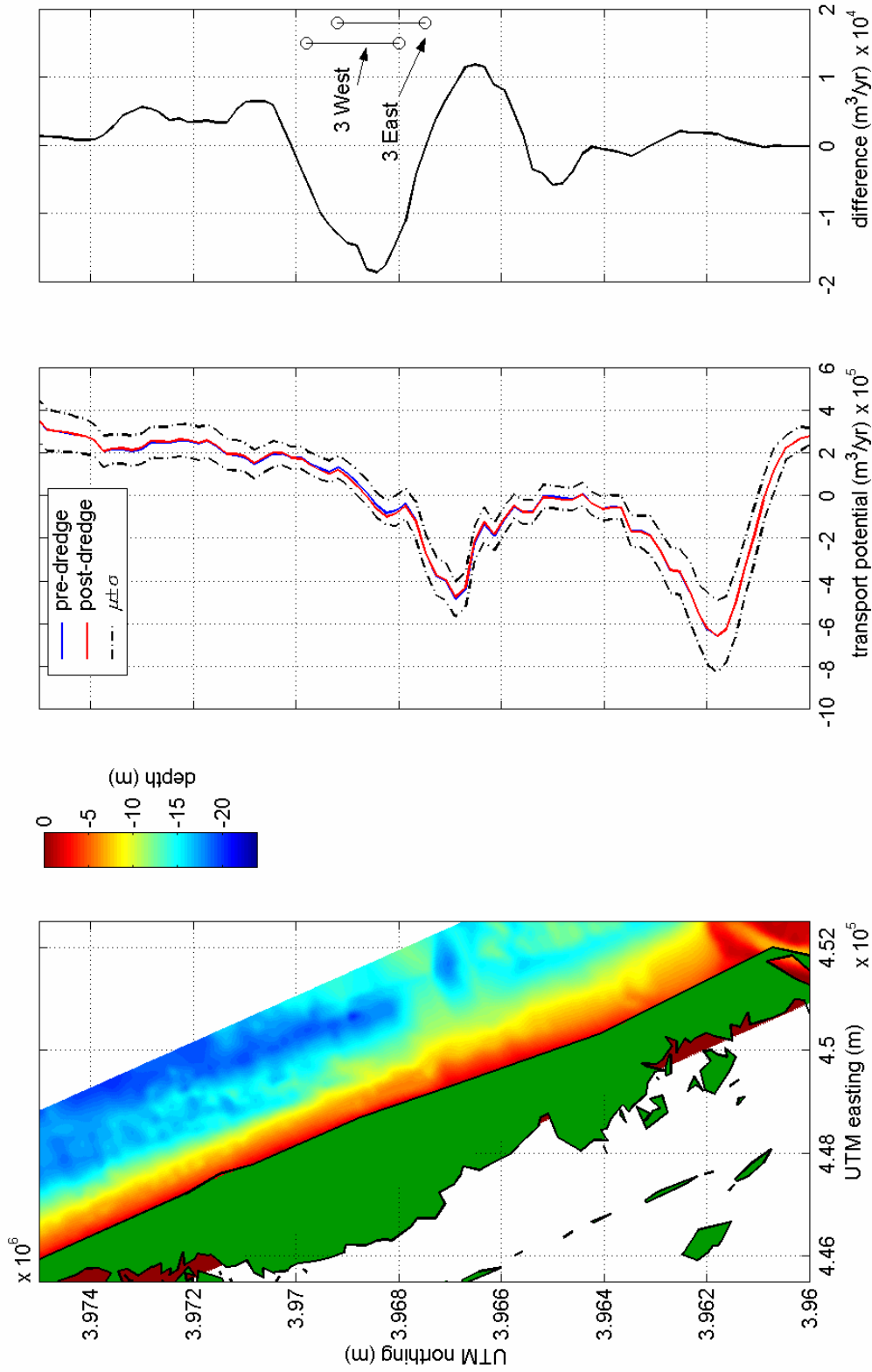


Figure 3-45. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore North Carolina, north of Oregon Inlet. The middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference.

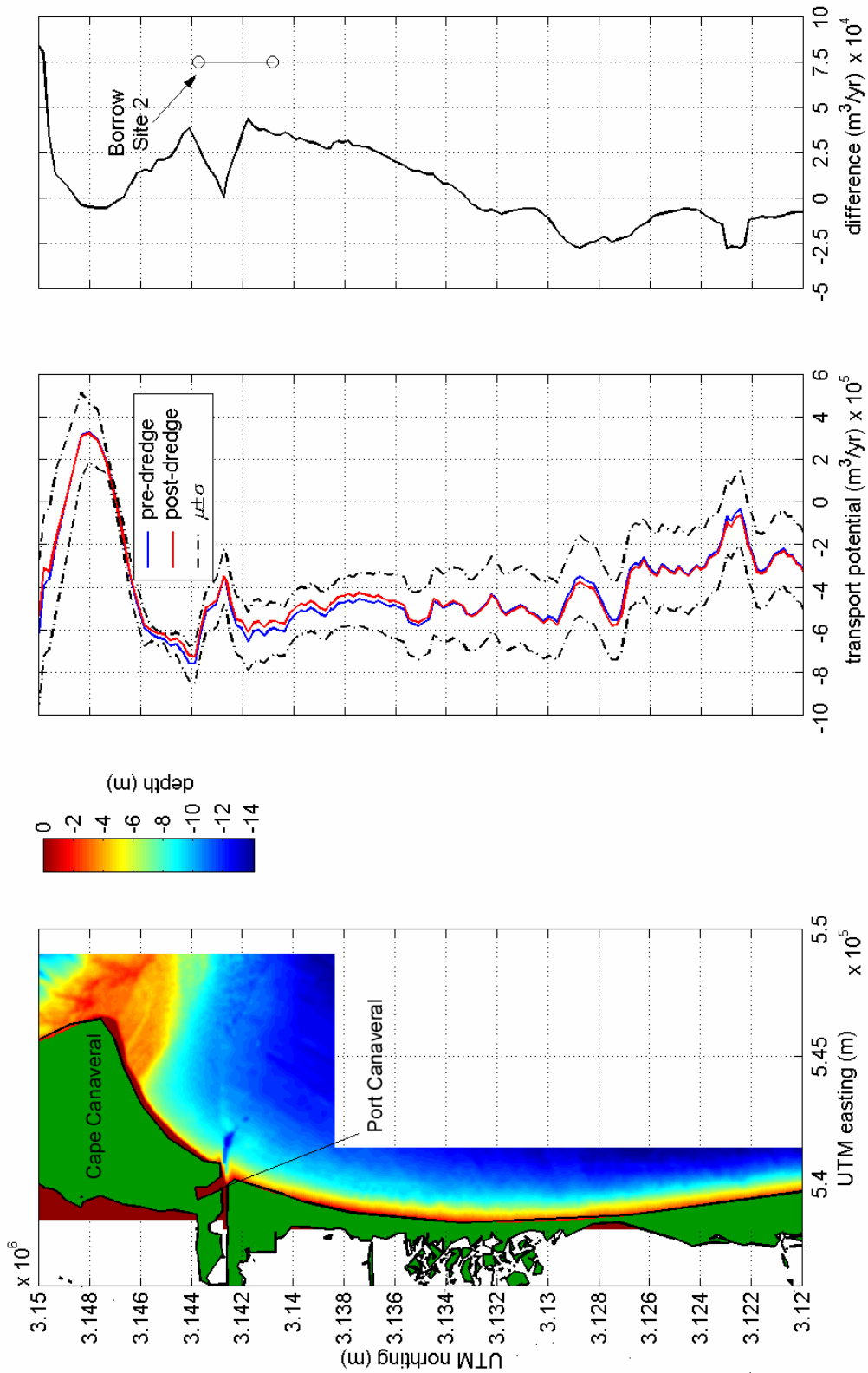


Figure 3-46. Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore Florida, near Cape Canaveral. The middle plot shows the dredging significance criterion envelope ($\pm\sigma$), and the plot of the shoreline and bathymetry is given for reference.

Jersey. For the modeled borrow sites (see Table 3-7, with depths not to exceed 50 ft NGVD), change in sediment transport potential for post-dredging conditions falls within the limits of the dredging significance criterion. So again, these proposed excavation depths (and sediment volumes) would be acceptable.

The existing and post-dredging difference plot shows that the greatest impact from the two borrow sites is located in the vicinity of Sandbridge and Dam Neck (approximately 25,000 m³/yr decrease in northerly directed transport), while approximately a 20 km segment of shoreline is affected in total. The shoreline region of borrow site impacts exists within the area of maximum inter-annual variability in sediment transport potential. In this area, the standard deviation of the sediment transport potential variability exceeds ±100,000 cubic meters per year. Based on the difference plot, it is not possible to discern the impacts associated with Sites A and B separately; however, the greatest influence of sand mining at both sites is to decrease northerly-directed littoral drift. Therefore, the region to the north of Dam Neck will have a reduced supply of sand and the region immediately landward of the borrow sites will experience an increase in shoreline stability as a result of the dredging. The magnitude of these anticipated alterations to the local sediment transport regime is within one standard deviation of the natural inter-annual variability.

Offshore North Carolina. Figure 3-45 illustrates model output to estimate the impact of sites 3 East and 3 West offshore North Carolina. North of the inlet, simulated net potential transport is to the north at approximately 250,000 m³/yr. Gross annualized north and south transport values are about 450,000 m³/yr and 200,000 m³/yr, respectively. Closer to the inlet, net transport values are primarily to the south, with largest potential transport values around 600,000 m³/yr and very little north-directed transport (approaching zero). The dredging significance criterion generally falls within ±30 to 40% of the computed net transport values, suggesting that the transport climate is similar to, but slightly more variable than, the southeastern Virginia example. For the modeled sand excavation conditions (Table 3-7), post-dredging model results fall within the significance criterion envelope, so again the modeled dredging plan would be acceptable.

The plot that presents transport differences between existing to post-dredging conditions at the two modeled sites indicates that the maximum impact from sand dredging at both borrow sites is an approximate 20,000 m³/yr increase in south directed transport. These borrow sites represent the smallest sand mining sites evaluated, with 3 East containing approximately 1,400,000 m³ and 3 West containing approximately 2,500,000 m³. Although the borrow sites are relatively small, impacts associated with sand mining in this region are comparable in magnitude to the Dam Neck/Sandbridge Shoal sites described above. This impact magnitude likely is a result of the combined influence of the two borrow sites along a relatively short section of shoreline, where the longshore region of influence is approximately 10 km. A more complete discussion of combined impacts associated with borrow sites in close proximity to each other is presented in Section 4 (Cumulative Effects).

Because the region of impacts associated with the North Carolina borrow sites straddles a sediment transport nodal point, the influence of an increase in south-directed transport (between UTM northing 3,967,500 and 3,970,000 m) will reduce the supply of sediment north of this region and increase the amount of sediment leaving this region to the south. Therefore, simulated sand dredging at 3 East and 3 West may generate an

erosion hot spot. However, the magnitude of impacts to sediment transport patterns is anticipated to be small relative to natural inter-annual variability of the local littoral processes.

Offshore Cape Canaveral. Due to the influence of Cape Canaveral and the series of migrating ridges and troughs on Canaveral Shoals, a direct relationship between the observed shoreline change and the longshore gradient in sediment transport potential could not be established. Therefore, the utility of comparing the changes in sediment transport potential associated with sand mining to the natural variability of sediment transport patterns may have limited applicability in the region north of Port Canaveral. This is most clearly illustrated by the change in transport rates at the northern limit of the model grid, where a *decrease* in south-directed transport of 80,000 m³/yr is predicted. Because the STWAVE model used for analysis does not include the influence of wave diffraction, modeled transport rates in regions influenced by diffraction effects are suspect. For Brevard County, this region influenced by wave diffraction would be north of Canaveral Inlet.

Model output for the region south of Port Canaveral (Brevard County) illustrates that in the area of greatest impact from the borrow site, the significance envelope is approximately $\pm 20\%$ of the mean computed net transport potential (Figure 3-46). The maximum modeled change for post-dredging conditions at the borrow site is about a 40,000 m³/yr *decrease* in south directed transport, just south of Port Canaveral. The modeled sand excavation volume of 26 MCM is considerably greater than the estimated 3.4 MCM for present beach nourishment requirements in Brevard County (USACE, 1999). Though the modeled difference is within the transport significance envelope, the magnitude of impact resulting from cumulative dredging of the full volume at this site suggests further analysis should be required to ensure that no detrimental impacts would occur.

3.2.2.3 Dredging Impacts at East Coast Sites

To establish useful criteria for estimating impacts of sand mining on the nearshore littoral system, a comparison of sediment transport potential analysis and long-term shoreline change was performed at each of the four sand borrow sites. The analysis provided a quantitative method for determining whether longshore wave-induced transport was responsible for observed shoreline change and whether the long-term shoreline change trends were consistent with the shorter time-period (20-year) sediment transport potential analysis. In general, the comparison indicated that the longshore gradient in computed wave-induced sediment transport followed similar trends as observed long-term shoreline change for nearly all cases. Exceptions occurred at locations where STWAVE modeling was not applicable (areas where wave diffraction was important) or where wave-induced processes may not govern sediment transport (in the vicinity of tidal inlets).

For the southern New Jersey shoreline, erosion and accretion trends are predicted well at all locations, including in the vicinity of tidal inlets. Along the southeastern Virginia coast, model results predict similar trends as observed long-term shoreline change, where much of the coastline is stable or slightly erosional. The location of highest erosion rates is predicted accurately by the modeling analysis. Overall agreement between modeled trends and measured shoreline change also was achieved for the North Carolina coast north of Oregon Inlet. Discrepancies between predicted and

measured results likely are a result of the significant historical migration of Oregon Inlet. Therefore, the peak erosion area determined from the gradient of modeled transport potential, based on 20 years of recent wave information, may be more representative of present conditions than long-term shoreline change (based on more than 100 years of shoreline data). Along the Cape Canaveral coast, STWAVE modeling was not capable of evaluating changes in wave climate resulting from wave diffraction processes across Canaveral Shoals. In addition, these shoals likely serve as a sediment source to the beach in this region. For shorelines where nearshore shoals exhibit significant diffraction and potentially serve as a sediment source to the beach system, modeled sediment transport potential cannot match observed trends in shoreline change. South of Port Canaveral, away from the influence of the Cape's topographic and bathymetric features, the trends predicted by the sediment transport potential model match well with historical shoreline change.

Because modeled longshore gradients in sediment transport potential generally matched the trends in observed shoreline change, wave and sediment transport modeling provided an appropriate basis for evaluating long-term impacts associated with offshore sand mining. The methodology utilized to determine impact significance depended on a region's site-specific wave characteristics, where the method considered temporal (inter-annual) and spatial variability in wave conditions. Because the natural variability in inter-annual shoreline migration changes along the coast, certain portions of a given shoreline naturally will be more tolerant of alterations to the wave climate and associated sediment transport. The methodology used to evaluate borrow site impacts provided a reliable quantitative technique for developing acceptable site-specific limits associated with changes in sediment transport potential.

Based on site-specific analyses for each of the four sites, the impacts associated with dredging at all borrow sites were deemed acceptable. For the southern New Jersey coastline, the significance criterion envelope was typically ± 10 to 15% of the modeled annualized net transport potential, with values of about $\pm 30\%$ close to Great Egg Harbor Inlet. Overall, the significance criterion envelope (representing plus or minus one standard deviation about the mean) for New Jersey was relatively narrow compared with the other three modeled areas. This results from limited variability in inter-annual wave climate along the southern New Jersey coast.

For southeastern Virginia and North Carolina coastal regions, the dredging significance criterion envelope generally falls within ± 20 to 40% of the computed net transport values. For the modeled sand excavation conditions (Table 3-7), post-dredging model results fall within the significance criterion envelope for both cases, so again the modeled dredging plan would be acceptable. Model output for the region south of Port Canaveral, Florida (Brevard County) illustrates that in the area of greatest impact from the borrow site, the significance envelope is approximately $\pm 20\%$ of the mean computed net transport potential. Again, the modeled impacts in this region associated with potential offshore dredging are well within the significance envelope. However, due to limitations with the wave modeling effort, further analyses would be required to accurately assess impacts caused by dredging for the shoreline north of Port Canaveral.

4.0 CUMULATIVE IMPACTS

The borrow site analyses described in Section 3 document potential impacts associated with large-scale dredging of various offshore borrow areas. As shown in Table 3-6, all borrow sites contain a substantial volume of sand, most in excess of 5,000,000 m³. Because typical beach nourishment projects require significantly less sand than exists within these borrow sites, it is likely that several dredging events will occur before the entire borrow site is excavated. The analysis in Section 3 assumes that the entire borrow site is excavated at one time; therefore, this analysis provides the cumulative impacts associated with potentially numerous dredging events at a single site.

To evaluate cumulative impacts associated with incremental dredging of a single site and/or the combined effects of dredging borrow sites in the same region, a cumulative assessment strategy was developed. For evaluating cumulative impacts of sand dredging at an offshore borrow site, two types of borrow site configurations were investigated. The first group of cumulative impacts involves the interaction of multiple sites in close proximity, such that they have overlapping areas of shoreline impact. The second grouping of cumulative impacts involves multiple dredging events at a single site.

4.1 SITES IN CLOSE PROXIMITY

An investigation of cumulative impacts resulting from borrow sites in close proximity was performed to determine how potential wave impacts at individual sites may interact to produce additive effects along the coast. The assumption is that net changes in sediment transport patterns along a section of coast, where multiple borrow sites have an overlapping influence, can be evaluated by superimposing individual changes resulting from excavation at each borrow site, as if the other sites in the grouping did not exist.

To determine the validity of the stated assumption, two areas were studied, 1) Sandbridge Shoal, offshore southeastern Virginia, and 2) offshore North Carolina, in the vicinity of Oregon Inlet. At Sandbridge Shoal, the two borrow sites are oriented side-by-side and parallel to the shoreline. An example of wave model output for these sites is given in Figure 4-1, which shows wave height changes between existing and post-dredging conditions. It appears that the two sites have an overlapping influence on offshore wave heights. For offshore North Carolina, sites 3 East and 3 West are oriented front-to-back in a line perpendicular to the shoreline. Wave model output for this simulation illustrates how site 3 East has an area of influence which includes the perimeter of site 3 West (Figure 4-2).

Wave model runs were executed for the wave conditions presented in Section 3.2. However, each borrow site was modeled independently, so that each site's own area of influence could be determined. Sediment transport potential computations also were performed. Figure 4-3 shows the results of model runs for Sandbridge Shoal. Transport potential difference for three modeled cases is shown for Sites A and B modeled individually and for these two sites modeled together. In addition, the sum of the differences computed for Sites A and B alone is included. In this case, the influence on sediment transport potential along the shoreline by these two sites individually is roughly of the same magnitude, which would be expected in a case where the borrow sites are positioned similar distances offshore and are similar in size. Differences resulting from

the two sites modeled together is similar to differences derived by adding the results of the two sites modeled independently (i.e., both methods correlate well). These results suggest that any possible interaction of sites positioned side-by-side is weak.

For sites 3 East and 3 West in North Carolina, Figure 4-4 shows transport potential difference computed for cases similar to the Sandbridge Shoal model runs. In this case, the eastern borrow site has much less influence on transport potential change than the western site, which is located closer to the shoreline. Similar to the southeastern Virginia example, the sum of transport potential difference, computed for model runs at each site modeled separately, correlates well with differences computed using model output from the two sites modeled together. Therefore, for sites positioned front-to-back and perpendicular to the shoreline, interaction between these sites also is limited.

The results from these two cases (Virginia and North Carolina) suggest that borrow sites located in close proximity illustrate additive impacts. Therefore, the influence of multiple sites on sediment transport along a coastline is a simple additive effect, rather than a more complicated non-linear effect or amplification.

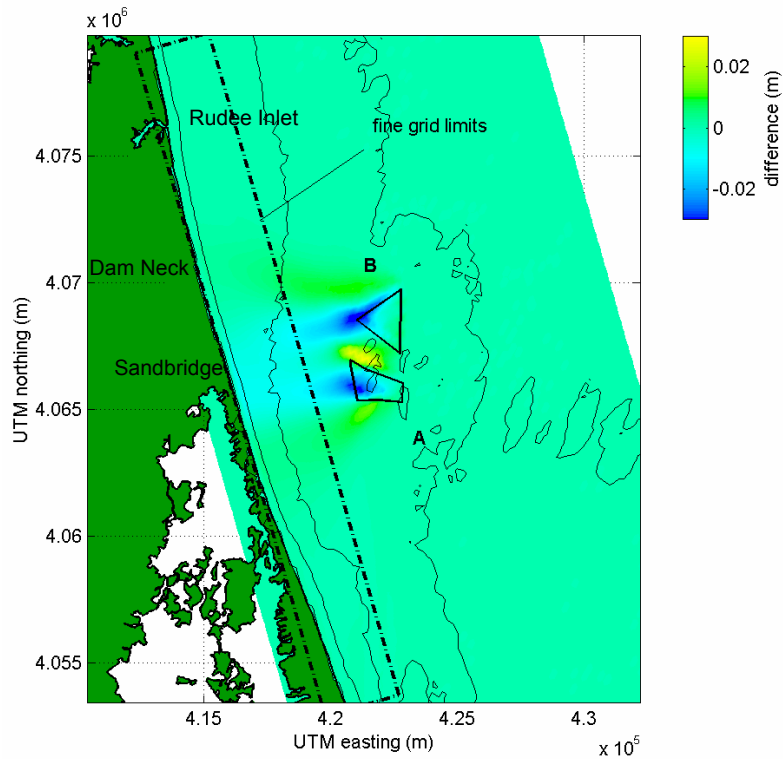


Figure 4-1. Difference plot of wave heights for existing and post-dredging conditions at sites A and B for Sandbridge model wave case 3.

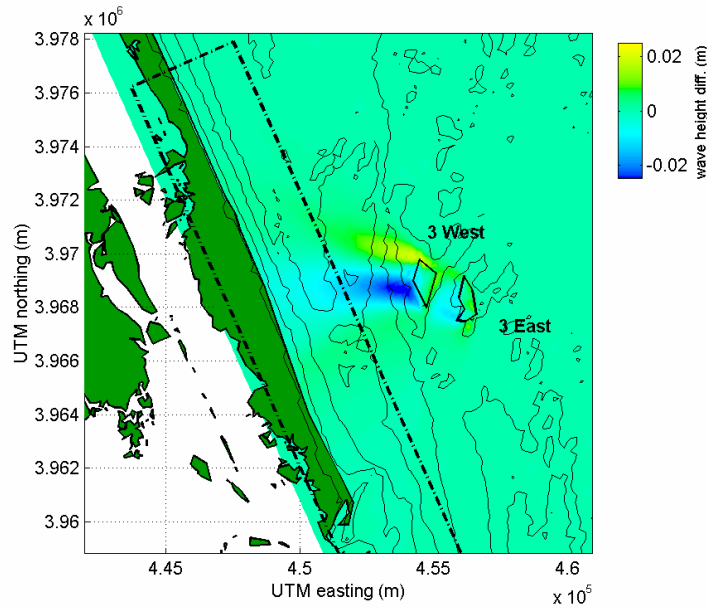


Figure 4-2. Difference plot of wave heights for existing and post-dredging conditions at sites 3 East and 3 West for North Carolina model wave case 4.

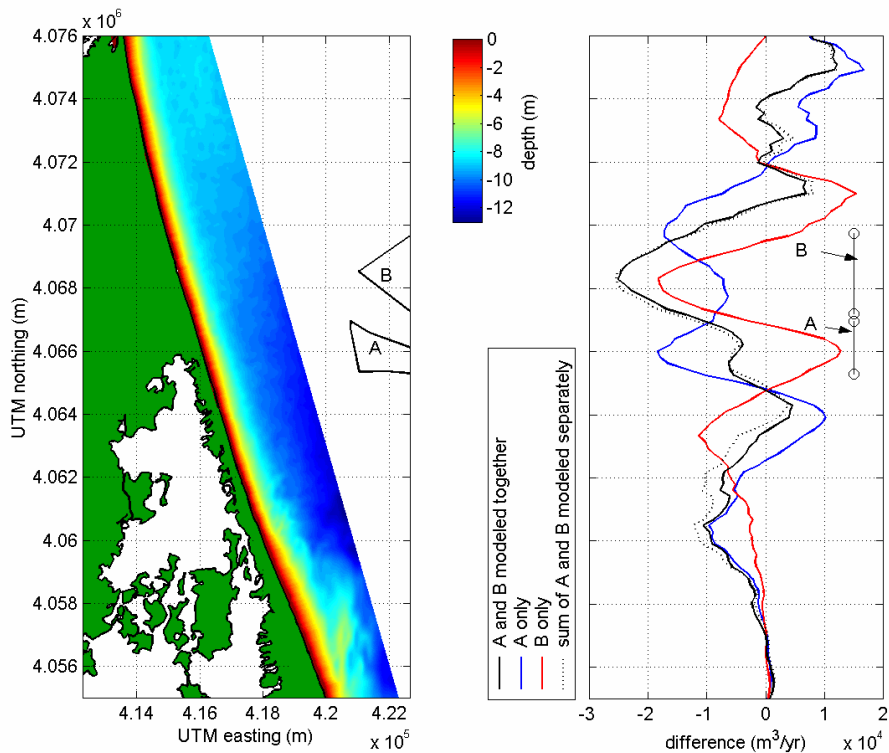


Figure 4-3. Plot of sediment transport potential difference between existing and post-dredging model runs including Sites A and B (southeastern Virginia) modeled together (solid black line) and separately (solid blue and red lines). The sum of transport difference computed for the separate runs of A and B (dotted black line) is presented for comparison with the curve of A and B modeled together (coefficient of determination, $r^2=0.970$).

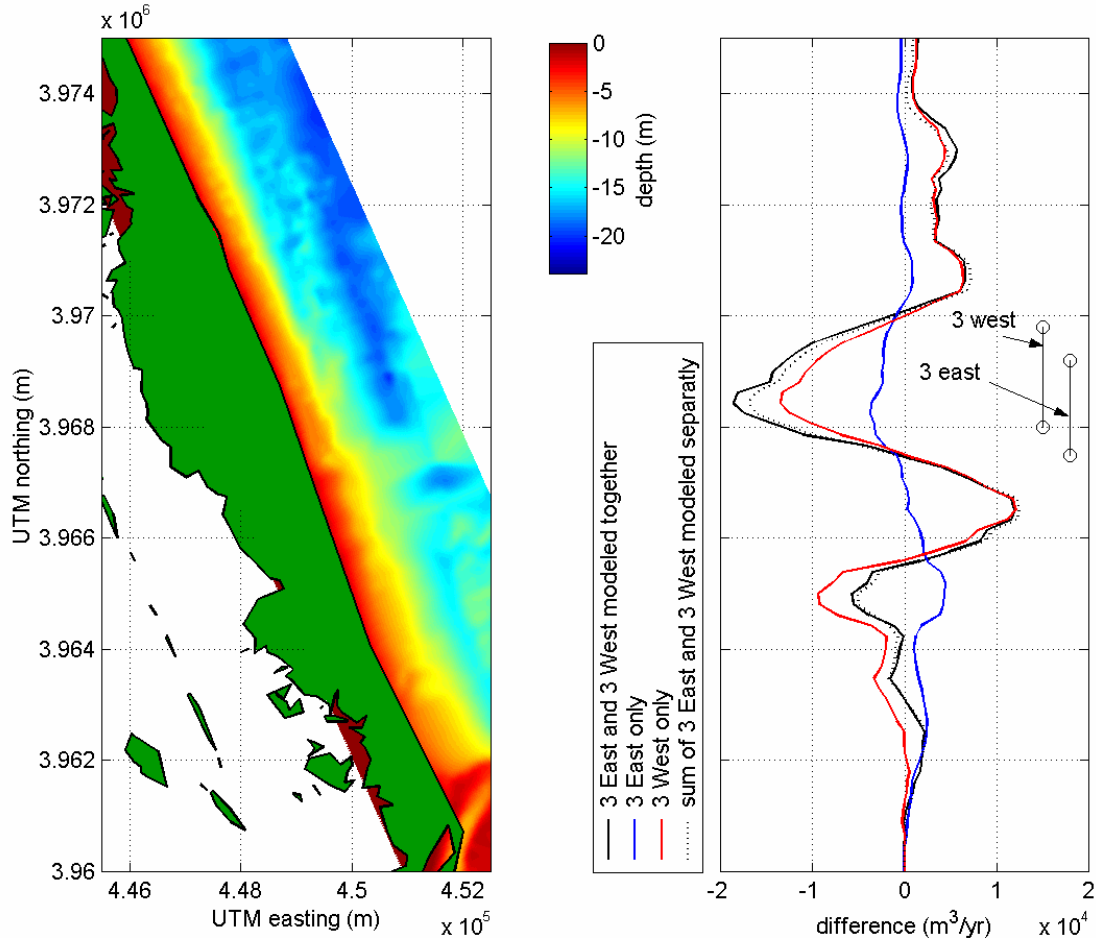


Figure 4-4. Plot of sediment transport potential difference between existing and post-dredging model runs including sites 3 East and 3 West (North Carolina) modeled together (solid black line) and separately (solid blue and red lines). The sum of transport difference computed for the separate runs of 3 East and 3 West (dotted black line) is presented for comparison to the curve of 3 East and 3 West modeled together (coefficient of determination, $r^2=0.990$).

4.2 MULTIPLE DREDGING EVENTS AT A SINGLE SITE

The second type of cumulative impact analysis evaluated the effect of multiple dredging events at a single site. As a borrow site is excavated to greater depths, the impact that it has on sediment transport along the shoreline will increase. Taken to extreme depths, the magnitude of impacts would be expected to reach some asymptotic value, but how these impacts vary through a range of reasonable depths was the emphasis of this study. In addition, the performance significance criterion established in Chapter 3 was tested to see what depths of excavation the criterion would be violated. Site M8, offshore southern New Jersey, was used in this analysis because the site is positioned close to shore and it has a relatively large perimeter. Therefore, deep excavations at this location would have pronounced (and therefore easily observable) effects on modeled sediment transport patterns at the shoreline.

Model runs were made for several excavated depths at Site M8, including 2, 3, 5, 7, and 9 m. The results of sediment transport potential calculations from these model runs are shown in Figure 4-5. This figure shows transport potential computed for Site M8 alone, without sites A1 and A2 included in the analysis. Included with the plot of transport difference is a shaded area that represents the envelope of maximum change allowed by the impact significance criterion. According to the significance criterion, excavation depths greater than 5 m would not be permitted, as the allowable limit criterion is exceeded along the shoreline south of Corsons Inlet. In this case, borrow site excavations greater than 5 m would be rejected no matter how small a section of shoreline that the significance criterion is exceeded.

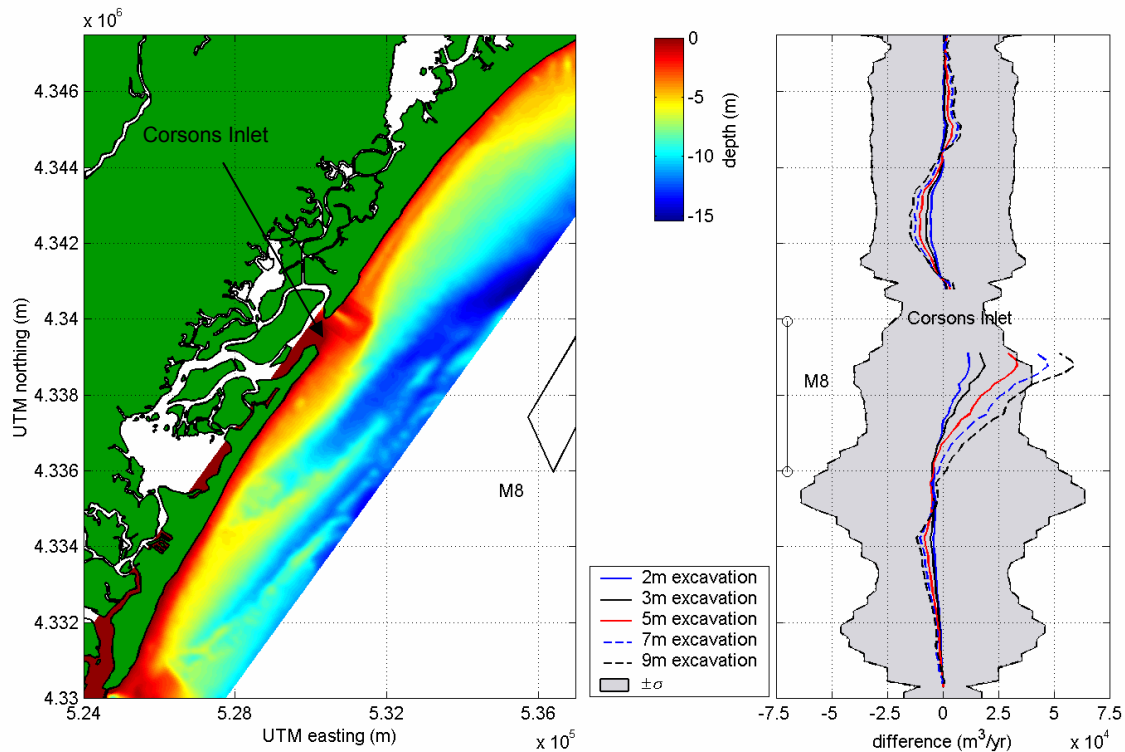


Figure 4-5. Plot of change in sediment transport potential computed for five excavated depths at site M8, offshore Corsons Inlet, New Jersey. The shaded area represents the envelope of maximum transport influence that is allowed by the impact significance criterion.

From the five model runs, change in transport potential is seen to vary linearly with depth of excavation. Figure 4-6 is a plot showing this relationship. The maximum-modeled differences are plotted with a least squares fit of the data. The fit correlates very well with the model data.

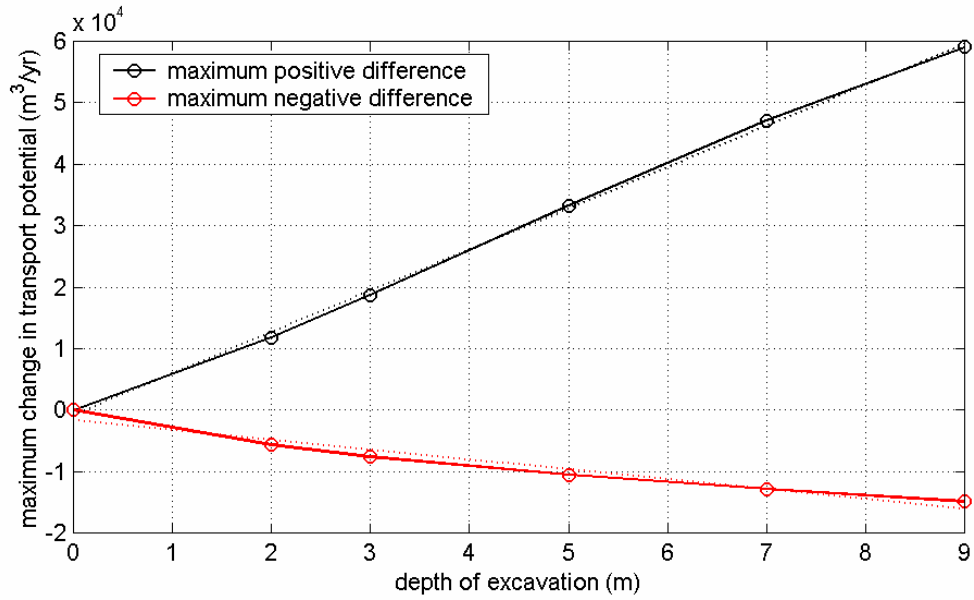


Figure 4-6. Plot of excavation depth *versus* change in modeled sand transport potential. Dotted lines represent linear least squares fits of the model output (for black line $r^2=0.999$, and for the red line $r^2=0.954$).

5.0 CONCLUSIONS

A four-phase approach was implemented to assess the potential for negative impacts from alterations to the local wave climate and sediment transport regime associated with offshore sand mining. First, a detailed evaluation of three readily-available, project-tested spectral wave models was conducted to determine the most effective simulation routine for predicting potential wave impacts due to dredging at offshore borrow sites. Second, a standard method was developed to qualify the significance of changes associated with borrow site excavation to determine the influence of borrow site geometry on local wave refraction and sediment transport patterns. The method developed for this study is based on historical wave climate variability, as well as local wave climate changes directly attributable to borrow site excavation. The third phase of the project focused on wave spectra development, wave transformation modeling, and coastal sediment transport calculations. Wave transformation modeling and sediment transport potential calculations were performed for existing and post-dredging bathymetric conditions at four sites along the U.S. East Coast. In addition, a site-specific determination of acceptable limits of borrow site impacts relative to sediment transport potential was determined for each case. The fourth and most significant phase of the project addressed potential cumulative effects of sand dredging from offshore sand borrow sites. These analyses were designed to determine how potential wave impacts at individual sites may interact to produce additive physical environmental effects along the coast.

5.1 WAVE MODEL ASSESSMENT

The primary quantitative technique used to evaluate nearshore processes is wave transformation modeling. Wave models have been developed to numerically solve the equations governing change in wave height and direction (through processes such as refraction, shoaling, and breaking). As better offshore wave data sets have been developed (both wave gauge and hindcast information), wave transformation models have become standard tools for evaluating the nearshore wave climate. The analysis techniques presented in this report involve spectral wave modeling, based primarily on wave hindcast information, combined with standard longshore sediment transport equations to evaluate impacts associated with offshore sand mining.

A comparison of numerical wave transformation models was performed to determine the most appropriate tool for assessing impacts associated with offshore borrow sites. The results of this analysis are shown in Appendix A. STWAVE, REF/DIF S, and SWAN were selected for this comparison because they all are spectral wave models and are easily accessible to the coastal engineering community. Spectral models can simulate real ocean wave conditions, where waves of varying frequency and direction propagate simultaneously through the same physical domain. These models can be described as either action density models, like STWAVE and SWAN, or as propagation models like REF/DIF S. Action density models use the distribution of energy in a spectrum to compute wave transformations, whereas propagation models propagate individual waves through the model domain, each with a different frequency and different initial direction.

Based on this model comparison and other factors, it is recommended that future MMS wave modeling projects use STWAVE. This recommendation is provided because:

- STWAVE is a fully spectral model with an efficient numerical scheme that requires a minimum of computing resources and which has acceptable accuracy when compared to physical model data.
- The USACE is actively updating STWAVE for its own use, and further improvements to the model will be made (e.g., diffraction is currently being added).
- STWAVE is able to compute mean wave angles, which is necessary input in sediment transport modeling, whereas currently available versions of REF/DIF S do not have a rigorous method for mean wave angle computations.
- Though the basic model approach of SWAN is very similar to STWAVE, it has many additional features that are not included in STWAVE. However, these advanced capabilities will not be required in the wave modeling projects for the MMS. Otherwise SWAN offers no performance advantage over STWAVE.

5.2 MANAGEMENT TOOL FOR ASSESSING IMPACT SIGNIFICANCE

To directly assess the impacts of offshore sand mining to coastal wave and sediment transport processes, an approach was developed that considers spatial (longshore) and temporal aspects of the local wave climate. This method uses a similar wave modeling effort as that applied by Basco (1999) and Byrnes et al. (1999); however, wave modeling is performed for the entire 20-year WIS record and five 4-year blocks of the WIS record. As such, temporal variations in wave climate are considered relative to average annual conditions. From these wave model runs, sediment transport potential curves are derived for average annual conditions (based on the full 20-year WIS record) and each 4-year period (based on the five 4-year wave records parsed from the full record). Based on this information, the average and standard deviation in calculated longshore sediment transport potential is determined every 200 m along the shoreline.

Assuming the temporal component of sediment transport potential is normally distributed, the suggested criterion for accepting or rejecting a potential borrow site is based on a range of one standard deviation about the mean. If any portion of the sediment transport potential curve associated with a sand mining project exceeds one standard deviation of the natural temporal variability (which incorporates 2/3 of the variability) in sediment transport potential, the site would be rejected. Although using the standard deviation of each 4-year period is more conservative than using a 1-year period, the methodology provides a useful indication of sediment transport variability relative to the natural system.

As a management tool for the MMS, this methodology provides several advantages over methods previously employed to assess the significance of borrow site impacts. The primary advantages include:

- Observed long-term shoreline change is compared with computed longshore change in sediment transport potential. Close comparison between these two curves indicates that longshore sediment transport potential calculations are appropriate for assessing long-term natural change. Therefore, this methodology has a model-independent component (observed shoreline change) used to ground truth the model results.

- The method is directly related to sediment transport potential and associated shoreline change. Therefore, impacts associated with borrow site excavation can be directly related to their potential influence on observed coastal processes (annualized variability in shoreline position).
- Site-specific temporal variability in wave climate and sediment transport potential is calculated as part of the methodology. For sites that show little natural variability in inter-annual wave climate, allowable coastal processes impacts associated with borrow site dredging similarly would be limited, and *vice versa*. In this manner, the inter-annual temporal component of the natural wave climate is a major component in the determination of impact significance.
- Similar to methodologies incorporated in previous MMS studies, the longshore spatial distribution of borrow site impacts is considered. However, the allowable limit of longshore sediment transport variability is computed from the temporal component of the analysis. Therefore, the final results of this analysis provide a spatially-varying envelope of allowable impacts in addition to the modeled impacts directly associated with borrow site excavation. The methodology accounts for spatial and temporal variability in wave climate, as well as providing a defensible means of assessing significance of impacts relative to site-specific conditions.

5.3 WAVE AND SEDIMENT TRANSPORT ANALYSIS

Spectral wave input for STWAVE model runs performed for each of the study areas was developed using WIS hindcast data for borrow sites offshore southern New Jersey, Dam Neck/Sandbridge Beach (Virginia), Dare County North Carolina, and Cape Canaveral (Florida). Alternatively, for the Sandbridge Shoal area offshore southeastern Virginia, a five-year spectral wave data record from an offshore buoy maintained by the National Data Buoy Center (NDBC) was used to develop model input spectra. The NDBC data were used over available WIS data for southeastern Virginia because the buoy record was adequately long and represented actual long-term wave conditions in the area. Along with input spectra, bathymetry grids were developed for existing and post-dredging scenarios. For each of the four modeled areas, two coarse grids were developed that have the same geographical coverage and differ only by modifications to bathymetry in the borrow area. The maximum cumulative dredged volumes and mean depths for the modeled borrow sites for each region are shown in Table 3-6.

Overall, post-dredging wave model output for the four study sites illustrates reduced wave heights landward of borrow sites and increased wave heights at the longshore limits of the borrow site. This effect is more pronounced for cases with larger wave heights and longer periods. As waves propagate across a borrow site (deeper water than the surrounding area), wave refraction bends waves away from the center of the borrow site and toward the shallower edges. The net effect is to create a shadow zone of reduced wave energy immediately landward of the borrow site and a zone of increased wave energy updrift and downdrift of the borrow site. The effect of this redirected wave energy is to alter nearshore wave patterns responsible for longshore sediment transport.

By developing average annual sediment transport potential curves from wave modeling results, the influence of borrow site excavation on nearshore sediment transport quantitatively can be quantified. Comparisons of average annual sediment transport potential were performed for existing and post-dredging conditions to indicate

the relative impact of dredging to longshore sediment transport processes. Sediment transport potential is a useful indicator of shoreline impacts caused by offshore borrow sites because the computations include the borrow site influence on wave height and direction.

5.4 APPLICATION OF MANAGEMENT TOOL

To establish useful criteria for estimating impacts of sand mining on the nearshore littoral system, a comparison of sediment transport potential analysis and long-term shoreline change was performed at each of the four sand borrow sites. The analysis provided a quantitative method for determining whether longshore wave-induced transport was responsible for observed shoreline change and whether the long-term shoreline change trends were consistent with the shorter time-period (20-year) sediment transport potential analysis. In general, the comparison indicated that the longshore gradient in computed wave-induced sediment transport followed similar trends as observed long-term shoreline change for nearly all cases. Exceptions occurred at locations where STWAVE modeling was not applicable (areas where wave diffraction was important) or where wave-induced processes may not govern sediment transport (in the vicinity of tidal inlets).

For the southern New Jersey shoreline, erosion and accretion trends are predicted well at all locations, including in the vicinity of tidal inlets. Along the southeastern Virginia coast, model results predict similar trends as observed long-term shoreline change, where much of the coastline is stable or slightly erosional. The location of highest erosion rates is predicted accurately by the modeling analysis. Overall agreement between modeled trends and measured shoreline change also was achieved for the North Carolina coast north of Oregon Inlet. Discrepancies between predicted and measured results likely are a result of the significant historical migration of Oregon Inlet. Along the Cape Canaveral coast, STWAVE modeling was not capable of evaluating changes in wave climate resulting from wave diffraction processes across Canaveral Shoals. In addition, these shoals likely serve as a sediment source to the beach in this region. South of Port Canaveral, away from the influence of the Cape's topographic and bathymetric features, the trends predicted by the sediment transport potential model match well with historical shoreline change.

Because modeled longshore gradients in sediment transport potential generally matched the trends in observed shoreline change, wave and sediment transport modeling provided an appropriate basis for evaluating long-term impacts associated with offshore sand mining. The methodology utilized to determine impact significance depended on a region's site-specific wave characteristics, where the method considered temporal (inter-annual) and spatial variability in wave conditions. Because the natural variability in inter-annual shoreline migration changes along the coast, certain portions of a given shoreline naturally will be more tolerant of alterations to the wave climate and associated sediment transport. The methodology used to evaluate borrow site impacts provided a reliable quantitative technique for developing acceptable site-specific limits associated with changes in sediment transport potential. Based on site-specific analyses for each of the four sites, the impacts associated with dredging at all borrow sites were deemed acceptable. However, due to limitations with the wave modeling effort, further analyses would be required to accurately assess impacts caused by dredging for the shoreline north of Port Canaveral.

5.5 CUMULATIVE EFFECTS

To evaluate cumulative impacts associated with incremental dredging of a single site and/or the combined effects of dredging borrow sites in the same region, a cumulative assessment strategy was developed. For evaluating cumulative impacts of sand dredging at an offshore borrow site, two types of borrow site configurations were investigated. The first group of cumulative impacts involves the interaction of multiple sites in close proximity, such that they have overlapping areas of shoreline impact. The second grouping of cumulative impacts involves multiple dredging events at a single site.

For the analysis of borrow sites in close proximity to each other, two case studies were evaluated: 1) Sandbridge Shoal, offshore southeastern Virginia, and 2) offshore North Carolina, in the vicinity of Oregon Inlet. At Sandbridge Shoal, the two borrow sites are oriented side-by-side and parallel to the shoreline. For offshore North Carolina, sites 3 East and 3 West are oriented front-to-back in a line perpendicular to the shoreline. To evaluate the influence of individual borrow sites relative to the combined influence of both borrow site excavations, wave model runs were performed for cases where each borrow site was excavated individually and both borrow sites were excavated in a single event. Annual sediment transport calculations were then performed for each wave modeling scenario. Superimposing the effects of individual borrow site excavations onto the sediment transport potential curve developed from the combined excavation model run was used as the basis for comparison. The results from these two cases (Virginia and North Carolina) suggest that borrow sites located in close proximity illustrate additive impacts. Therefore, the influence of multiple sites on sediment transport along a coastline is a simple additive effect, rather than a more complicated non-linear effect or amplification.

The second type of cumulative impact analysis evaluated the effect of multiple dredging events at a single site. As a borrow site is excavated to greater depths, the impact that it has on sediment transport along the shoreline will increase. Taken to extreme depths, the magnitude of impacts would be expected to reach some asymptotic value, but how these impacts vary through a range of reasonable depths was the emphasis of this study. In addition, the performance significance criterion established in Chapter 3 was tested to see what depths of excavation the criterion would be violated. Site M8, offshore southern New Jersey, was used in this analysis because the site is positioned close to shore and it has a relatively large perimeter. Therefore, deep excavations at this location would have pronounced (and therefore easily observable) effects on modeled sediment transport patterns at the shoreline. From the five model runs, change in transport potential varied linearly with depth of excavation.

6.0 REFERENCES

- Basco, D.R., 1999. A methodology and criteria to assess the impacts of sand volume removed in federal waters on the nearshore wave climate. Coastal Engineering Centre, Old Dominion University, Norfolk, VA.
- Battjes, J.A. and J.P. Janssen, 1978. Energy loss and set-up due to breaking of random waves. Proc. 23rd Int. Conf. Coastal Engineering, ASCE, pp. 569-587.
- Bretschneider, C.L., 1968. Significant waves and wave spectrum. Ocean Industry, pp. 40-46.
- Byrnes, M.R. and M.W. Hiland, 1994. Compilation and analysis of shoreline and bathymetry data (Appendix B). In: N.C. Kraus, L.T. Gorman, and J. Pope (editors), Kings Bay Coastal and Estuarine Monitoring and Evaluation Program: Coastal Studies. Technical Report CERC-94-09, Coastal Engineering Research Center, Vicksburg, MS, p. B1-B90.
- Byrnes, M.R. and N.C. Kraus, 1999. Regional sediment transport patterns adjacent to Canaveral Harbor, Florida. In: N.C. Kraus and W.G. McDougal (editors), Coastal Sediments '99, American Society of Civil Engineers, New York, NY, pp. 750-760.
- Byrnes, M.R., R.M. Hammer, B.A. Vittor, J.S. Ramsey, D.B. Snyder, K.F. Bosma, J.D. Wood, T.D. Thibaut, and N.W. Phillips, 1999. Environmental Study of Identified Sand Resource Areas Offshore Alabama: Volume I: Main Text, Volume II: Appendices. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 99-0052, 326 pp. + 132 pp. appendices.
- Byrnes, M.R., R.M. Hammer, B.A. Vittor, J.S. Ramsey, D.B. Snyder, J.D. Wood, K.F. Bosma, T.D. Thibaut, N.W. Phillips, 2000. Environmental Survey of Potential Sand Resource Sites: Offshore New Jersey. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 2000-052, Volume I: Main Text 380 pp. + Volume II: Appendices 291 pp.
- Byrnes, M.R., R.M. Hammer, B.A. Vittor, J.S. Ramsey, D.B. Snyder, J.D. Wood, T.D. Thibaut, N.W. Phillips, 2001. Collection Of Environmental Data Within Sand Resource Areas Offshore North Carolina And The Implications Of Sand Removal For Coastal And Beach Restoration. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 2000-056, Volume I: Main Text + Volume II: Appendices.
- Dean, R.G., 1977. Equilibrium beach profiles: U.S. Atlantic and Gulf coasts. Dept of Civil Engineering, Ocean Engineering Rept. No. 12, Univ. of Delaware, Newark, DE.

- Goda, Y., 1985. Random Seas and Design of Maritime Structures. University of Tokyo Press, Tokyo, Japan.
- Hammer, R.M., B.J. Balcom, M.J. Cruickshank, and C.L. Morgan, 1993. Synthesis and Analysis of Existing Information Regarding Environmental Effects of Marine Mining. Final Report by Continental Shelf Associates, Inc. for the U.S. Department of the Interior, Minerals Management Service, Office of International Activities and Marine Minerals, Herndon, VA, OCS Study MMS 93-0006, 392 pp.
- Hoffman, C.W., 1998. Preliminary Assessment of Potential Sand Resource Areas Offshore of Nags Head, Kitty Hawk, and Kill Devil Hills, North Carolina. North Carolina Geological Survey, Raleigh, NC, 12 pp.
- Inman, D.L. and R. Dolan, 1989. The Outer Banks of North Carolina: Budget of sediment and inlet dynamics along a migrating barrier system. *Journal of Coastal Research*, 5(2): 193-237.
- Jensen, R.E., 1983. "Methodology for the calculation of a shallow-water wave climate." WIS Report 8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Kamphuis, J.W., 1990. Alongshore sediment transport rate. Proc. 22nd Coastal Engineering Conference, ASCE.
- Kimball, S.M. and J.K. Dame, 1989. Geotechnical Evaluation of Sand Resources on the Inner Shelf of Southern Virginia. Final Report to the City of Virginia Beach, Two Volumes. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.
- Kimball, S.M., J.K. Dame, and C.H. Hobbs, 1991. Investigation of Isolated Sand Shoals on the Inner Shelf of Southern Virginia. Final Contract Report. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA, 73 pp. plus Appendices.
- Kraus, N.C., M.R. Byrnes, and A.L. Lindquist, 1999. Coastal processes assessment for Brevard County, Florida, with special reference to test plaintiffs. Technical Report CHL-99-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- McKinney, T.G., W.L. Stubblefield, and D.J.P. Swift, 1974. Large-scale current lineations, central New Jersey shelf: Investigations by sidescan sonar. *Marine Geology*, 17: 79-102.
- Mitsuyasu, H. et al., 1975. Observation of the directional spectrum of ocean waves using a cloverleaf buoy. *Journal of Physical Oceanography*, 5(4), 750-760.
- National Ocean Service, 1998. Geophysical data system for hydrographic survey data. Version 4.0, National Ocean Service, Washington, DC.
- Rosati, J.D., and N.C. Kraus, 1991. Practical Considerations in Longshore Transport Calculations. CETN II-24, U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS, 6 pp.

- Smith, J.M., D.T. Resio, and A.K. Zundel, 1999. STWAVE: Steady-state spectral wave model. Instruction Report CHL-99-March 1999, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Svendson, I.A., and I.G. Jonsson, 1976. Hydrodynamics of Coastal Regions. Technical University of Denmark, 285 pp.
- Swift, D.J.P., J.W. Kofoed, F.P. Salsbury, and P. Sears, 1972. Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey (editors), Shelf Sediment Transport: Process and Pattern. Dowden Hutchinson, and Ross. Stroudsburg, PA, p. 499-575.
- USACE, 1984. Shore Protection Manual. U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg MS.
- USACE, 1999. Final Environmental Assessment and Finding of No Significant Impact, Canaveral Shoals Borrow Area II. USACE-Jacksonville District, Jacksonville, FL, 13 pp.
- Williams, S.J., 1987. Geological Framework and Sand Resources of Quaternary Deposits Offshore Virginia, Cape Henry to Virginia Beach. U.S. Geological Survey Open-File Report 87-667, 60 pp.