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Wave Climate and Littoral Sediment Transport Potential, Cape Fear River Entrance and Smith Island to Ocean Isle Beach, North Carolina

by *Edward F. Thompson, Lihwa Lin, Doyle L. Jones*

Prepared for U.S. Army Engineer District, Wilmington

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Preface

This study was authorized by the U.S. Army Engineer District, Wilmington (SAW), and was conducted by personnel of the Coastal Hydrodynamics Branch (CHB), Navigation and Harbors Division (NHD), Coastal and Hydraulics Laboratory (CHL), of the U.S. Army Engineer Research and Development Center (ERDC). The study was conducted during the period May 1998 through April 1999. Messrs. William A. Dennis and James T. Jarrett, SAW, oversaw progress of the study.

Dr. Edward F. Thompson, CHB, was the WES point of contact for the study. This report was prepared by Dr. Thompson, Dr. Lihwa Lin, and Mr. Doyle L. Jones, all of CHB. Ms. Mary A. Cialone and Mr. Mark B. Gravens, both of Coastal Processes Branch, Coastal Sediments and Engineering Division, CHL, provided valuable consultation. Direct supervision was provided by Dr. Martin C. Miller, former Chief, CHB. General supervision was provided by Mr. C. E. Chatham, Chief, NHD, Mr. Charles C. Calhoun, Jr., former Assistant Director, CHL, and Dr. James R. Houston, Director, CHL. Mr. William A. Dennis, SAW, provided helpful information about littoral transport processes around Fort Fisher and New Inlet, NC.

At the time of publication of this report, Dr. Lewis E. Link was Acting Director, and COL Robin R. Cababa, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02832	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
knots (international)	0.5144444	meters per second
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609347	kilometers

1 Introduction

Background

Brunswick County, North Carolina, encompasses a section of the Atlantic Coast stretching from the South Carolina border to slightly beyond Cape Fear. This study covers most of the Brunswick County coast, between 78 deg 25 min west longitude and Cape Fear (Figure 1). Beach areas include Ocean Isle Beach, Holden Beach, Long Beach, Yaupon Beach, Caswell Beach, and Bald Head Island.

The Brunswick County coastline consists of a succession of sandy beaches punctuated by occasional inlets. The general shape of the coastline is a gentle, south-facing arc, abruptly changing to an east-facing orientation east of Cape Fear. The Cape Fear land feature extends toward the south southeast into Frying Pan Shoals, a long, shallow feature that blocks much of the wave energy coming from the North Atlantic Ocean. On the landward side, Cape Fear and Bald Head Island connect through marsh areas into Smith Island.

Brunswick County beaches experience active movement of littoral sediment in both eastward and westward directions, depending on incident wave conditions. Dynamic shoal features accompany each inlet. The net impact of littoral transport emerges as sediment accretion in some coastal areas and persistent erosion in some other areas.

A deep draft navigation channel approaches from the southwest and passes just west of Smith Island. The channel, leading into Cape Fear River and Wilmington Harbor, was originally a natural river channel, now enhanced and stabilized by periodic dredging. The existing Federally-maintained entrance channel is 12.2 m (40 ft) deep, 152 m (500 ft) wide, and about 9.6 km (6 miles) in length between open water and the Cape Fear River mouth.

The existing navigation channel from the Atlantic Ocean into Cape Fear River and Wilmington Harbor cannot accommodate the larger ships increasingly being used for maritime trade. A deepened and possibly realigned entrance channel is being considered to help provide access for larger ships. Changes to the entrance channel may expose ships to a different wave climate, especially if the alignment changes and waves tend to approach from a different direction relative to the ships.

Plans for upgrading the entrance channel include a relocation of the offshore area used for placement of dredged material. The new Offshore Dredged Material Disposal Site

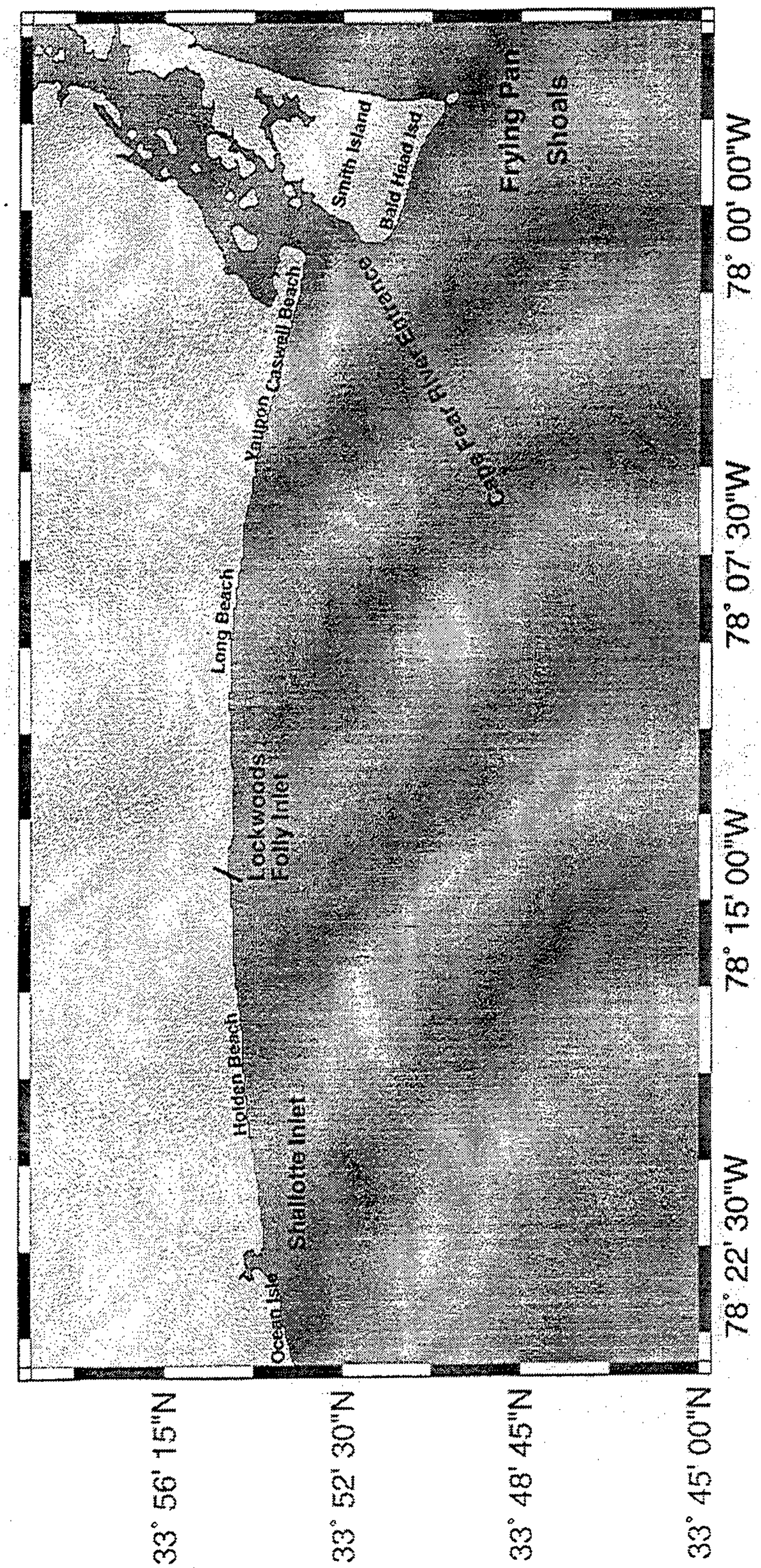

Figure 1. Study area location map

(ODMDS) is planned to be about 12-20 km (7-12 miles) south of the western tip of Bald Head Island, though the precise confines are yet to be determined. Wave climate information in the ODMDS area will be important for evaluating stability of bottom material.

The navigation channel presence and its influence on shoaling patterns has likely affected littoral transport along nearby beaches. The U.S. Army Engineer District, Wilmington (SAW), needs information about the impact of the present channel and, more importantly, the impact of any significant changes to the channel on littoral transport.

The present study was conducted to assist SAW with wave climate and littoral transport information needed in conjunction with design of the Wilmington Harbor deepening project and with preparation of General Reevaluation Reports (GRR). The GRR requirement in this study extends from the middle of Ocean Isle Beach (west longitude 78 deg 25 min) to Bald Head Island. The study was actually conducted in two phases, since SAW initially funded the navigation channel wave climate tasks and later provided funding for littoral transport tasks.

Need and Objectives

Wave climate information in existing and proposed entrance channels is needed to evaluate impacts on ship motion. This information will be used in a ship simulator study of vertical motion due to waves.

Littoral transport information is needed to evaluate impacts of the existing and proposed navigation channels on stability of adjacent beaches and for preparation of GRR reports.

In response to these needs, the objectives of this study are: 1) to provide wave climate information in existing and proposed navigation channels, with potential for extracting similar information at the ODMDS, and 2) to provide estimates of longshore sediment transport potential rates and differences between existing, historical, and proposed configurations.

Study Approach

The study described in this report was performed by the U.S. Army Engineer Waterways Experiment Station (WES), Coastal and Hydraulics Laboratory (CHL). The approach consisted of the following components:

a. Evaluate offshore wave climate.

b. Use a numerical model to transform offshore wave climate to entrance channel and coastal areas, including existing, historical, and proposed configurations; include the anticipated new ODMDS area within the model domain.

c. Estimate littoral transport potential along the coast, including differences between existing and other configurations.

Offshore wind wave and swell climate was investigated primarily with numerical hindcast information covering the 20-yr time period 1976-95. Buoy measurements were used to help validate the hindcasts. The offshore wave climate evaluation is presented in Chapter 2.

A numerical wave model was set up to transform offshore wave conditions around Frying Pan Shoals and other shallow bathymetry. The numerical model used for the studies, STWAVE, is a standard WES tool for shallow water wave transformation. Development of the numerical model grids, model output stations, longshore sediment transport calculation procedures, and other aspects of the modeling approach are described in Chapter 3. In addition to existing bathymetry, the following bathymetric configurations were included:

a. Historical Bathymetry. Bathymetric survey data from the year 1872 were used to represent historical ebb tide delta conditions, prior to the establishment of a dredged entrance channel.

b. Plans 1 and 2 (Figure 2). Plan 1 and 2 entrance channels are deepened to 12.8 m (42 ft) and widened to 183 m (600 ft). The outer entrance channel is realigned along 15 deg W of S. The realigned channel joins the existing channel about 2.4 km (1.5 miles) seaward of the Cape Fear River mouth. Plan 2 differs from Plan 1 only in that it has a widener inside the turn from the realigned channel into the existing channel.

c. Plans 1 and 2 with Adjusted Ebb Tide Shoals. The natural adjustment of shoal configurations around Cape Fear River entrance in response to the Plan 1/Plan 2 entrance channel was estimated by SAW. This anticipated equilibrium configuration of the ebb tide delta is expected to be more representative of the ultimate impact of the proposed channel.

d. Plan 3 (Figure 2). Plan 3 is a straight entrance channel which joins the existing channel at a point east of Caswell Beach. The Plan 3 alignment is 20 deg W of S. As with other plans, Plan 3 channel depth and width are 12.8 m (42 ft) and 183 m (600 ft).

Study results are presented in Chapter 4 and 5. Navigation channel results needed for ship motion studies are summarized in Chapter 4. Littoral transport results needed for assessing navigation channel impact on erosion and accretion of adjacent beaches and for preparation of General Reevaluation Reports are presented in Chapter 5.

Conclusions and recommendations are given in Chapter 6. This chapter is followed by references and appendices with detailed information supporting the main report.

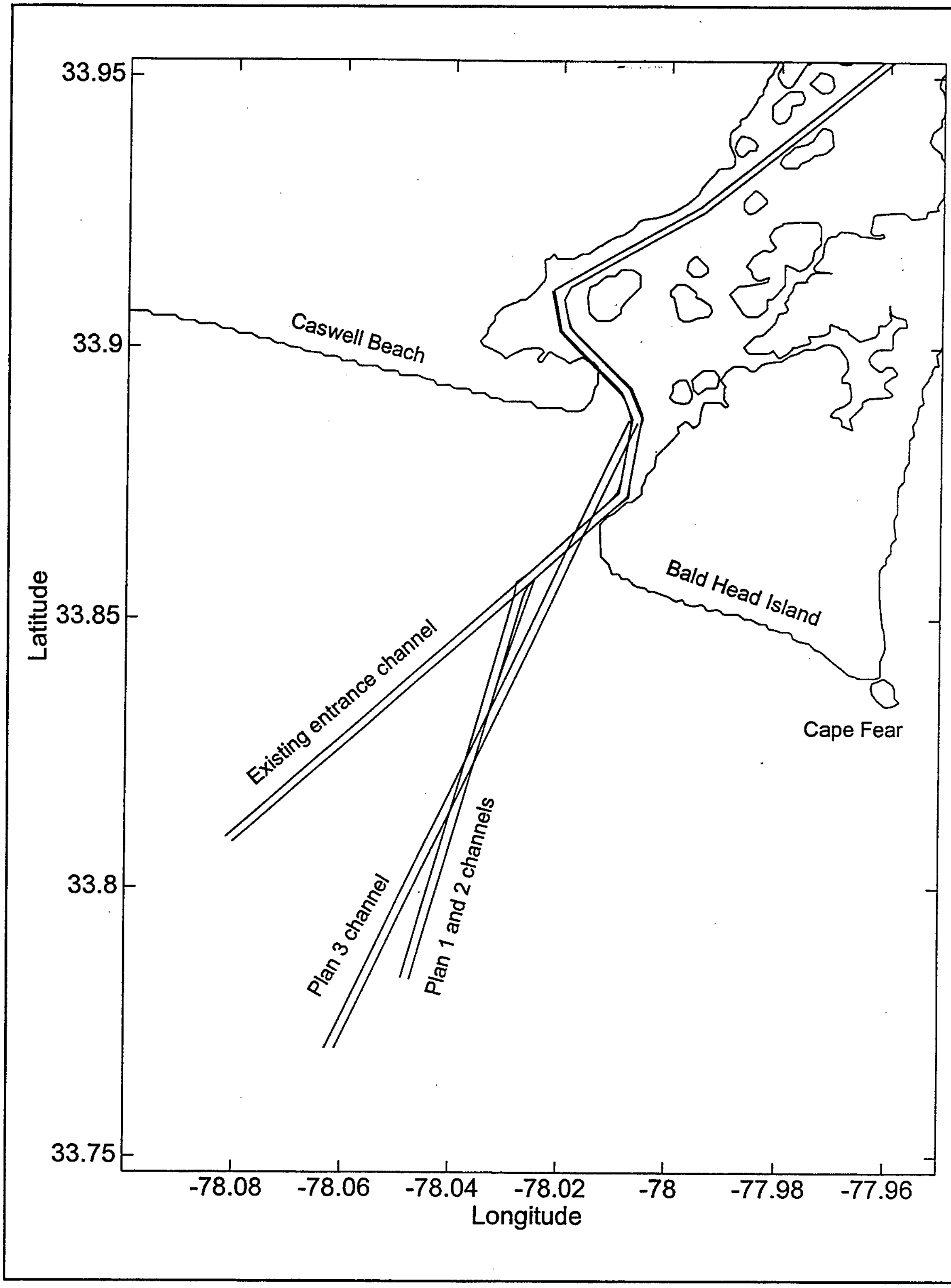

Figure 2. Existing and proposed entrance channel configurations

2 Offshore Wave Climate

Evaluation of the incident wave climate is a critical first step in nearshore wave climate and littoral transport studies. Ideally, a long-term, high-quality hindcast is available with at least a few years of concurrent deep water directional wave measurements in the same area to validate the hindcast. This study used a relatively recent 20-yr hindcast, as discussed in the following section, but no nearby directional measurements were available for confirmation. Previous studies of this general area have used a variety of sources for wave information, including nondirectional gages mounted on fishing piers, shipboard wave observations, and Coast Guard station observations (SAW 1973; Jarrett 1977).

WIS Hindcasts

The WES Wave Information Studies (WIS) has developed wave information along U.S. coasts by computer simulation of past wind and wave conditions. This type of simulation is termed hindcasting. The present hindcast information base consists of two 20-yr blocks. WIS produced the first block, covering years 1956-75, in the early 1980's (Corson et al. 1982). The second block, covering years 1976-95, was produced in the mid 1990's (Brooks and Brandon 1995). The more recent hindcast is considered to be more reliable since it was produced using an improved wave hindcast model and results were evaluated against an extensive array of wave measurements which were not available during the initial study. Also, the 1976-95 hindcasts include tropical storms whereas the previous hindcasts do not.

The 1976-95 WIS parameters are available at 3-hr intervals over the 20-yr period. At each 3-hr interval, a number of wave parameters are given. Parameters typically used to represent waves are significant wave height, H_s, peak spectral period, T_p, and peak direction, θ_p. WIS parameters of importance to this study include overall H_s, T_p, and θ_p, and, when more than one wave component is present (such as a locally-generated sea and a swell coming from a distant storm), H_s, T_p, and θ_p values for primary and secondary wave components.

Hindcast information for the period 1976-1995 from two nearby WIS stations, AU2041 and AU2042, was used to estimate offshore wave climate. Station AU2041 is located about 10 km (6 miles) south of the mouth of the Cape Fear River entrance and Station AU2042 is located about 24 km (15 miles) northeast of Cape Fear (Figure 3). Hindcast information at the two stations does not account for the sheltering effect of Bald Head Island since

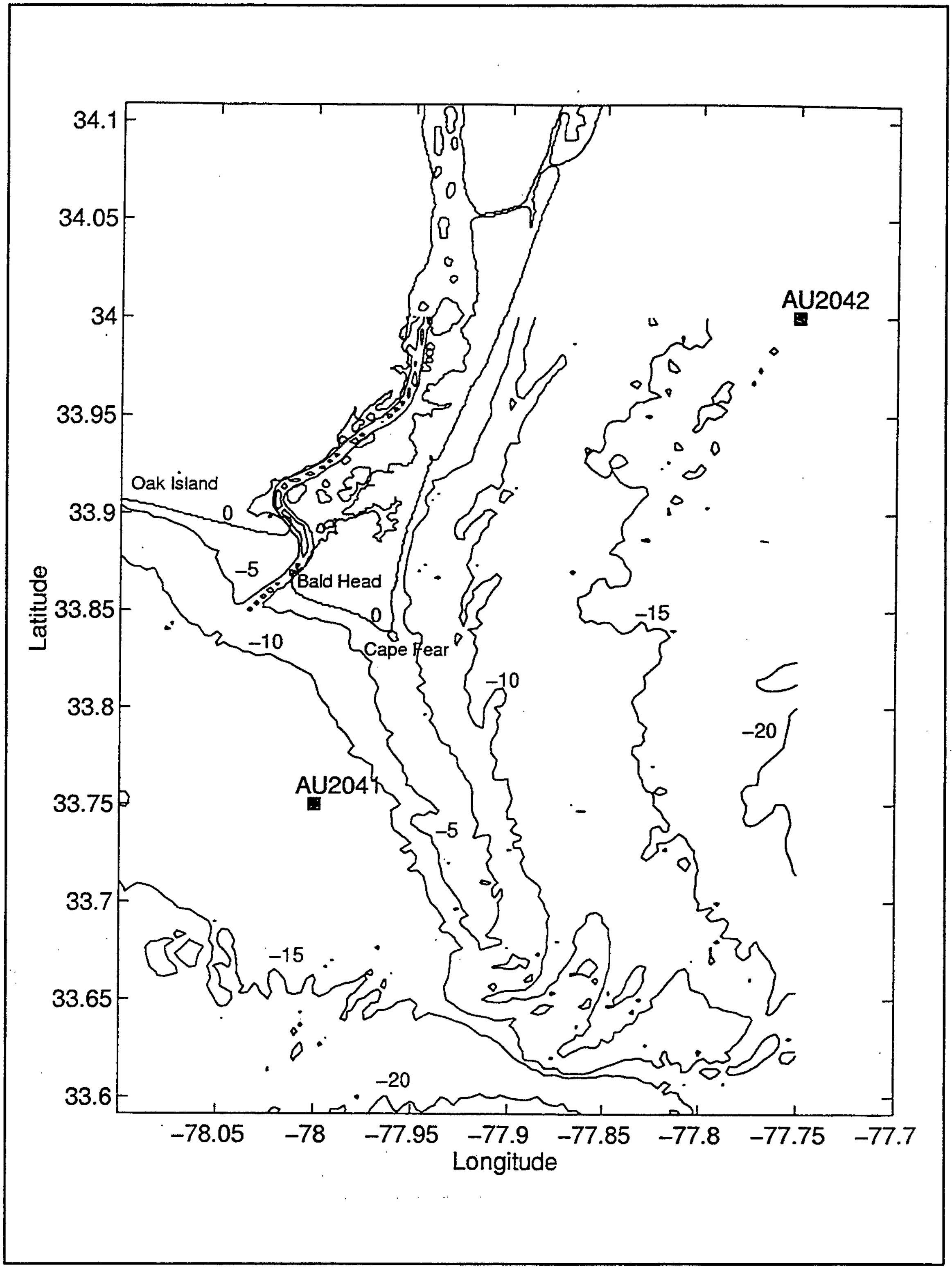

Figure 3. Bald Head Island complex and location of WIS stations AU2041 and AU2042

the hindcast was conducted on a rather coarse grid (1/4-deg) covering the continental shelf along the eastern U.S. coast. Also, wave refraction around Frying Pan Shoals, which extends over 32 km (20 miles) from Cape Fear to the south-southeast, is not represented in WIS hindcasts. Since sheltering of Bald Head Island and refraction due to Frying Pan Shoals are critical to waves in the study channel and coastal areas, they need to be included in wave climate analysis.

For studies of wave climate in the navigation channel, percent occurrence tables of significant wave height, peak period, and direction were constructed for the AU2041 and AU2042 stations (Appendix A). Figures 4 and 5 show waverose diagrams for the two stations. At Station AU2042, waves typically approach the study area from between 101.25 and 123.75 deg azimuth. At Station AU2041, the dominant direction is shifted to between 123.75 and 146.25 deg azimuth. The shift of wave direction is caused by refraction over the continental shelf as waves approach shore.

A similar approach was used for littoral transport studies, except that the primary and secondary wave components were taken separately. Breaking wave height and direction are critical to longshore sediment transport. Hence, it was useful to retain information about both components of the offshore wave climate. The primary component wave rose for Station AU2041 is very similar to Figure 4. The secondary component wave rose shows an increased frequency of southwest wave conditions (Figure 6). These waves tend to move sediment toward the east along most of the study beaches. Even though wave heights are relatively low, it was desirable to include the secondary components for littoral transport studies.

NDBC Buoy 44010

The offshore directional wave measurement station nearest the study area is National Data Buoy Center (NDBC) buoy 44010, located at 36.0 N, 75.0 W (Figure 7). Water depth at the buoy is 47.5 m (156 ft). Directional wave data were available for about one year, from July 94 to June 95. Data were collected hourly for 1024 sec at a rate of 1 Hz.

Although NDBC buoy 44010 is distant from the study area, it provides a valuable indication of the WIS wave climate quality. Wave roses for buoy 44010 and for the nearest WIS station (AU2055) are shown in Figures 8 and 9. The buoy and WIS stations indicate very similar directional wave height climates. The wave rose for the WIS station east of the study area (AU2042) is quite consistent with buoy 44010, considering that the WIS station is sheltered by the North Carolina coast from directions north of about 70 deg azimuth. Hence the more northerly directions common at buoy 44010 appear as waves from the east and east-southeast at station AU2042. Also, wave heights in the more exposed buoy 44010 location tend to be higher than at the study area. Overall, the study area offshore wave climate as represented by WIS stations AU2041 and AU2042 appears acceptable.

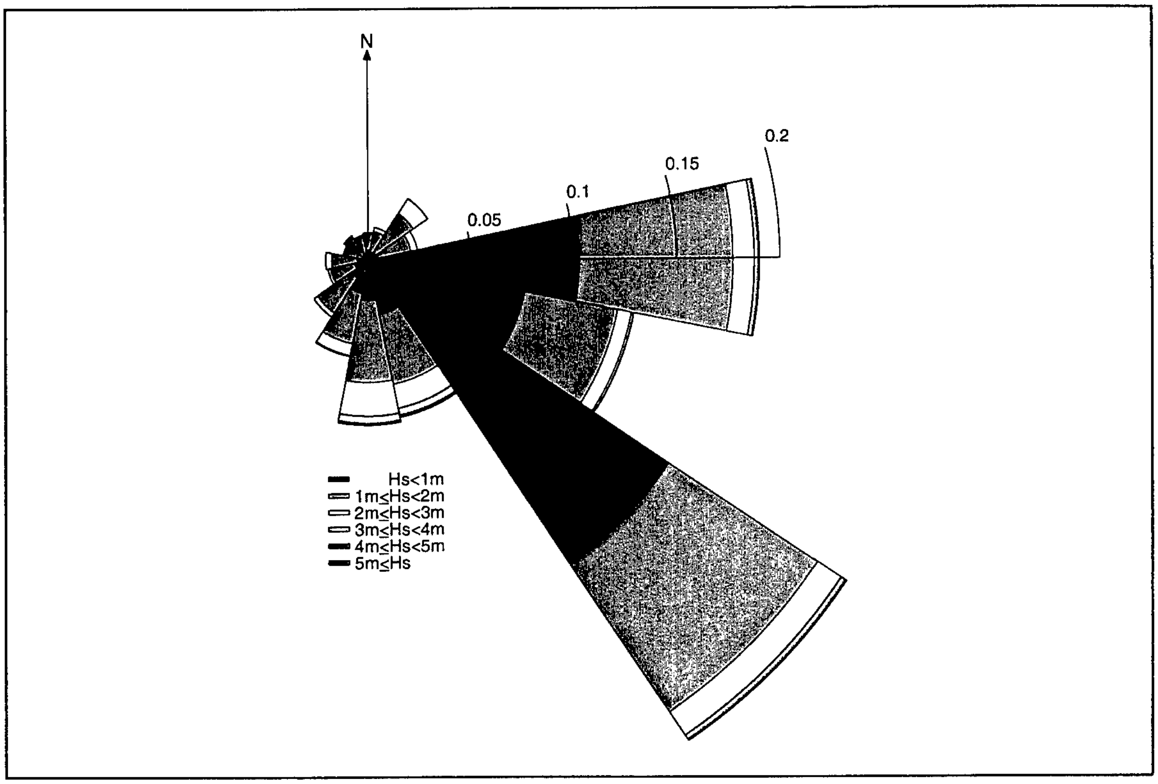

Figure 4. Waverose, WIS station AU2041

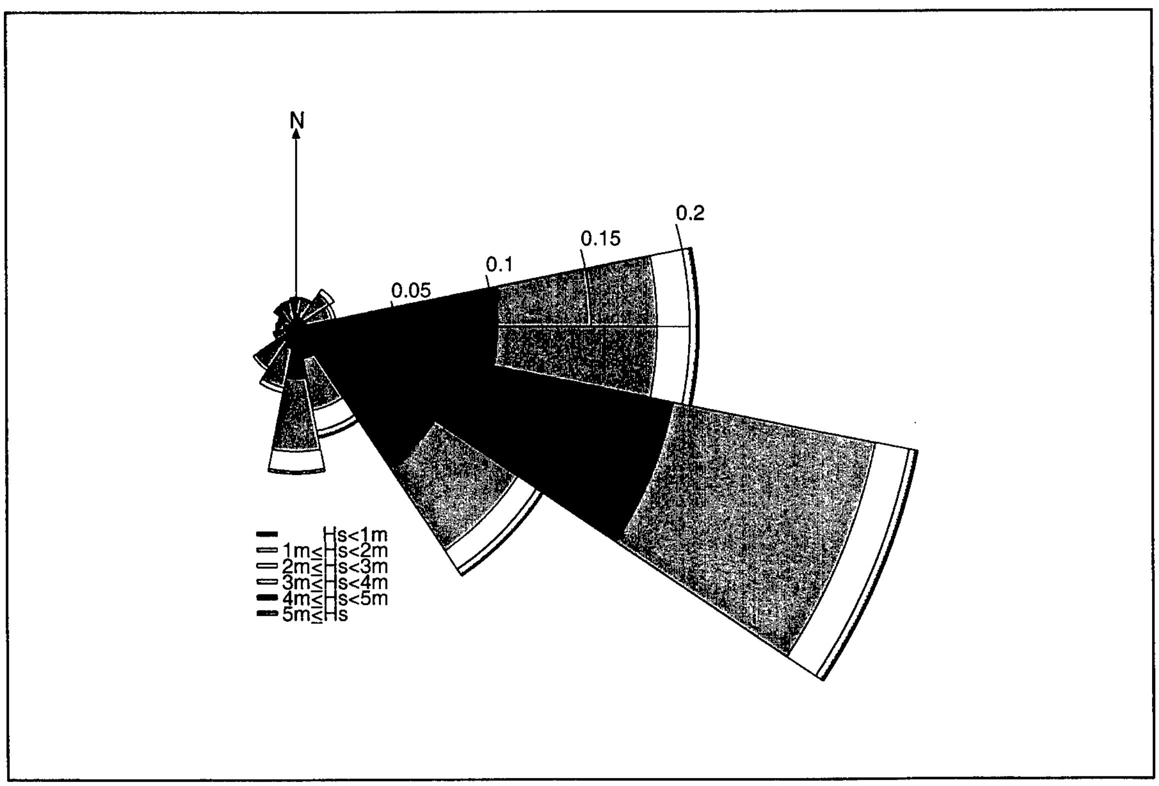

Figure 5. Waverose, WIS station AU2042

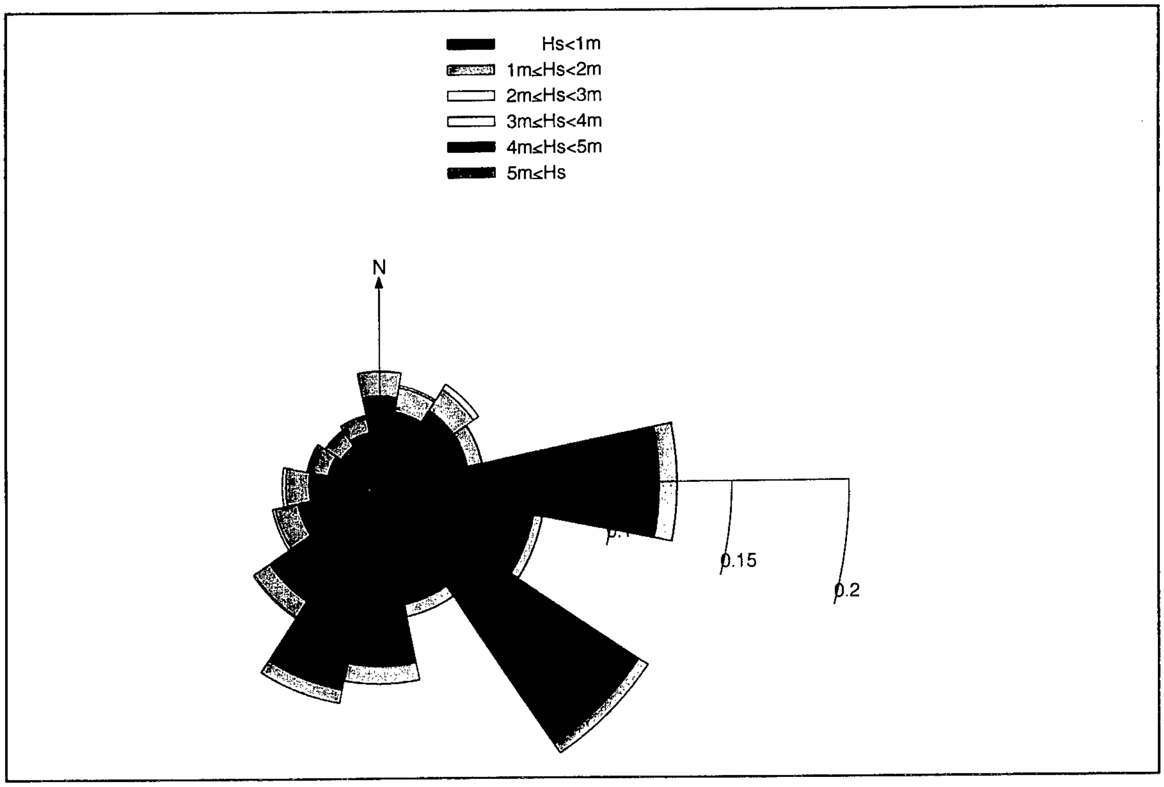

Figure 6. Waverose, WIS station AU2041, secondary wave components

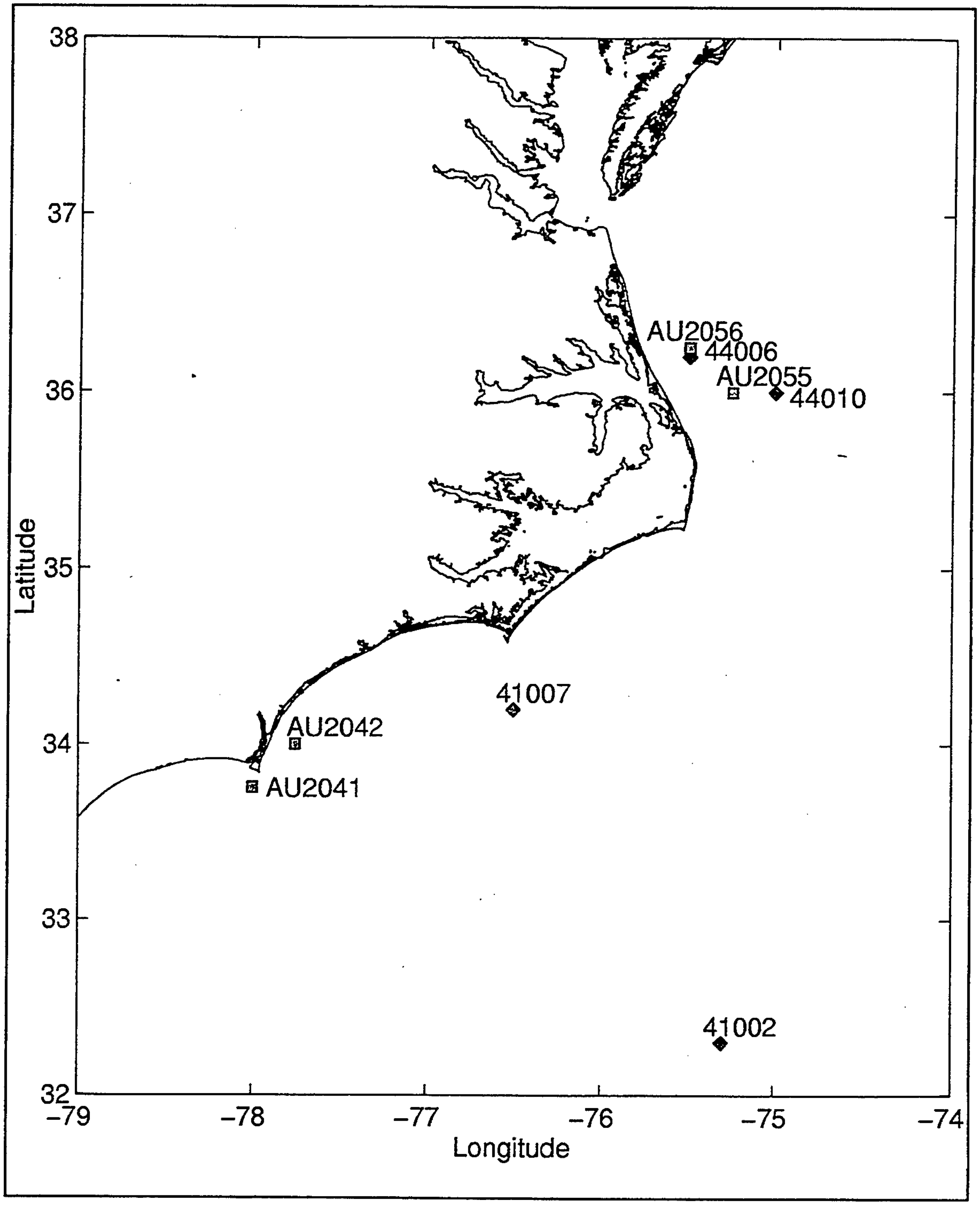

Figure 7. Location map, NDBC buoys and selected WIS stations

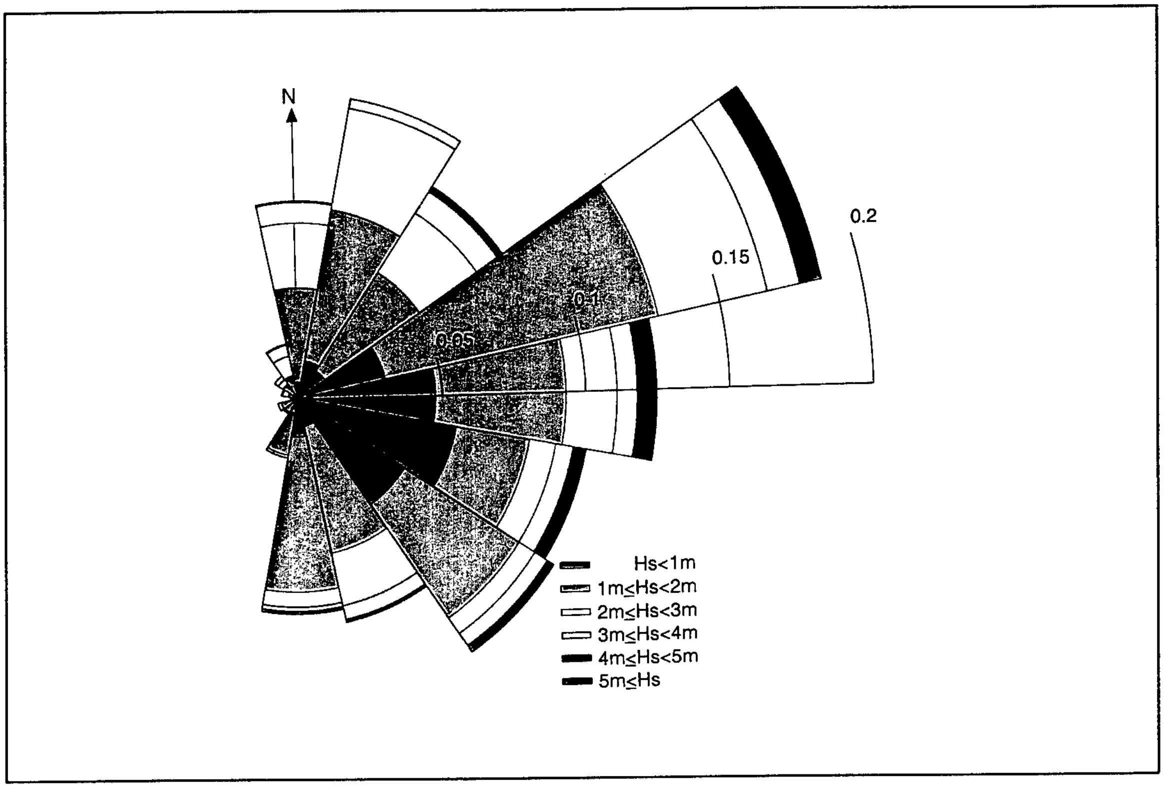

Figure 8. Waverose, NDBC buoy 44010

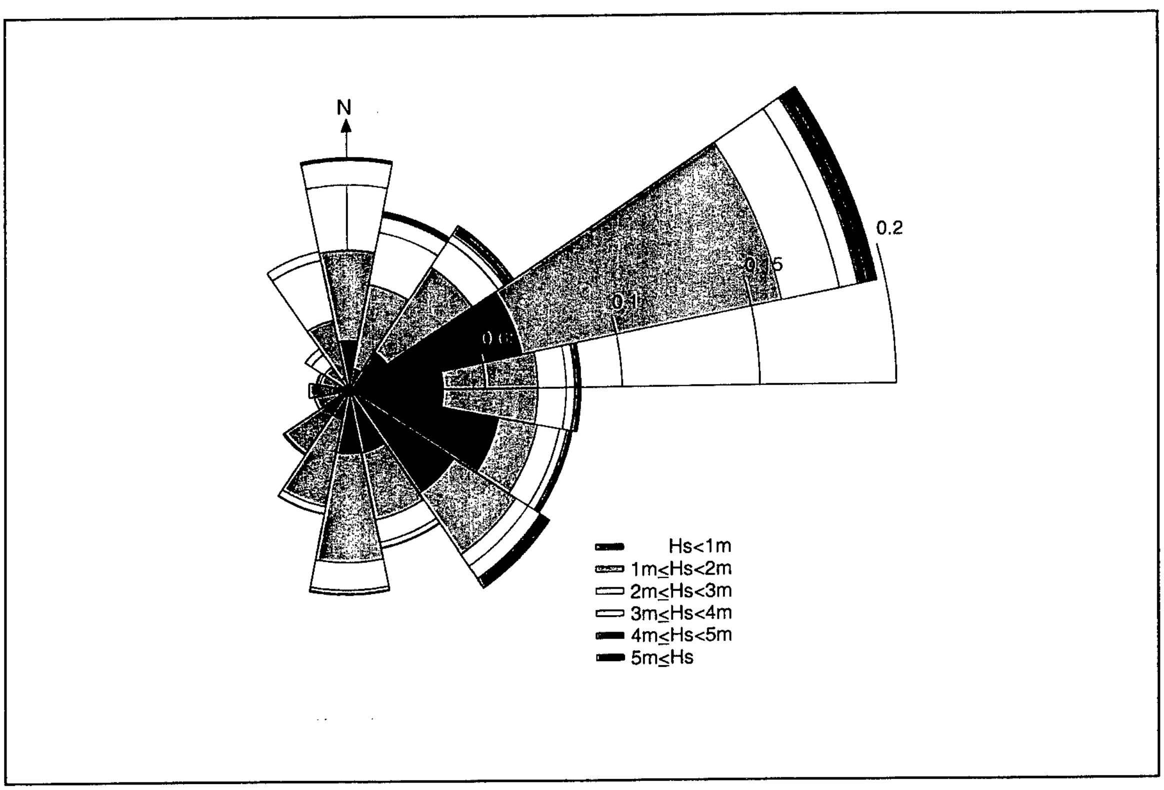

Figure 9. Waverose, WIS station AU2055, 1976-95

3 Modeling Approach

Wave Model and Grids

Wave Model

The WES spectral wind-wave growth and propagation model STWAVE (STeady-state spectral WAVE) was chosen for wave transformation modeling in this study (Appendix B). The spectral representation was expected to be advantageous for transforming waves around the complex bathymetry of Frying Pan Shoals and other major shoal areas.

Grids

The WIS information from Stations AU2041 and AU2042 was used to characterize offshore wave climate beyond the effects of Frying Pan Shoals, Cape Fear, and other nearshore bathymetry and sheltering. An STWAVE grid was developed to include coastal bathymetry extending from Station AU2042 west to the middle of Ocean Isle Beach (Area I in Figure 10). The grid encompasses Frying Pan Shoals. Wave transformation between offshore and the vicinity of the navigation channel can be modeled with this grid. It also includes coverage of areas considered for offshore dredged material disposal sites.

The grid covering Area I has a spatial resolution of approximately 335 m (1100 ft), and it is too coarse to represent the navigation channel and its impact on waves. Therefore, fine grids, with approximately 55-m (180-ft) resolution, were developed for nearshore areas (Areas II and III in Figure 10). The Area III grid was needed for investigation of sediment transport potential along beaches to the west, outside the immediate influence of Cape Fear River entrance.

Offshore waves can approach the study area from a wide range of directions. To accommodate these incident directions, two versions of the Area I grid were prepared, one with seaward boundary along the east edge and the other with seaward boundary along the south edge. Area I results were saved along the boundaries of area II and III to provide incident wave conditions for those grids. Since wave conditions come from a wide range of directions, two versions of the Area II grid, with seaward boundaries along the east and south edges, were also required. The fine grid covering Area III has only a south-facing seaward boundary.

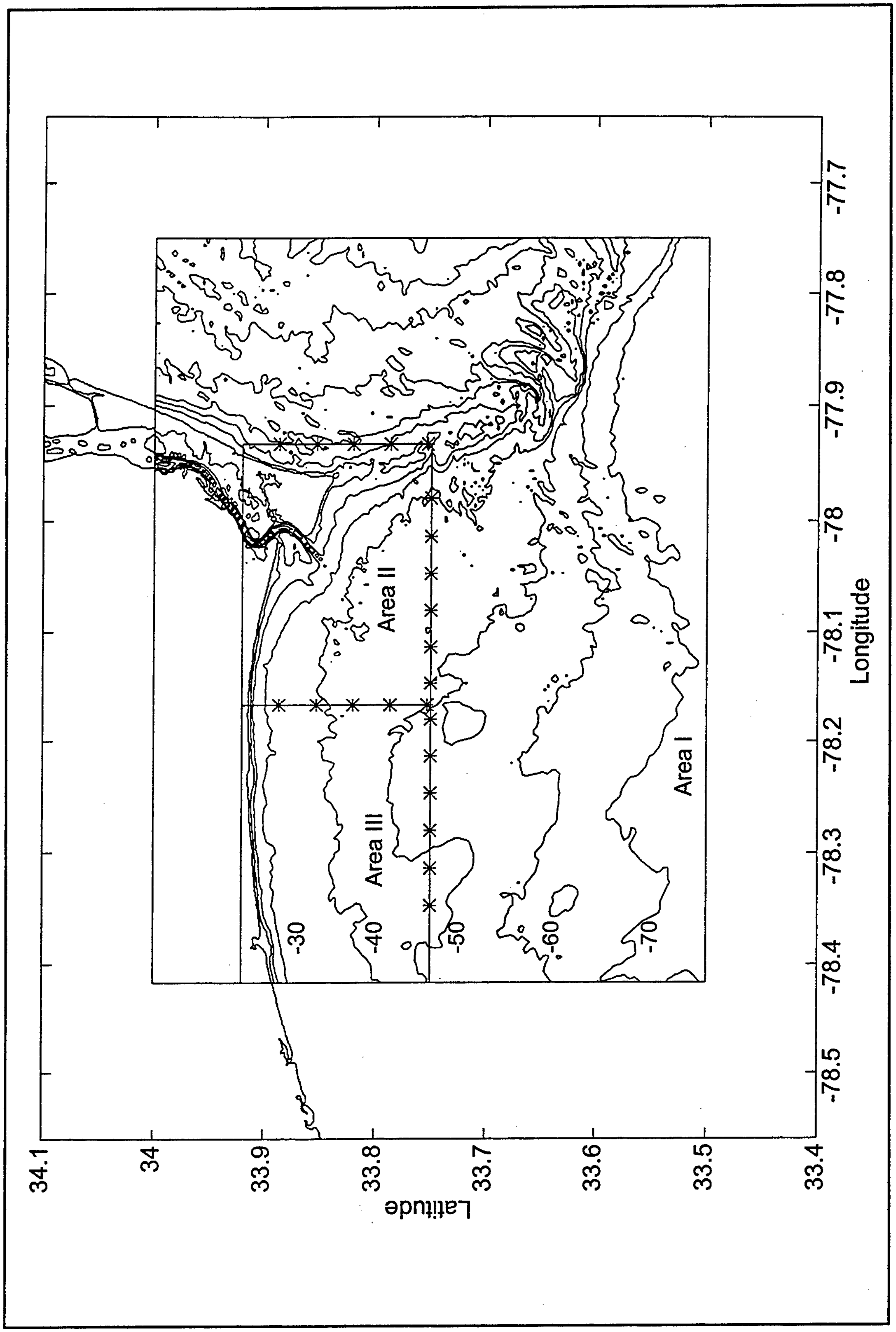

Figure 10. Numerical grid areas for wave transformation study

Bathymetry data were taken from National Ocean Survey (NOS) nautical charts. The digital bathymetry was input to a user-friendly modeling system to build the uniform rectangular grids needed for STWAVE. Bathymetry for the five Area II grid configurations and the Area III grid is shown in Figures 11-16.

In the navigation channel phase of the study, funded initially, grids were built with the ACES 2.0 software package (Leenknecht and Tanner 1997). Grid specifications are given in Table 1. Area II grid cells are 2 seconds of latitude/longitude on each side. When the second study phase was funded, an advantageous STWAVE capability had become available in the PC-based SMS modeling system (SMS 1995). Hence, SMS was used for additional grid building and output visualization in the second study phase. Specifications for grids built with SMS are given in Table 2. Actual SMS input parameters differ slightly from those in the table because SMS counts cell centers rather than cell boundaries in grid building.

Grids in SMS were built in a State Plane coordinate system. Advantages included direct overlaying of SAW channel plans on the grid for editing and direct measures of distance in meters or feet along beaches. However, a complication introduced by using SMS and State Plane coordinates was that the Area II grids used in the first phase of the study, built in ACES 2.0 with a latitude/longitude coordinate system, were distorted relative to the SMS grids. The SMS Area II grids were adjusted to cover approximately the same area as the ACES grids and to minimize distortion impacts on the study.

The historical 1872 bathymetry covered only a portion of the grid, extending about (2.5 miles) seaward of the entrance over a fan-shaped area and including nearshore data along Bald Head Island up to Cape Fear. Other parts of the grid were based on existing bathymetry with assumed smooth transitions blending existing into historical bathymetry. The adjusted ebb tide shoals used with Plan 1 and 2 channels also required some blending to smoothly join existing bathymetry in the model.

Table 1
Specifications for STWAVE Grids from ACES 2.0

Parameter	Area I	Area II[1]
Cell size in x-direction, Dx'	0.003333° (≈335 m)	0.0005555° (≈55 m)
Cell size in y-direction, Dy'	0.003333° (≈335 m)	0.0005555° (≈55 m)
Geological x origin, X0	-77.75°	-77.93333°
Geological y origin, Y0	33.5°	33.75°
x-axis length, Rx'	0.6667°	0.23333°
y-axis length, Ry'	0.5°	0.17°
Azimuth (bearing) of x-axis	0°	0°
No. of I's (columns)	151	307
No. of J's (rows)	201	421

[1] Used for existing, Plan 1/Plan 2, and Plan 3

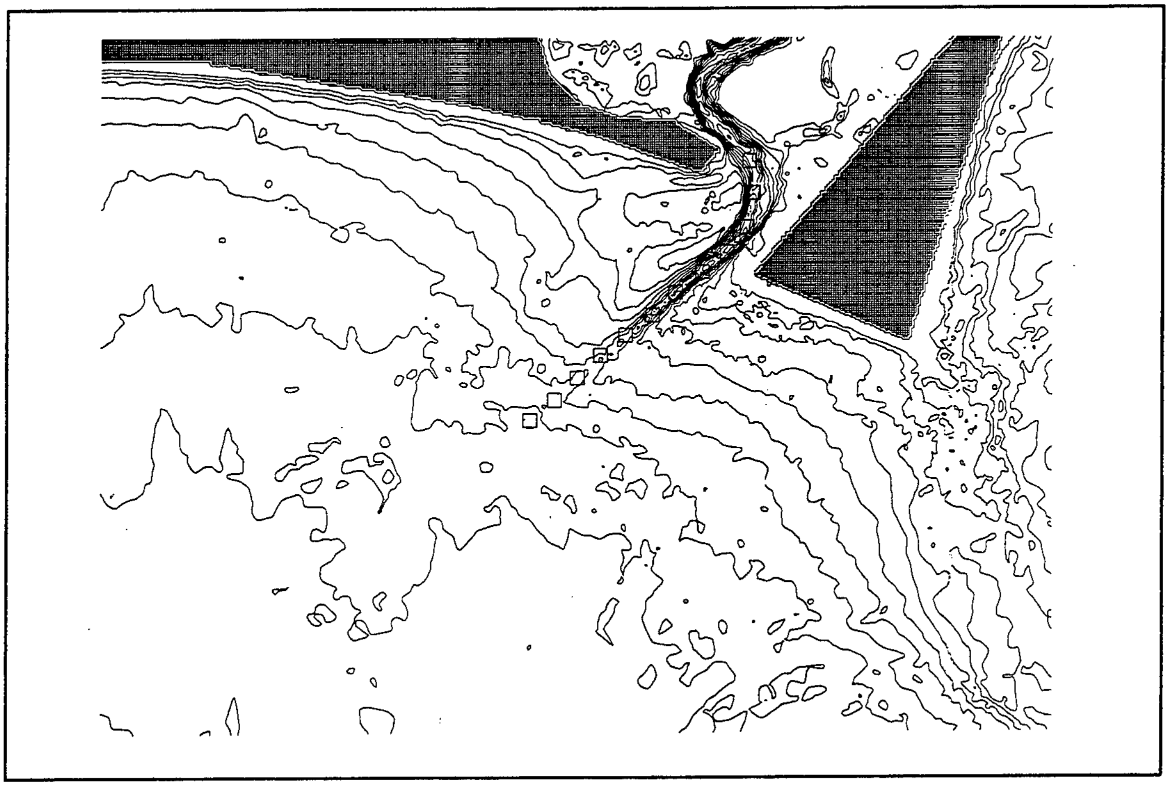

Figure 11. Existing entrance channel, including channel stations

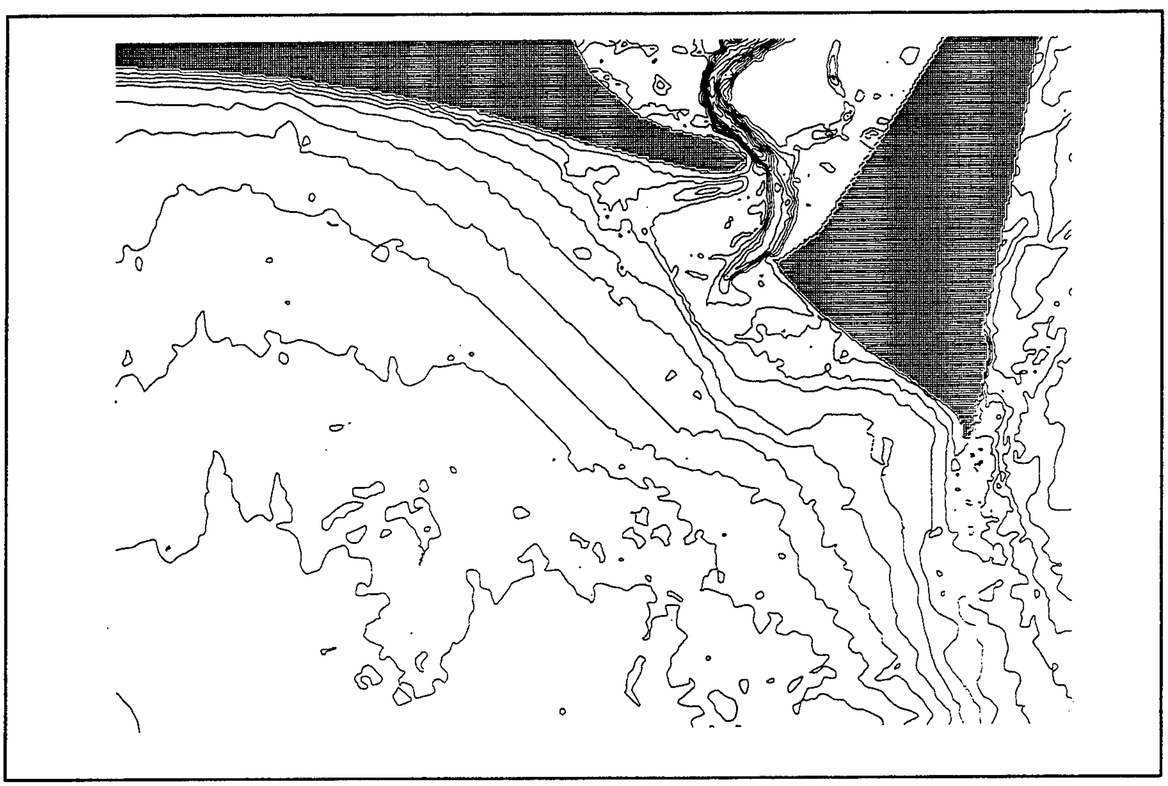

Figure 12. Historical entrance channel, 1872 bathymetry

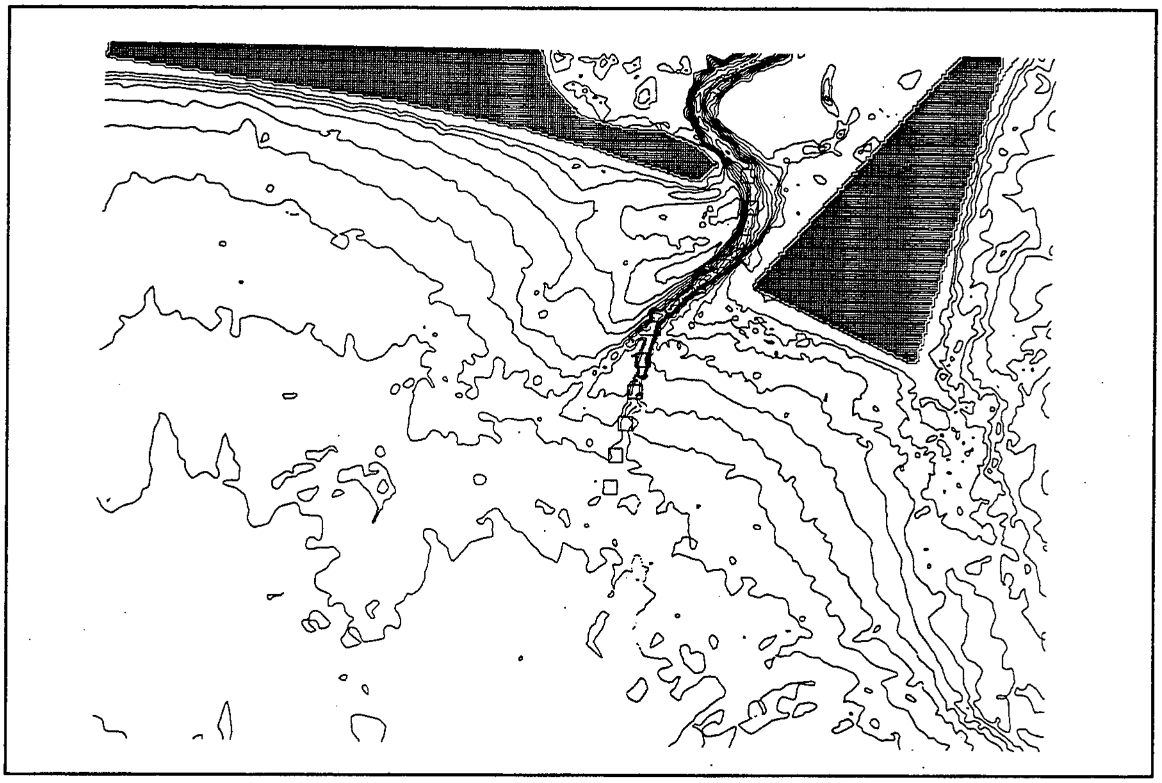

Figure 13. Plan 1 and 2 entrance channel, including channel stations

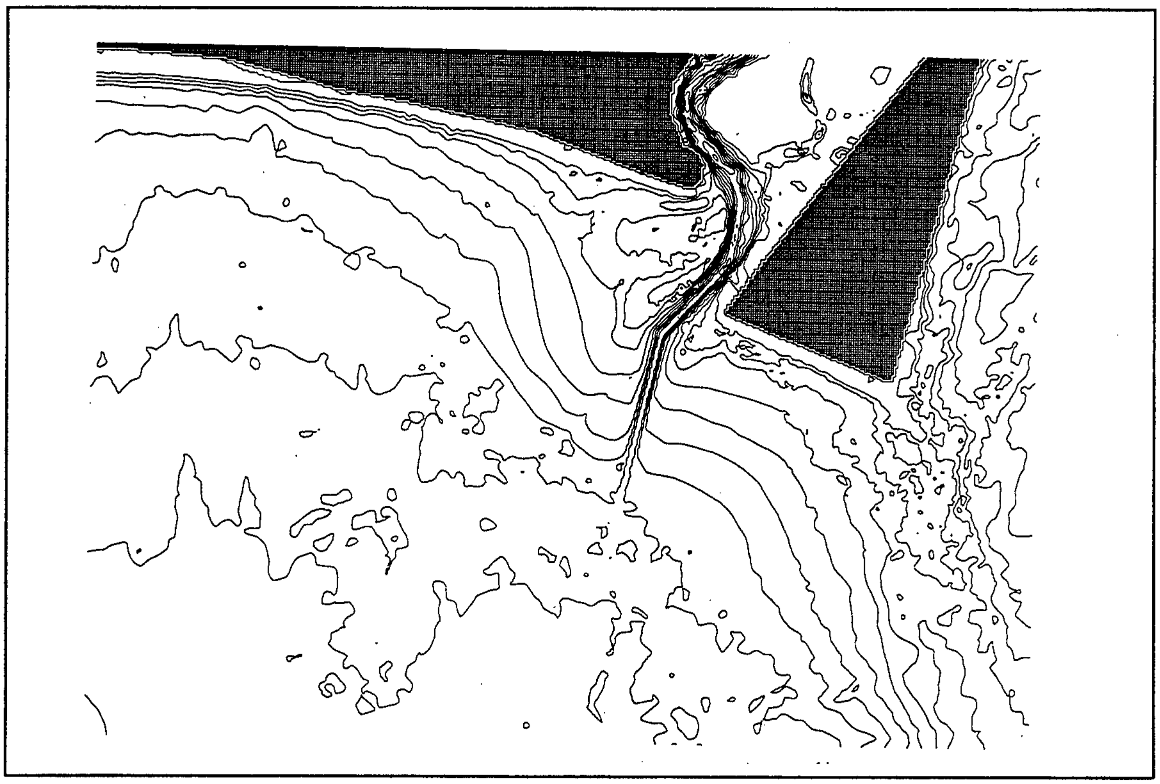

Figure 14. Plan 1/2 entrance channel with adjusted ebb tide shoal

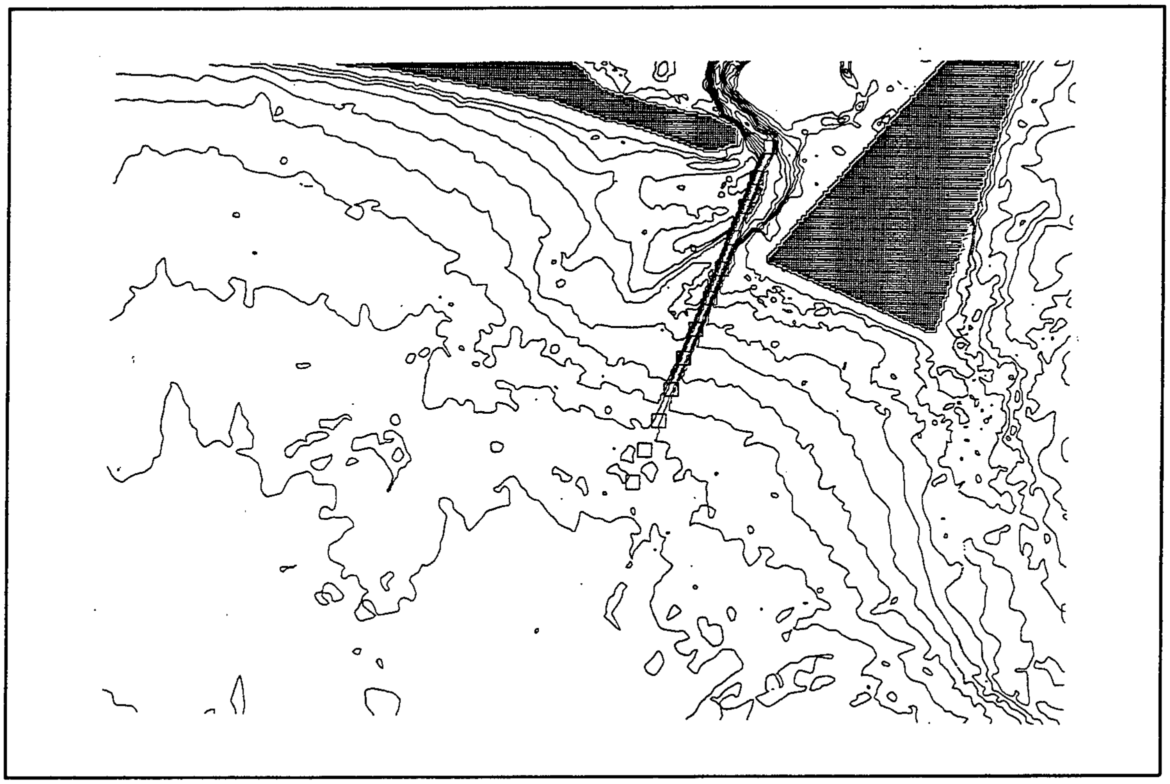

Figure 15. Plan 3 entrance channel, including channel stations

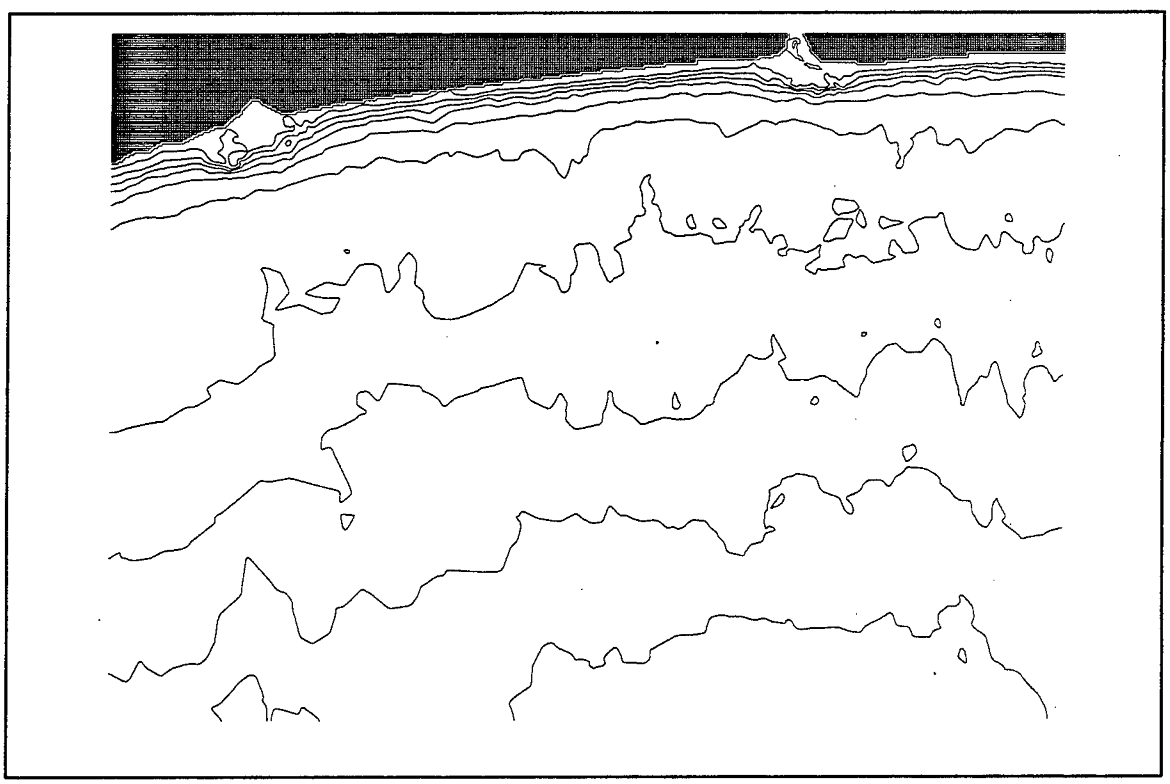

Figure 16. Existing bathymetry, Area III

Table 2
Specifications for STWAVE Grids from SMS

Parameter	Area II[1]	Area III
Cell size	54.86 m (180 ft)	54.86 m (180 ft)
Origin, x (state plane)	708827 m (2325520 ft)	686658 m (2252787 ft)
Origin, y (state plane)	2321 m (7614 ft)	2321 m (7614 ft)
x-axis length	16789 m (55080 ft)	16789 m (55080 ft)
y-axis length	23043m (75600 ft)	23098 m (75780 ft)
Angle of rotation	90°	90°
No. of I's (columns)	307	307
No. of J's (rows)	421	422

[1] Used for 1872 and Plan 1/Plan 2 with adjusted bathymetry

Incident Wave Conditions

Percent occurrence tables were computed from the WIS parameters at stations AU2041 and AU2042. Intervals used were 1 m for wave height, 2 sec for peak period, and 22.5 deg for direction. Station AU2041 yielded 115 height/period/direction combinations with nonzero occurrence coming from directions between 157.5 and 270 deg. Station AU2042 gave 151 nonzero combinations from 45 to 112.5 deg. An STWAVE run was done for each nonzero combination, a total of 266 incident wave cases. The Station AU2041 cases were applied to the Area I grid with south-facing seaward boundary. The Station AU2042 cases were applied to the Area I grid with east-facing seaward boundary. After review of the initial phase of this study (navigation channel wave climate in existing and Plans 1 and 2), the 135-deg cases were rerun on the south-facing Area I grid to better accommodate wave refraction.

For each STWAVE input height/period/direction combination, the ACES 2.0 software was used to generate a directional wave spectrum in water depth appropriate to the corresponding Area I grid seaward boundary. Spectral frequencies ranged from 0.033 Hz to 0.294 Hz at 0.009 Hz intervals. Spectral direction components covered ±85 deg from normal incidence to the grid, in 5-deg increments. A single water level was used in all simulations, representing Mean Sea Level (0.67 m or 2 ft above the MLW datum).

For navigational channel wave climate studies, wave spectra from the east-facing Area I grid were saved at 5 points along the east boundary of Area II; and spectra from the south-facing Area I grid were saved at 6 points along the south boundary of Area II. Spectra along the Area II boundaries were averaged for each case to give a representative incident spectrum for the Area II grids. Boundary points which were not consistent with the more representative boundary points, typically those falling in shallow water near Frying Pan Shoals, were omitted from averaging.

For littoral transport studies, incident wave conditions were treated differently. Incident waves from easterly directions tend to refract toward the north. The angle of refraction can be large, especially at the point where the waves reach nearshore breaking. The STWAVE model cannot accomodate wave energy propagating backwards, toward the seaward boundary. Instead, the model truncates any offshore-directed part of the directional wave spectrum . When wave angles deviate by about 60 deg or more from perpendicular to the seaward boundary, such model-induced energy losses are usually significant. This problem was tolerable for navigation channel wave climate analysis but not for littoral transport studies. Hence, all Area II and III grids used in littoral transport studies were south-facing. Incident spectra were computed from Area I grid results as before, but along the south boundaries of Area II and III grids for all offshore wave directions. Finally, the 135-deg direction cases were rerun on the south-facing Area I grid to help minimize model effects. The Station AU2041 wave climate was used for all incident wave directions in littoral transport studies.

STWAVE Output

The main output from STWAVE runs consists of arrays of significant wave height, peak period, and peak direction over the grid for each incident wave case. These relatively large files are useful for visualizing wave transformation over the grid. The height/period/direction information at selected stations in the grid is another, much more condensed output. Station output can be generated during the STWAVE runs or it can be extracted from the main output arrays as a post-processing step. Station output in the navigation channels and in shallow water along the coast was needed for this study, as discussed in the following sections. Since the Area II grids cover the ODMDS area, wave information can be extracted for ODMDS studies when necessary.

Wave Transformation Examples

Figures 17 and 18 illustrate the wave transformation pattern for the existing channel configuration on coarse and fine grids, respectively, for one incident wave case. This case is a representative wave height and longer than average peak period selected to illustrate wave transformation over Frying Pan Shoals. In Figure 17, the model result is plotted for every fourth grid cell in order to display a readable wave pattern. In Figure 18, results are plotted for every eighth grid cell. Similarly, Figures 19 and 20 show computed wave patterns on the coarse and fine grids for the case with same offshore wave height and peak period and wave approaching from southeast direction. In these cases, wave heights are greatly reduced as waves propagate from the offshore boundary into the nearshore area. The wave height reduction in shallow water is mainly due to the effects of refraction and nonlinear wave-wave interaction introduced in the STWAVE model. The wave-wave interaction induces significant loss of wave energy in the high frequency range through energy transferring from spectral peak to high frequency components.

Figures 17 to 20 also show the sheltering effect of Bald Head Island. Waves coming from the east boundary become very small as they travel close to the mouth of Cape Fear River. Shoaling and refraction of waves are most significant over Frying Pan Shoals. Interestingly, wave direction around the inner part of the entrance channel and near adjacent beaches is about the same for both incident wave cases. The effect of Frying Pan Shoals is to converge wave direction into a narrow band and to reduce wave height. As expected, wave height for the east-northeast incident direction is more reduced by the shoals than for the southeast incident direction. In some nearshore areas, wave direction is turned far enough toward the north that a significant fraction of wave

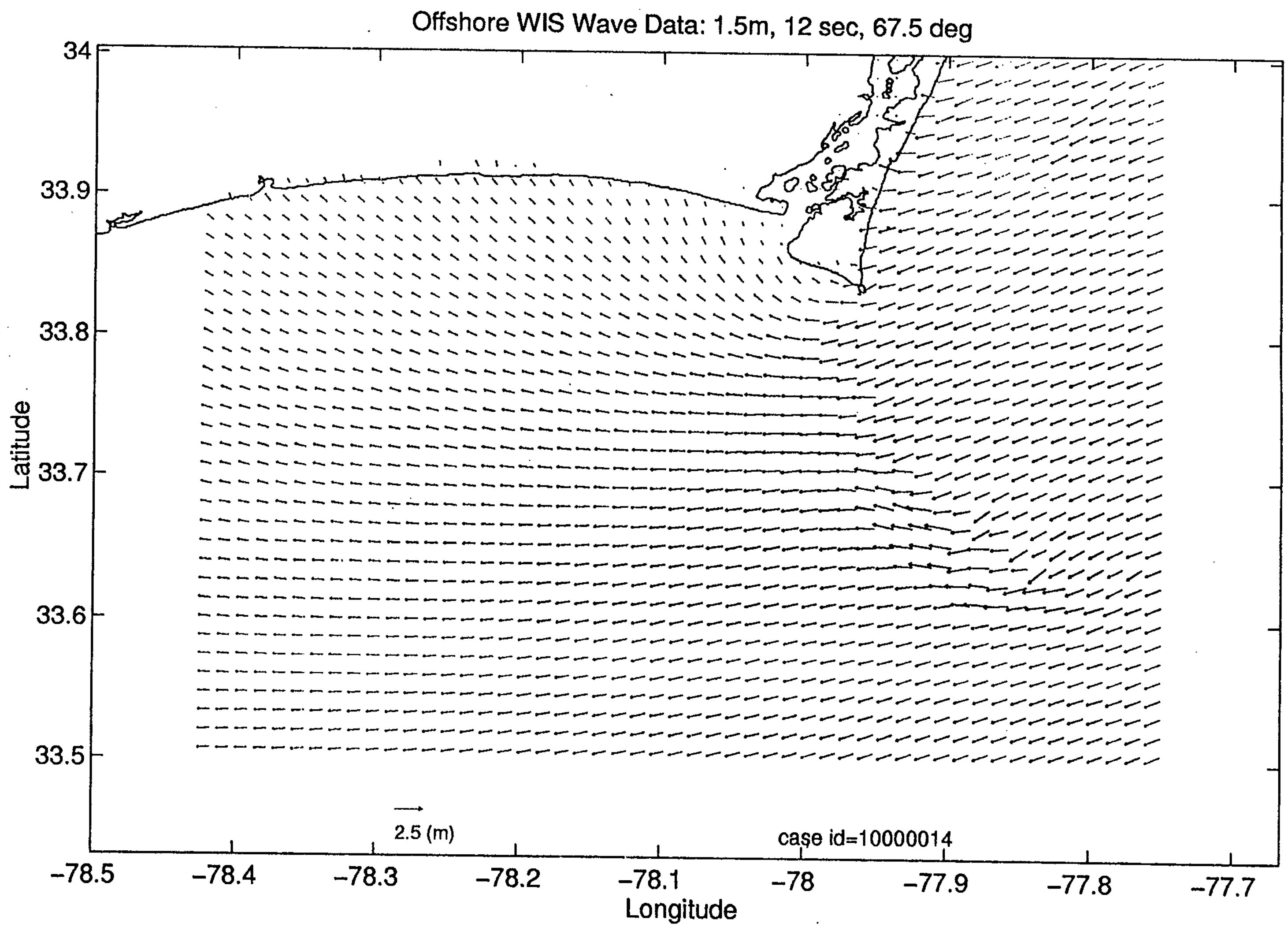

Figure 17. Example wave transformation, Area I, incident waves: H_s = 1.5 m (4.9 ft), T_p = 12 sec, θ_p = 67.5 deg

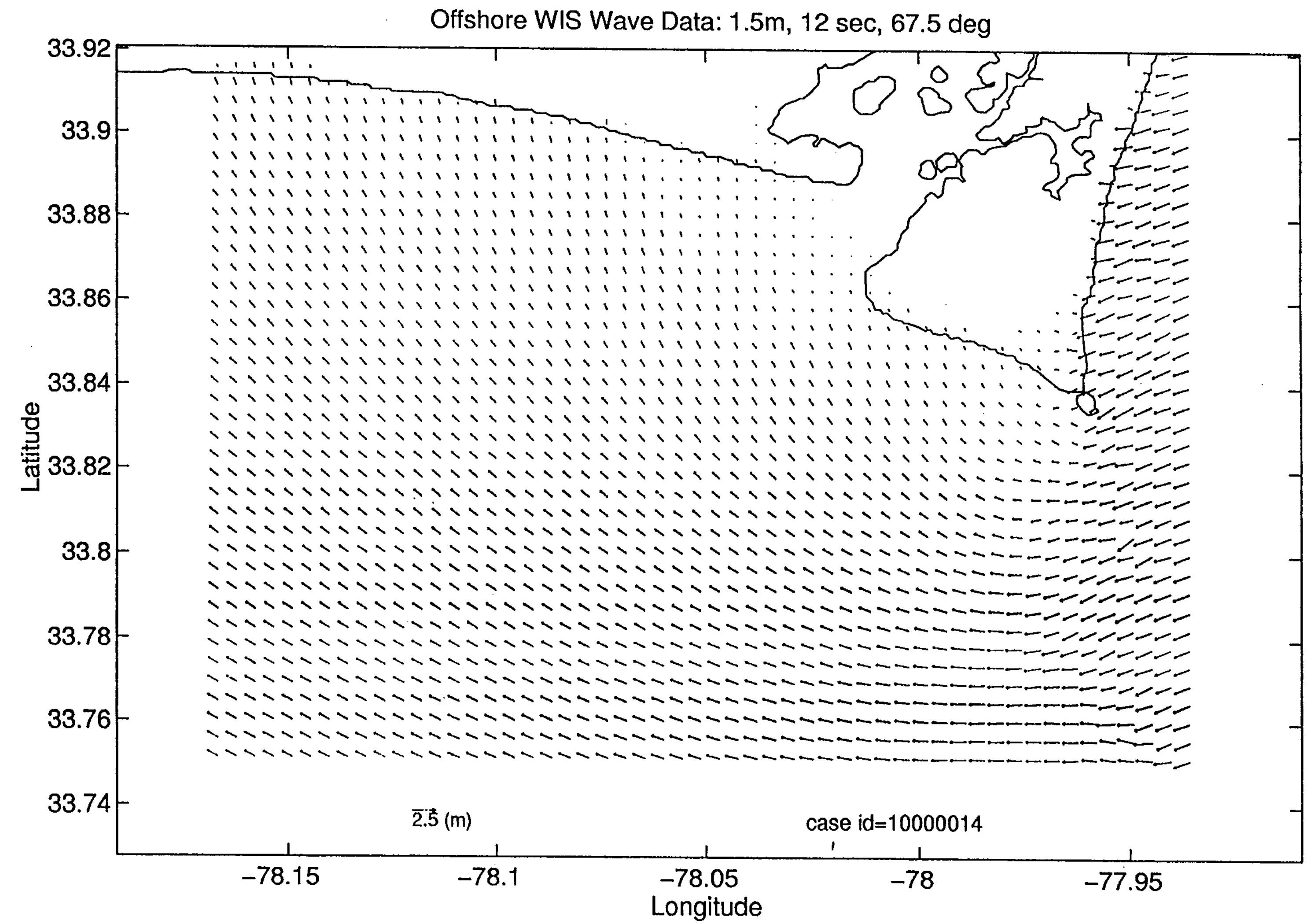

Figure 18. Example wave transformation, Area II, incident waves: H_s = 1.5 m (4.9 ft), T_p = 12 sec, θ_p = 67.5 deg

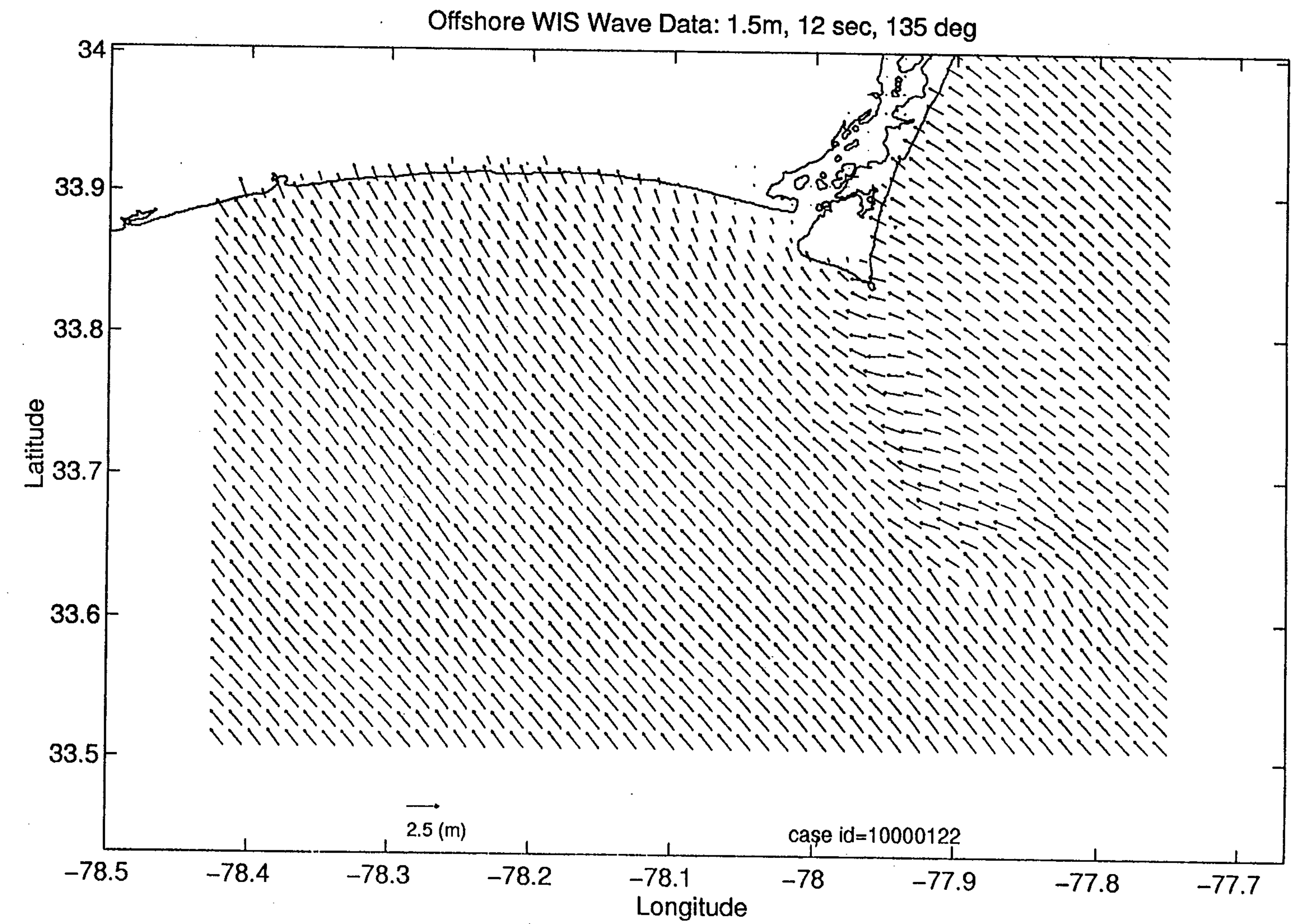

Figure 19. Example wave transformation, Area I, incident waves: H_s = 1.5 m (4.9 ft), T_p = 12 sec, θ_p = 135 deg

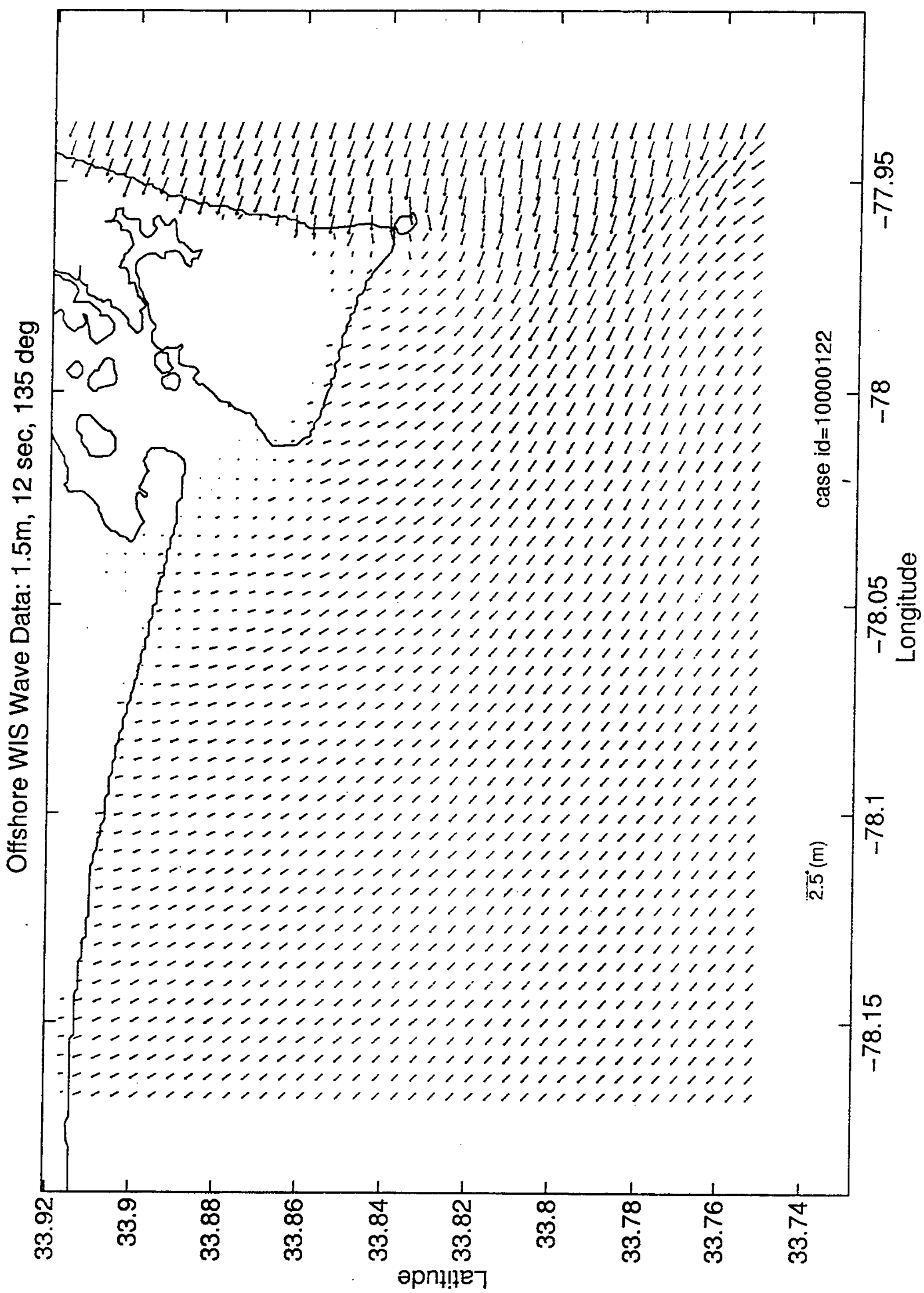

Figure 20. Example wave transformation, Area II, incident waves: H_s = 1.5 m (4.9 ft), T_p = 12 sec, θ_p = 135 deg

energy in the directional spectrum may be headed to the east of north. As noted earlier, an STWAVE grid with seaward boundary on the east edge could not model those directions. Hence, there is potential for model-induced wave energy loss in areas where wave direction begins to approach parallel with the offshore grid boundary.

Navigation Channels

Wave transformation results were saved for wave climate analysis at even intervals of 1600 m (0.5 mile) along the entrance channel of interest (Figures 11, 13, and 15). A total of 12 stations along the existing and proposed entrance channel configurations was used in the analysis. Since the proposed Plan 1 and Plan 2 were computed as one single plan in wave transformation, they share the same stations for wave climate analysis. Tables 3-5 summarize station locations for existing and proposed channel configurations. The distance associated with stations starts with +0.0 at the mouth of Cape Fear River and increases seaward towards the outer channel.

Table 3
Station Locations along Existing Entrance Channel

Station ID	Range in Entrance Channel (km)	Latitude (deg)	Longitude (deg)	x index* I	y index* J	Depth, m (ft) MLW
E1	+0.0 (+0.0 mi)	33.8899 N	-78.0077 W	252	135	13.7 (44.9)
E2	+1.6 (+0.5 mi)	33.8821 N	-78.0066 W	238	133	12.2 (40.0)
E3	+3.2 (+1.0 mi)	33.8738 N	-78.0083 W	223	136	13.6 (44.6)
E4	+4.8 (+1.5 mi)	33.8677 N	-78.0133 W	212	145	13.1 (43.0)
E5	+6.4 (+2.0 mi)	33.8627 N	-78.0194 W	203	156	12.2 (40.0)
E6	+8.0 (+2.5 mi)	33.8577 N	-78.0260 W	194	168	12.8 (42.0)
E7	+9.6 (+3.0 mi)	33.8521 N	-78.0316 W	184	178	10.5 (34.4)
E8	+11.2 (+3.5 mi)	33.8471 N	-78.0382 W	175	190	9.8 (32.2)
E9	+12.8 (+4.0 mi)	33.8421 N	-78.0443 W	166	201	10.0 (32.8)
E10	+14.4 (+4.5 mi)	33.8366 N	-78.0499 W	156	211	11.5 (37.7)
E11	+16.0 (+5.0 mi)	33.8310 N	-78.0554 W	146	221	11.8 (38.7)
E12	+17.6 (+5.5 mi)	33.8260 N	-78.0615 W	137	232	12.3 (40.4)

* Based on Area II grid defined in Table 1.

Table 4
Station Locations along Proposed Entrance Channel, Plans 1 and 2

Station ID	Range in Entrance Channel (km)	Latitude (deg)	Longitude (deg)	x index* I	y index* J	Depth, m (ft) MLW
P1 - P6	Same as Stations E1 through E6 (Table 2)					
P7	+9.6 (+3.0 mi)	33.8521 N	-78.0277 W	184	176	13.0 (42.7)
P8	+11.2 (+3.5 mi)	33.8444 N	-78.0299 W	170	180	13.0 (42.7)
P9	+12.8 (+4.0 mi)	33.8366 N	-78.0321 W	156	183	13.0 (42.7)
P10	+14.4 (+4.5 mi)	33.8288 N	-78.0349 W	142	187	12.9 (42.3)
P11	+16.0 (+5.0 mi)	33.8210 N	-78.0377 W	128	191	13.0 (42.7)
P12	+17.6 (+5.5 mi)	33.8133 N	-78.0399 W	114	193	13.0 (42.7)

* Based on Area II grid defined in Table 1.

Table 5
Station Locations along Proposed Entrance Channel, Plan 3

Station ID	Range in Entrance Channel (km)	Latitude (deg)	Longitude (deg)	x index* I	y index* J	Depth, m (ft) MLW
P3-1	+0.0 (+0.0 mi)	33.8899 N	-78.0077 W	253	133	12.8 (42)
P3-2	+1.6 (+0.5 mi)	33.8829 N	-78.0107 W	239	139	12.8 (42)
P3-3	+3.2 (+1.0 mi)	33.8760 N	-78.0138 W	226	144	12.8 (42)
P3-4	+4.8 (+1.5 mi)	33.8691 N	-78.0168 W	212	149	12.8 (42)
P3-5	+6.4 (+2.0 mi)	33.8622 N	-78.0199 W	198	154	12.8 (42)
P3-6	+8.0 (+2.5 mi)	33.8552 N	-78.0229 W	185	159	12.8 (42)
P3-7	+9.6 (+3.0 mi)	33.8482 N	-78.0260 W	171	165	12.8 (42)
P3-8	+11.2 (+3.5 mi)	33.8414 N	-78.0290 W	158	170	12.8 (42)
P3-9	+12.8 (+4.0 mi)	33.8344 N	-78.0321 W	144	175	12.8 (42)
P3-10	+14.4 (+4.5 mi)	33.8275 N	-78.0351 W	130	180	12.8 (42)
P3-11	+16.0 (+5.0 mi)	33.8206 N	-78.0382 W	117	186	12.8 (42)
P3-12	+17.6 (+5.5 mi)	33.8136 N	-78.0412 W	103	191	12.8 (42)

* Based on Area II grid defined in Table 1.

Littoral Transport

The approach to estimating littoral transport was to use STWAVE to transform each incident wave condition to near-breaking; transform the near-breaking wave to a point at which breaking begins, using the assumption of straight, parallel bottom contours; and compute potential longshore transport rate from that breaking wave height and angle. With consideration of the WIS percent occurrence tables, the potential transport rate due to each incident wave condition was then converted to an annual potential transport volume of sediment. Finally, potential transport contributions from all incident wave conditions were added to give estimates of annual westward, eastward, net, and gross longshore transport. Details of the approach are given in the following paragraphs.

Calculation of Breaking Wave Conditions

Stations for saving STWAVE wave parameters to be used in littoral transport estimation were selected with two primary objectives. First, the stations should be shoreward of all significant effects of irregular bathymetry, so that STWAVE will have included these effects in wave transformation. Second, stations should be seaward of the nearshore surf zone, so that STWAVE has not yet invoked breaking limits on wave height and the breaking wave height and angle needed for calculating longshore transport rates can be accurately estimated.

A nearshore station was selected for every grid J intersecting a study area beach. Stations in the Area II and III existing condition grids are illustrated in Figures 21 and 22. As shown in Figure 21, two stations with the same J can occur where the western end of Bald Head Island extends further west than the eastern end of Caswell Beach. Stations in Area II grids were placed around the 3.7-m to 4.6-m (12-15 ft) contours, where bottom contours were reasonably parallel to the shoreline. Area III is less sheltered by Frying Pan Shoals. The wave climate is more energetic than in Area II, and fairly straight, parallel bottom contours extend further seaward. Hence, stations in the Area III grid were placed in slightly deeper water, around 5.5-m to 6.0-m (18-20 ft) depth.

In areas where ebb tide and other shoals extend offshore, waves will break on the shoals rather than the nearshore beach slope. These breaking waves are not directly driving littoral transport at the beach. Hence, nearshore stations in shoal areas were placed regardless of water depth to follow a smooth line of stations reasonably parallel to the beach or along expected paths of longshore transport around small inlets. These stations are expected to be representative of the breaking wave conditions actually driving nearshore littoral transport across shoal areas.

A "shoreline" angle was specified for each nearshore station to establish the orientation of the straight, parallel bottom contours to be used in calculating wave breaking conditions. Shoreline angles were estimated from available charts.

A computer program adapted from the GENESIS model (Gravens, Kraus, and Hansen 1991) was used to iteratively calculate breaking wave heights and angles. Inputs to the program included nearshore station output from STWAVE and shoreline angles. The breaking criterion is $H_s = 0.78\ d$, where d = water depth.

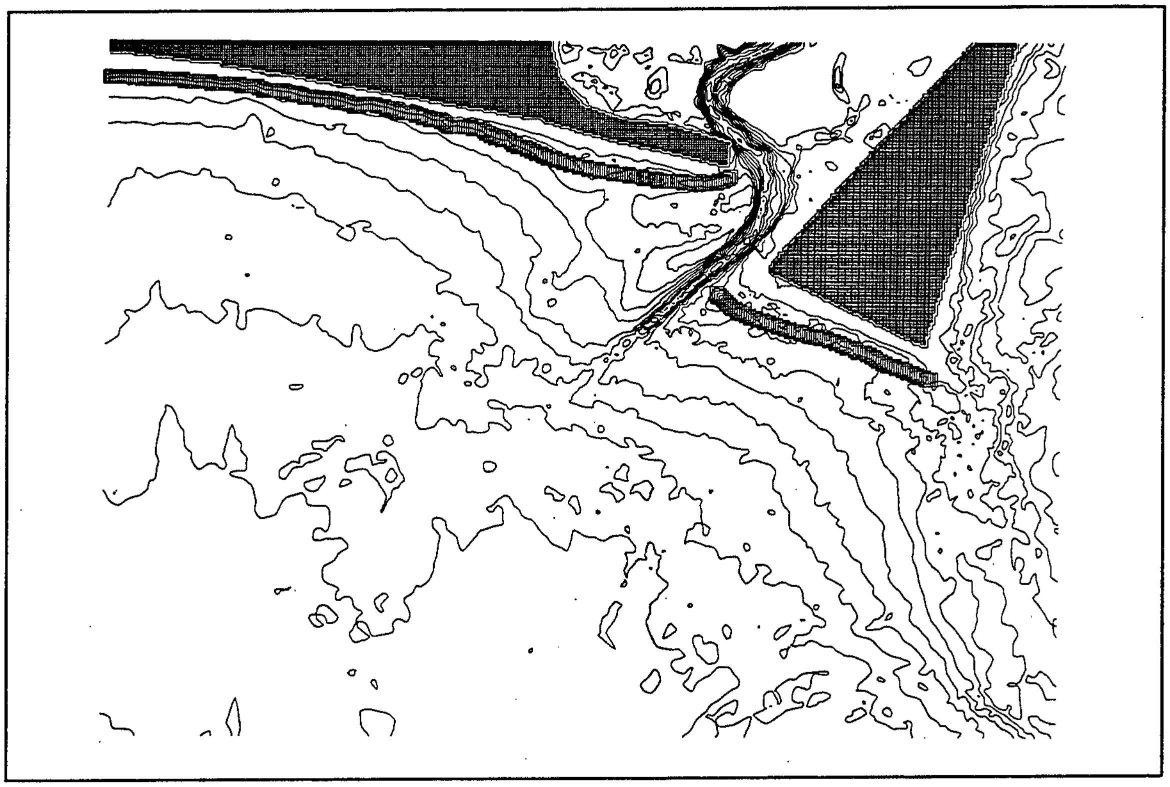

Figure 21. Nearshore stations for littoral transport estimation, Area II, existing bathymetry

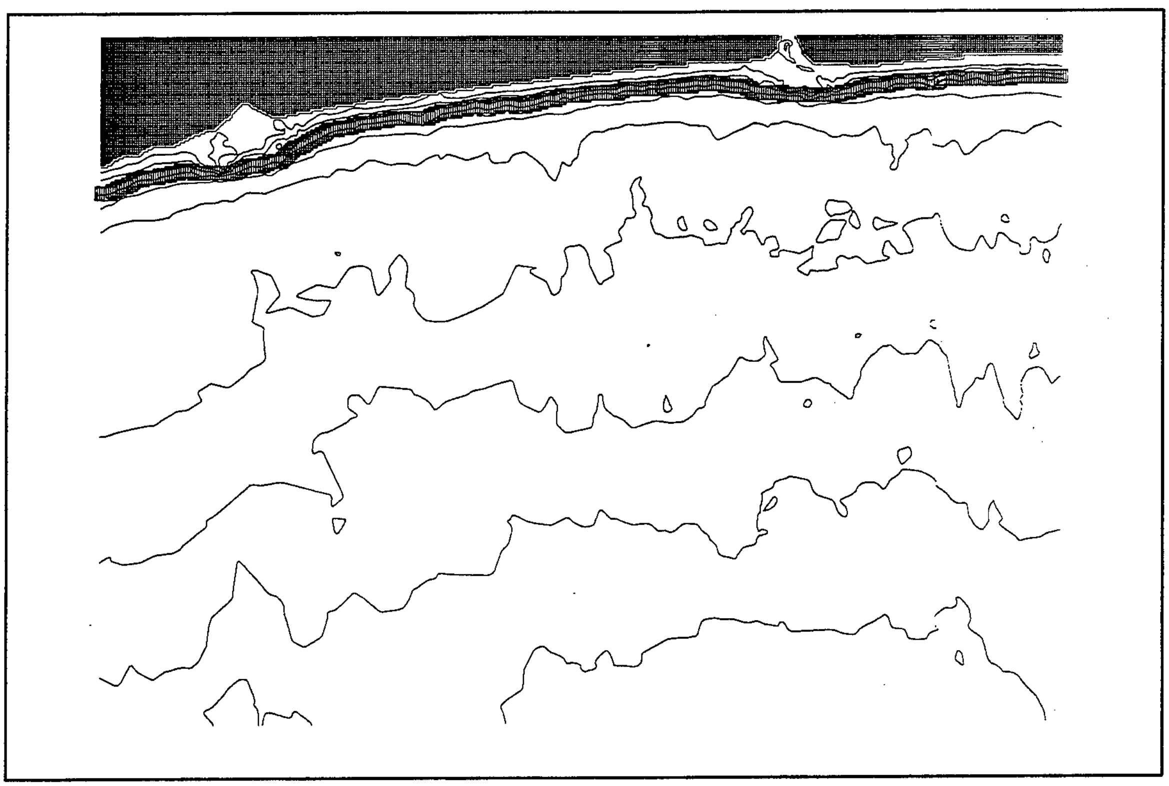

Figure 22. Nearshore stations for littoral transport estimation, Area III, existing bathymetry

Calculation of Longshore Transport Rates

The program also calculates potential longshore transport rates as

$$Q = K H_{bs}^{\frac{5}{2}} \sin(2\alpha_b) \qquad (1)$$

where Q = potential longshore transport rate
K = constant
H_{bs} = significant wave height at breaking
α_b = breaking wave angle relative to bottom contours

When H_{bs} is in meters and Q in cu m/day, the generally accepted value of K is $K = 5100$ (Equation 6-7b of USACE 1992). Program calculations were done in metric units with Q expressed in cu m/sec. The corresponding constant is $K = 0.0590$.

When Equation 1 is applied to the study area, longshore transport rates are unreasonably large. As in previous model studies, a calibration of the constant K was needed. Previous estimates of net and gross longshore transport rate along Holden and Long Beaches, utilizing dredging records from Lockwoods Folly Inlet, provided a reasonable basis for calibration (SAW 1973). The value of K in Equation 1 was reduced from 0.059 to 0.023 after calibration. The same calibration value of K was found in a concurrent STWAVE study of Long Beach Island, NJ (Cialone and Thompson 1999).

A Q was calculated with Equation 1 for each wave condition. Using percent occurrences from WIS, Q was converted to an annual longshore transport volume in cu m/yr or cu yd/yr. Following standard convention, longshore transport toward the right of an observer on the beach facing the ocean is positive (westward transport in this study), and transport toward the left is negative (eastward transport in this study).

Contributions from all wave conditions were added together to give total annual westward and eastward potential longshore transport volumes, which can be expressed as annual transport *rates*. Net potential longshore transport rates are determined as the difference between magnitude of the westward and eastward rates. Gross potential longshore transport rates are the combined magnitudes of westward and eastward transport rates.

This study used both primary and secondary WIS wave components, as represented in wave climate percent occurrence tables. This approach is expected to give a better estimate of net transport rates than if only overall WIS parameters were used. However, it tends to increase westward, eastward, and gross transport rates because wave components contribute individually rather than as combined events. The impact on longshore transport rates is expected to be small, but it is advisable to consider net transport rate as the most accurate littoral transport parameter in this study.

Validation of Longshore Transport Rates

Calculated longshore transport rates depend on offshore wave climate, model bathymetry, and modeling procedures. Because of the approximations involved, validation of calculated longshore transport rates by comparison to documented littoral transport information is desirable. The east-facing coast north of Bald Head Island provides a good opportunity for validation. This coastal area includes some natural indicators of net transport, such as long-term migration of New Inlet and shoreline response to natural coquina rock outcrops at Fort Fisher. Both of these features indicate a net southerly transport. Also, this area is less influenced by the complex bathymetry of Frying Pan Shoals.

This area has a history of active inlet behavior. Typically, an inlet opens, migrates south, and closes, giving way to a new inlet opening to the north. This cyclical pattern is evident in records dating back to the late 1800's (SAW 1974, Moorefield 1978). Coquina outcrops further north have functioned as a rocky headland, creating an embayment in the downdrift shoreline planform immediately to the south (SAW 1993). Coastal response at the inlets and coquina outcrops indicate a clear net littoral transport to the south.

Quantitative littoral transport estimates relevant to this area are available from SAW (1977). That study defined littoral cells along the coast and estimated transport at cell boundaries. The southernmost cell ended at Kure Beach, just north of Fort Fisher. Transport estimates are given in Table 6.

New Inlet is located near the northern boundary of the Area II grid (Figure 10). The Fort Fisher area extends north from New Inlet about halfway to the north boundary of the Area I grid. Model results from the Area I grid were used to calculate potential longshore transport rates in this area. Although the Area I grid is relatively coarse and cannot capture details of wave transformation desired for littoral transport calculations, it still provides an indication of littoral processes. Littoral transport rates calculated for 13 cells encompassing the Fort Fisher area were averaged together to give the overall trend (Table 6).

Model transport rates in the Fort Fisher area show the same trends as SAW's (1977) estimates. Transport toward the south dominates. The maginitudes of north, south, and gross littoral transport rates are significantly lower in this study by comparison to SAW's study, but net transport rates are remarkably similar. The successful representation of documented littoral transport trends and net transport rates serves as a useful validation of the present study.

Table 6
Potential Littoral Transport Rates, Fort Fisher, NC

Source	Longshore Transport Rate, cu yd/yr			
	Toward South	Toward North	Net	Gross
SAW (1977) study, Kure Beach	619,000	-318,000	301,000	937,000
Present study	384,000	-110,000	274,000	494,000

4 Wave Climate in Navigation Channels

Percent Occurrence Tables

Wave climate at stations along existing and plan navigation channels was computed by applying WIS percent occurrence information to STWAVE results at those selected points (Figures 11, 13, and 15, and Tables 3-5). Percent occurrence tables of wave height, peak period, and wave direction were computed for each channel station. Percent occurrence tables were constructed by using wave height bins with 0.5- or 1- m intervals, wave period bins between 4 and 22 sec, with 2 sec intervals, and wave directions between 0 and 360 deg, at 10 deg intervals. The tables were provided to SAW and to the vertical ship motion component of WES studies. They are not included in this report because of their volume. Some more condensed summaries are presented and discussed in this chapter.

Mean and Maximum Significant Wave Heights

Mean significant wave heights show a fairly regular pattern of increase between the first and last station in each channel (Table 7). Comparing the existing and Plan 1 and 2 channel, mean heights are essentially the same at the first six stations, where the channels coincide. At stations 7, 8 and 9, mean height is greater in the existing channel than in the plan channel. At the outer stations (10, 11 and 12), mean height is a little higher in the plan channel than in the existing channel.

Mean significant wave heights in the Plan 3 channel are higher than in the existing channel, except at Stations 6-8. Differences are small, but are indicative of the greater exposure of the inner and outer parts of the Plan 3 channel relative to existing.

Maximum significant wave heights are higher in the existing channel than in the Plan 1 and 2 channel for all but the very nearshore stations, especially at stations 7, 8 and 9 (Table 8). Approach directions for waves with maximum significant height are from the south (180 and 190 deg) in the outer channels, shifting toward southwest (220 deg) further landward. The Plan 3 channel shows a similar behavior relative to the existing channel, but maximum heights in the outer channel are more nearly comparable to existing.

Table 7
Mean Significant Wave Height Along Navigation Channels

Station	Mean H_s, m (ft)		
	Existing	Plans 1 & 2	Plan 3
1	0.11 (0.36)	0.11 (0.36)	0.16 (0.52)
2	0.07 (0.23)	0.07 (0.23)	0.14 (0.46)
3	0.08 (0.26)	0.08 (0.26)	0.10 (0.33)
4	0.15 (0.49)	0.15 (0.49)	0.20 (0.66)
5	0.38 (1.25)	0.37 (1.21)	0.41 (1.35)
6	0.49 (1.61)	0.47 (1.54)	0.48 (1.57)
7	0.66 (2.17)	0.54 (1.77)	0.66 (2.17)
8	0.79 (2.59)	0.65 (2.13)	0.76 (2.49)
9	0.81 (2.66)	0.74 (2.43)	0.84 (2.76)
10	0.83 (2.72)	0.84 (2.76)	0.87 (2.85)
11	0.86 (2.82)	0.89 (2.92)	0.90 (2.95)
12	0.87 (2.85)	0.94 (3.08)	0.92 (3.02)
AU2041	1.2 (3.94)		
AU2042	1.1 (3.61)		

The outer plan channels are more exposed to incident waves than the existing channel, so a higher mean significant height is expected. The reduced maximum height in the plan channel appears to be a consequence of the deeper channel and refraction by the northwest-southeast-oriented bathymetric contours south and east of the channel. Maximum wave conditions come from the south and have unusually long wave periods. They are refracted more strongly than routine wave conditions from the south at this site. Bathymetric contours around the outer part of the existing channel are oriented more in an east-west direction and would have less impact on waves from the south.

High mean and extreme significant wave heights in the middle part of the existing channel relative to the plan channels (Stations 7 to 9) are attributed mainly to relatively shallow depths in the existing channel and shallow depths adjacent to the channel. This part of the channel transects an active bar area. Also, flanks of the plan channels help refract energy away from the channel and reduce wave height in the channel when wave directions are near parallel to the channel alignment. This effect would be especially evident around stations 7, 8, and 9.

Table 8
Maximum Significant Wave Height and Direction Along Navigation Channels

Station	Existing		Plans 1 & 2		Plan 3	
	$H_{s,max}$, m (ft)	Dir., deg az.	$H_{s,max}$, m (ft)	Dir., deg az.	$H_{s,max}$, m (ft)	Dir., deg az.
1	0.57 (1.9)	230	0.57 (1.9)	230	0.53 (1.7)	230
2	0.36 (1.2)	220	0.36 (1.2)	220	0.49 (1.6)	220
3	0.54 (1.8)	220	0.53 (1.7)	220	0.45 (1.5)	210
4	0.92 (3.0)	220	0.89 (2.9)	210	1.00 (3.3)	210
5	1.66 (5.5)	200	1.55 (5.1)	210	1.41 (4.6)	230
6	2.24 (7.4)	200	1.95 (6.4)	190	1.62 (5.3)	190
7	3.98 (13.1)	200	2.77 (9.1)	220	2.83 (9.3)	180
8	5.03 (16.5)	180	3.08 (10.1)	220	3.78 (12.4)	180
9	5.21 (17.1)	190	3.95 (13.0)	180	5.04 (16.5)	180
10	5.88 (19.3)	190	4.87 (16.0)	180	5.57 (18.3)	190
11	6.03 (19.8)	190	5.65 (18.5)	180	5.72 (18.8)	180
12	5.95 (19.5)	180	5.68 (18.6)	180	5.87 (19.3)	180
AU2041	5.7					
AU2042	5.7					

Waveroses

Figures 23-28 display waverose diagrams along the entrance channel for existing and Plan 1 and 2 configurations. Waveroses along existing and Plan 1 and 2 channels are identical for the first 5 stations (up to Range +6.4 km or +2.0 mi). These 5 stations share the same location in existing and proposed channel configurations. Thus the changed outer channel has no significant impact on wave climate in the inner portion of the entrance channel.

Waveroses at Station 6 (Range +8.0 km or +2.5 mi), where the existing and proposed channels still coincide, begin to show a difference. For Stations 7 to 12, waveroses become different for the existing and proposed channel configurations since the plan channel alignment is very different from the existing channel alignment.

Waveroses for the first 3 stations in both existing and Plan 1 and 2 channels are very similar to each other and very different from the other 9 stations. The first 3 stations, around the Cape Fear River mouth, are sheltered by Bald Head Island from waves coming from the northeast, east, and southeast directions. For stations in the mid range and outer channel, at Station 4 and beyond, waves predominantly come from the

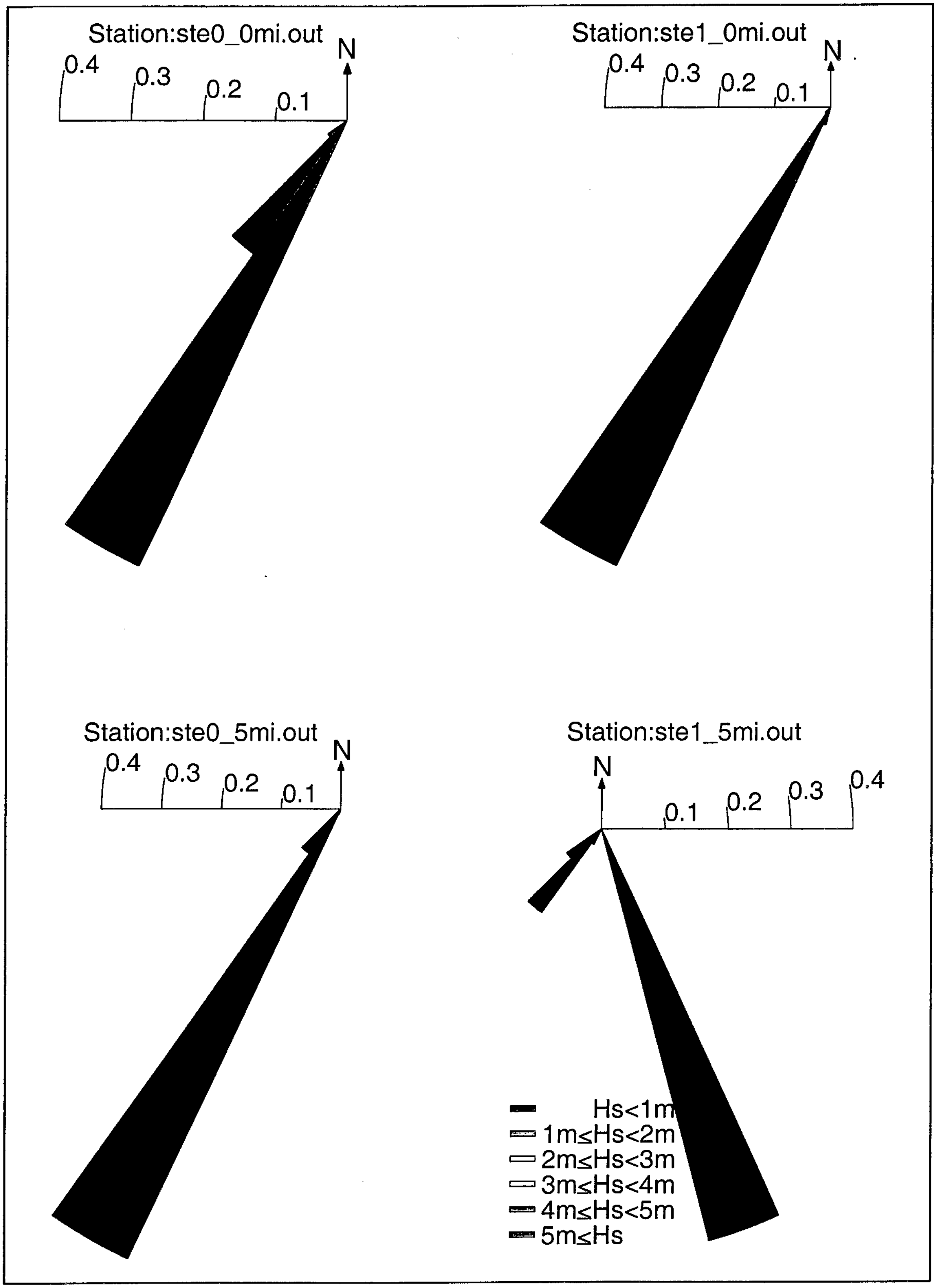

Figure 23. Waverose, existing channel, stations E1 to E4

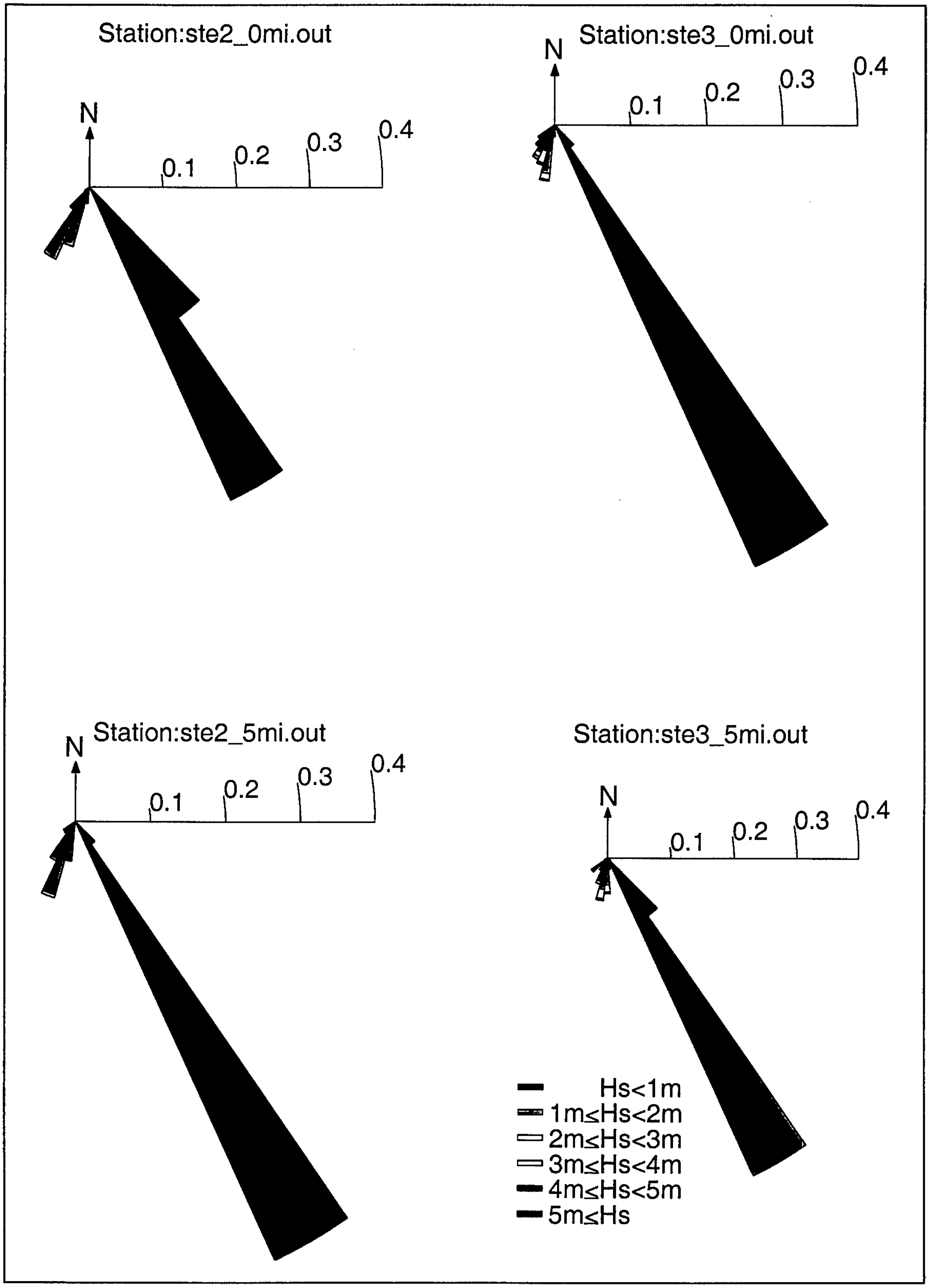

Figure 24. Waverose, existing channel, stations E5 to E8

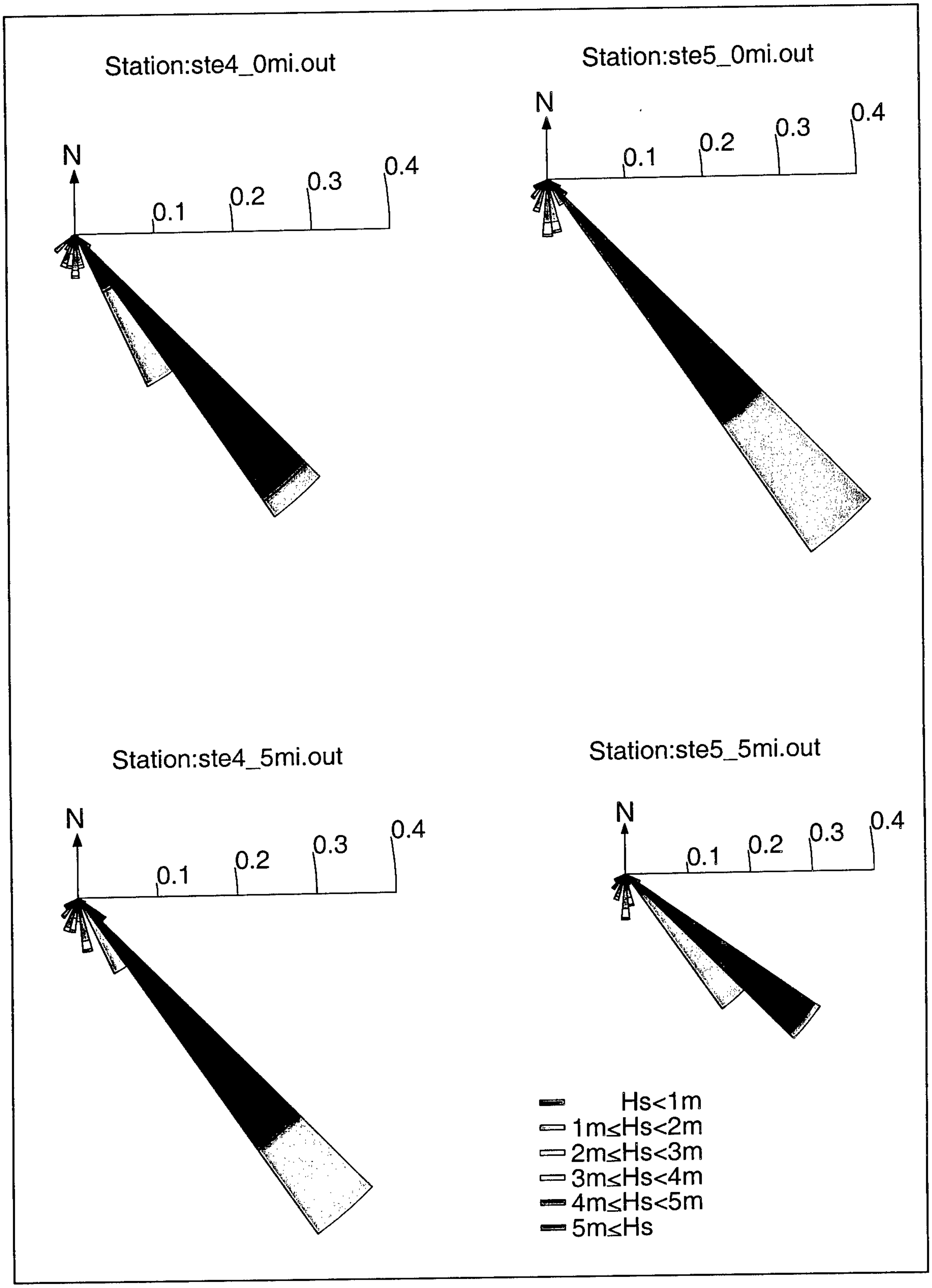

Figure 25. Waverose, existing channel, stations E9 to E12

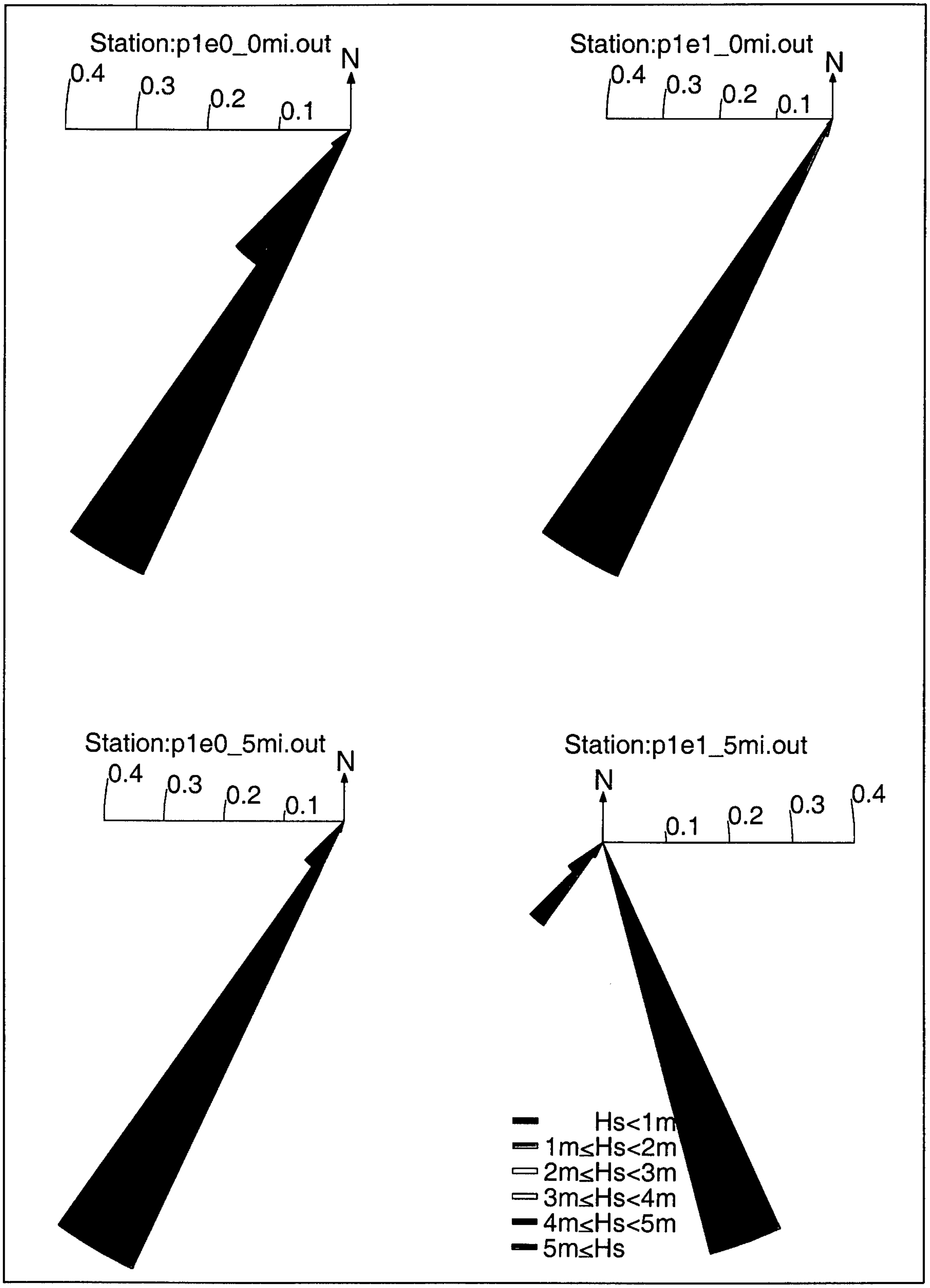

Figure 26. Waverose, Plan 1 and 2 channels, stations P1 to P4

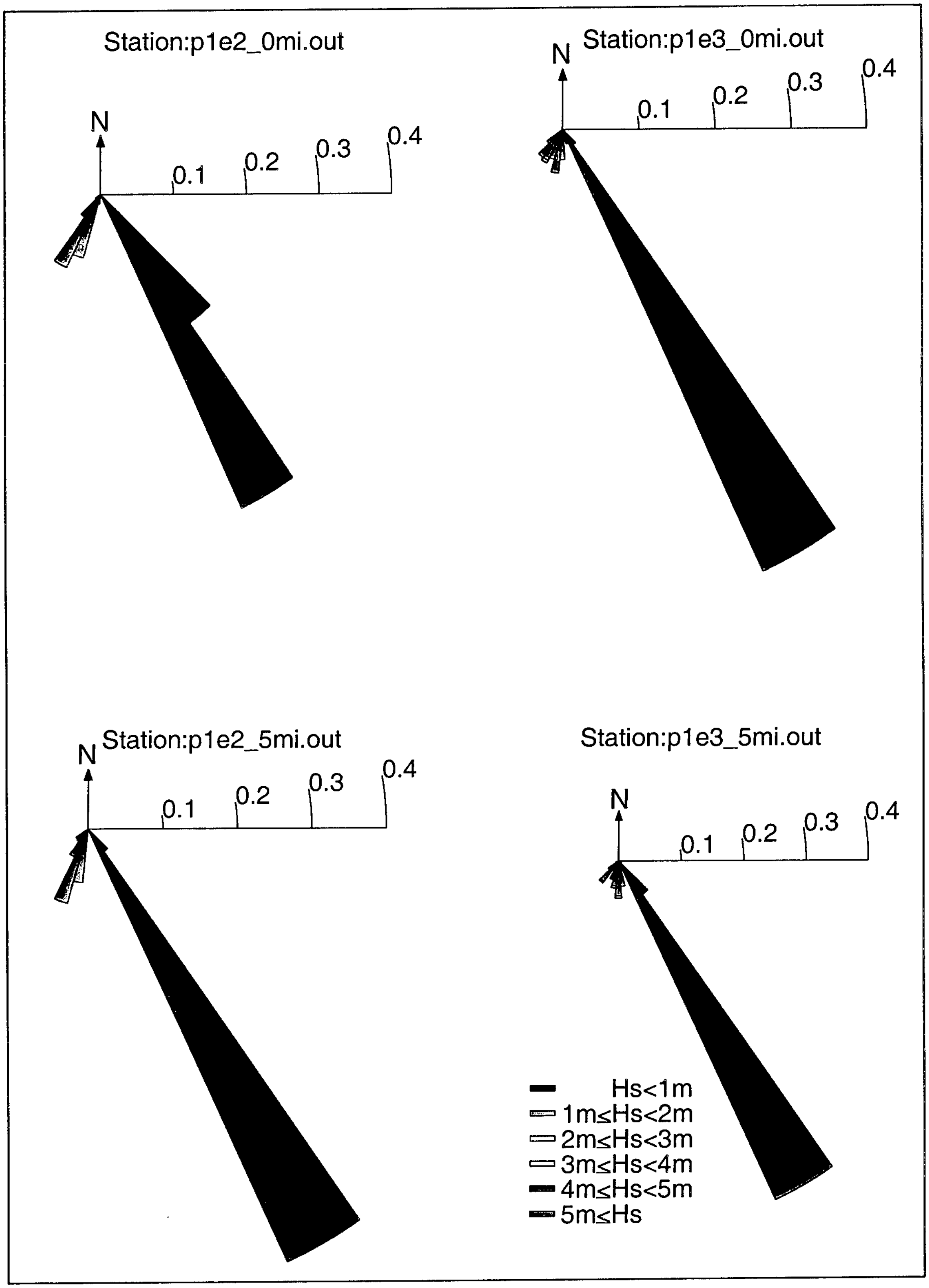

Figure 27. Waverose, Plan 1 and 2 channels, stations P5 to P8

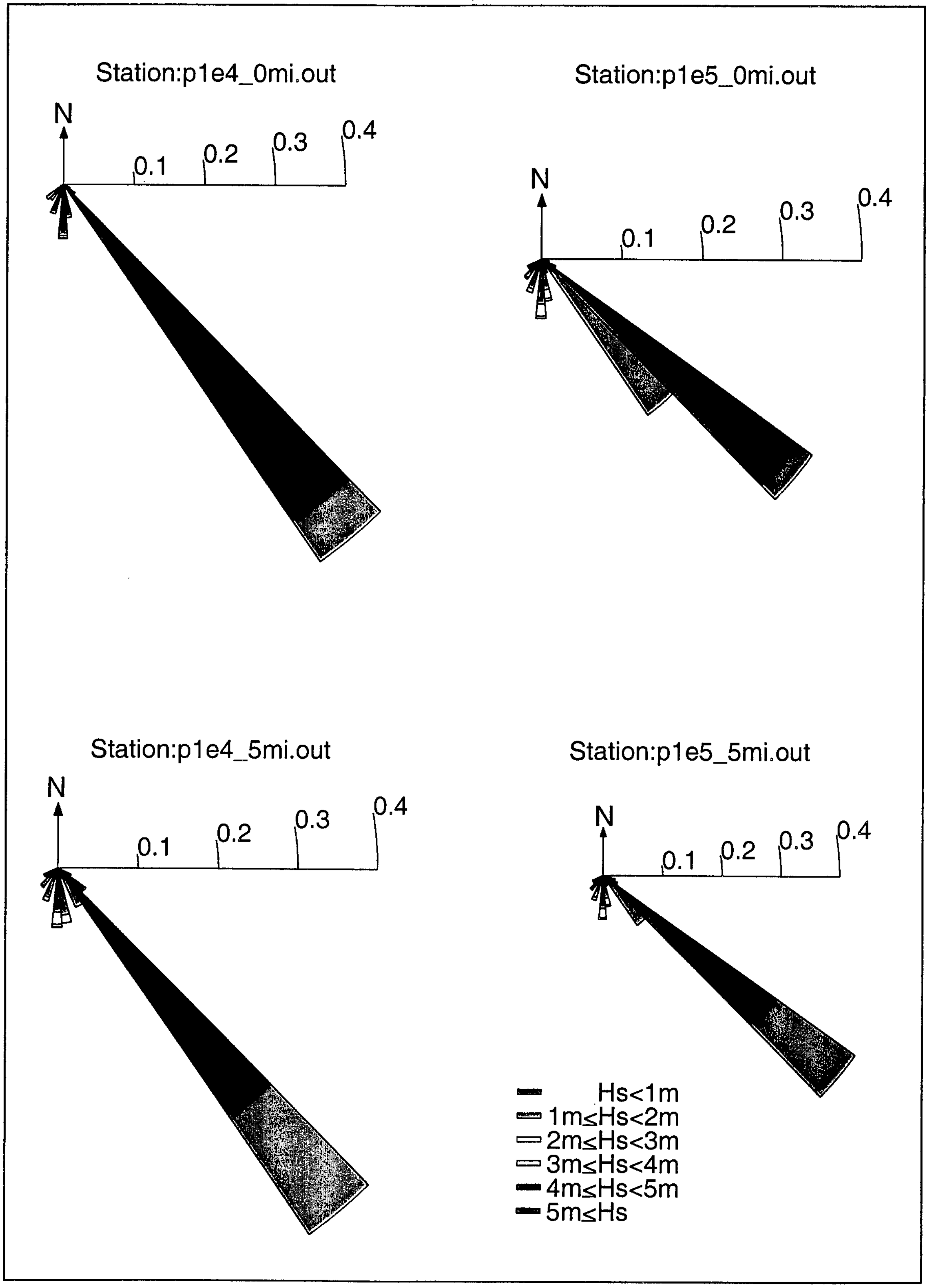

Figure 28. Waverose, Plan 1 and 2 channels, stations P9 to P12

southeast direction between 135 and 155 deg azimuth. These are waves incident from the northeast, east, and southeast, and refracted over Frying Pan Shoals before arriving at the navigation channel.

Some variability in directional distribution at the more seaward stations is due to the use of a 10-deg interval for station summaries while incident waves are run at 22.5-deg intervals. For example, the 160-deg direction has an unusually small number of occurrences. A more refined direction interval for incident waves is impractical. The 10-deg interval for channel station summaries is advantageous for evaluating wave attack direction relative to ships underway in the channel and corresponding ship motions.

Waveroses for the Plan 3 channel are shown in Figures 29-31. They are quite similar to the Plan 1 and 2 results except for a very noticeable shift of wave conditions from the southeast in Plans 1 and 2 to the southern sector in Plan 3. The shifted portion of the wave climate involves low to moderate wave conditions, with H_s less than 2 m. This difference is attributed primarily to modeling procedures rather than actual climate differences. As discussed in Chapter 3, 135-deg incident waves were initially run on east-facing grids for the initial phase of this study (existing and Plan 1 and 2 channels) and rerun on south-facing grids for the second phase (Plan 3 channel) to reduce model effects. The Plan 3 climate is expected to be more representative.

Significant wave heights greater than 2 m are evident only in the outer existing and plan channels. Extreme waves in the channel area are generated by hurricanes and tropical storms. They generally approach in a narrow direction band from the south. The plan channels are better aligned with high wave approach directions than the existing channel. This may allow ships to navigate more easily in the plan channels than in the existing channel during high wave conditions. Although the outer plan channels face an exposure to high wave conditions, there does not appear to be any significant negative impact of allowing higher waves to propagate up the channel.

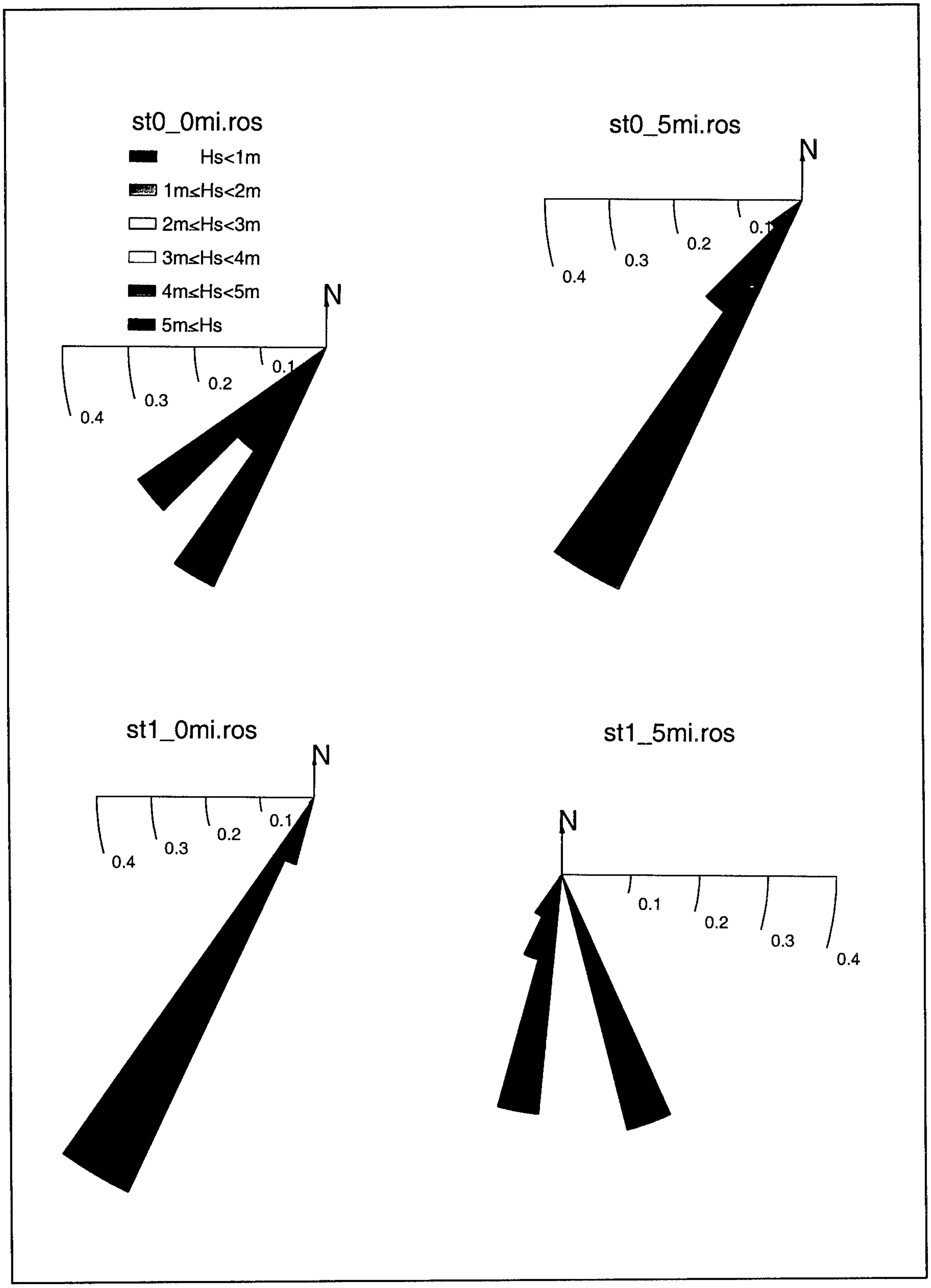

Figure 29. Waverose, Plan 3 channel, stations P3-1 to P3-4

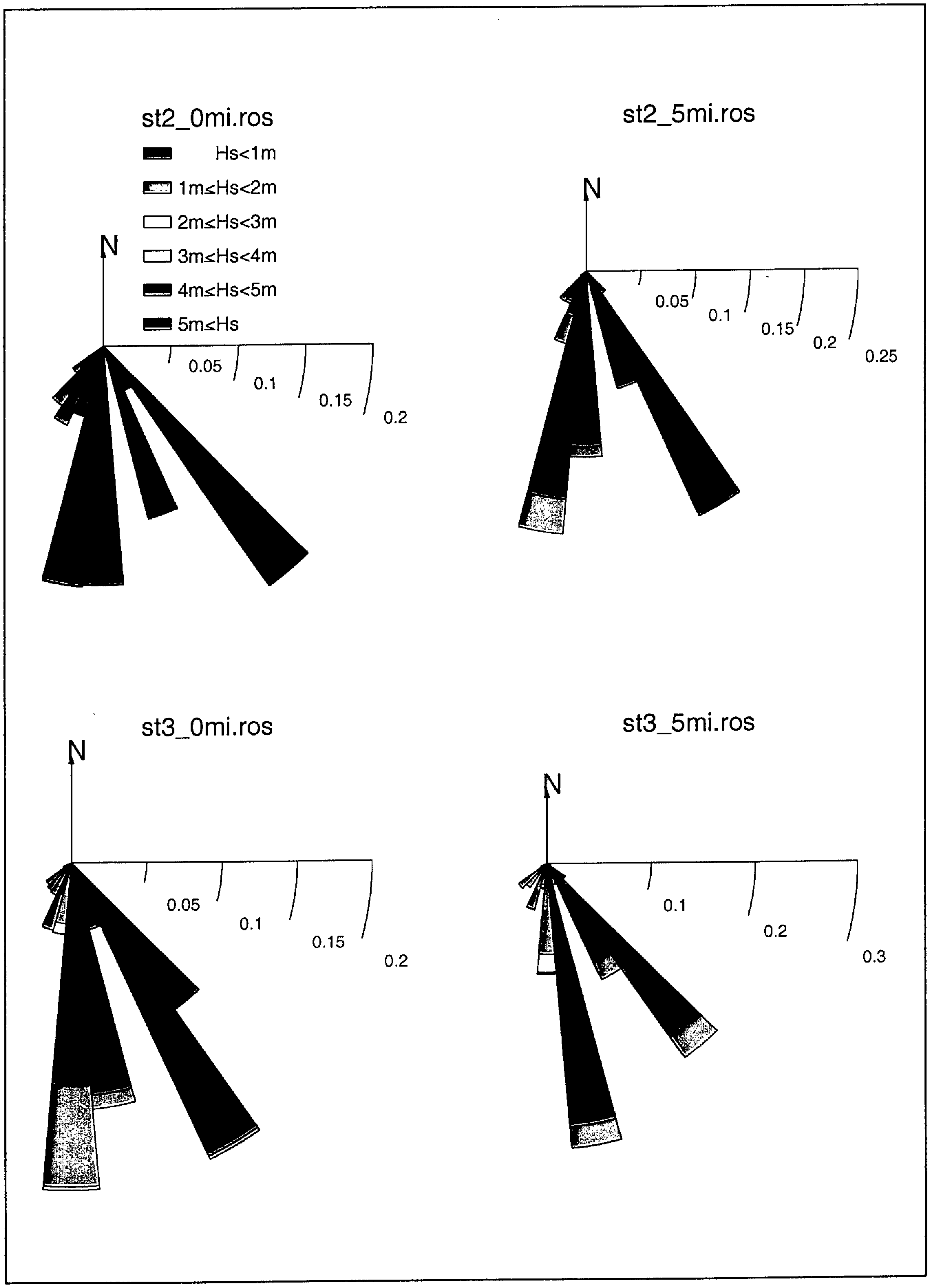

Figure 30. Waverose, Plan 3 channel, stations P3-5 to P3-8

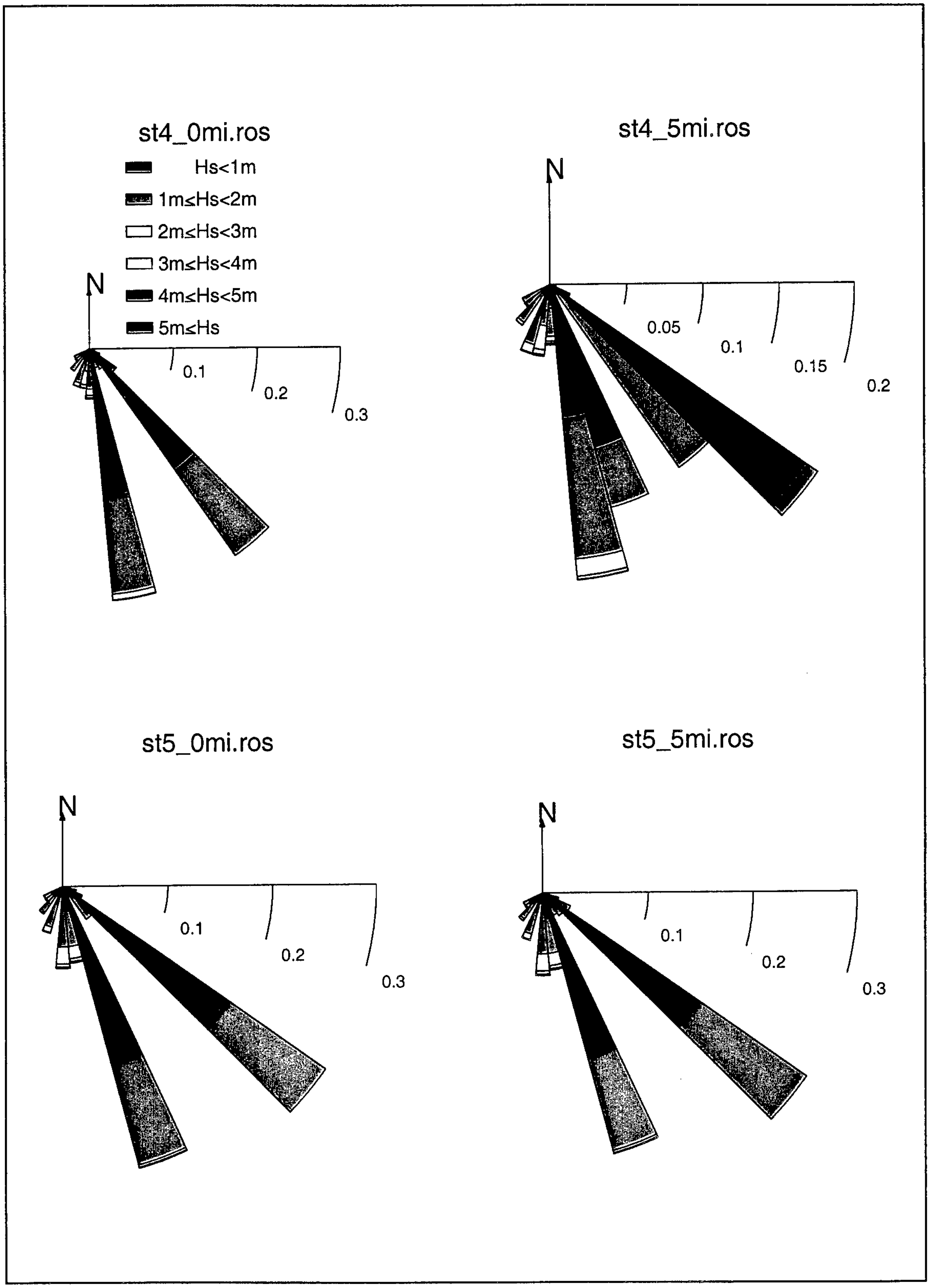

Figure 31. Waverose, Plan 3 channel, stations P3-9 to P3-12

5 Littoral Transport Potential

Existing Conditions

Westward and eastward potential longshore transport rates for existing bathymetry in Area II, between the middle of Long Beach and Bald Head Island, are given in Figure 32. Longshore transport rates are expressed in millions of cubic yards per year. It is important to remember that these are *potential* transport rates, and include no consideration of the availability of sediment. Distance along the coast is expressed as the distance in 1,000's of feet from west longitude 78 deg 25 min, the west edge of the Area III grid. Beach names and the Cape Fear River entrance are located with respect to distance markers.

Westward transport rates are greater than eastward rates over most of this region. Along beaches west of Cape Fear River entrance, westward transport rates range between about 250,000 and 500,000 cu yd per year. Eastward rates along these beaches are around 100,000 cu yd per year. Westward transport dominates along Bald Head Island, as well. The dominance of westward transport is a consequence of the orientation of bathymetric contours and coastline, which generally face toward southwest and south-southwest, and the strong representation in the WIS offshore wave climate of incident waves from easterly directions.

Littoral transport patterns within the area can be explained with reference to model bathymetry (Figure 11). Around distance 85,000 ft, westward transport rate drops from 600,000 to 300,000 cu yd/yr over a fairly short distance. This drop correlates with a nearshore trench feature in the bathymetry and a reorientation of bathymetric contours from nearly east-west toward southeast-northwest. The dramatic increase and decrease in eastward transport at distances 113,000-122,000 ft is a consequence of Jay Bird Shoals, the large shoal area immediately north of the navigation channel.

East of Cape Fear River entrance, eastward transport rates fall to near zero and slowly increase with distance from the entrance. Westward transport rates are high and steadily decrease to relatively low values at Cape Fear, where much of the wave energy from easterly directions is blocked by Frying Pan Shoals.

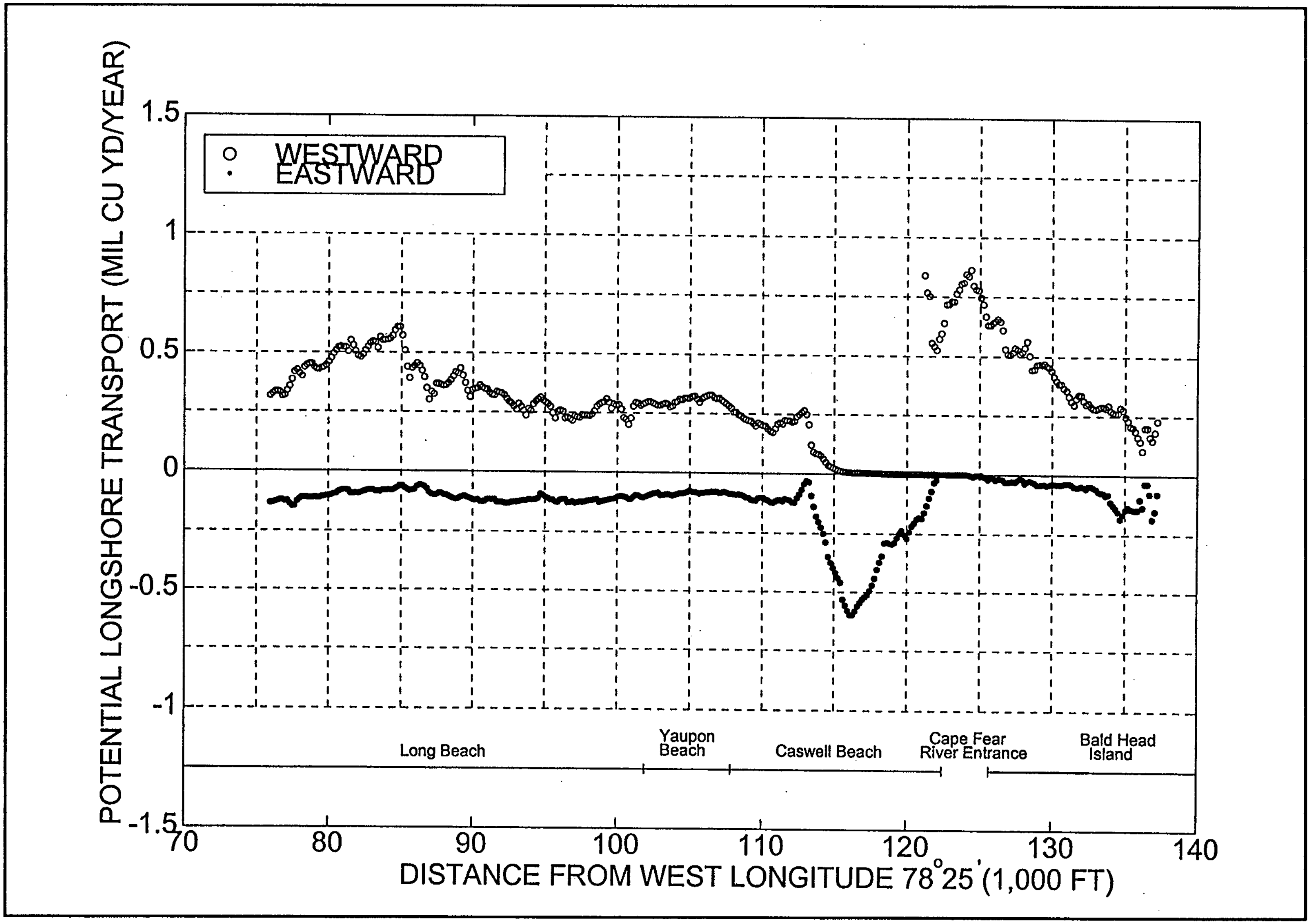

Figure 32. Westward and eastward *Q*, Area II, existing condition

Net and gross littoral transport rates for this area are given in Figure 33. Net transport is westward except along part of Caswell Beach. Net transport rate can be indicative of beach stability. Beach areas with a relatively constant net transport rate should be stable. Beach areas along which net transport rate changes significantly may be eroding or accreting.

Longshore transport rates in Area III, between Ocean Isle Beach and Long Beach, are given in Figures 34 and 35. This relatively smooth stretch of coast shows much less variability in longshore transport rates than the Cape Fear River entrance area. Westward and eastward transport rates are generally higher than in Area II, due to the reduced shadowing of Frying Pan Shoals and large ebb tide shoals. Westward transport rates tend to decrease and eastward rates tend to increase with distance West, a likely consequence of the gently curving orientation of coastline and bathymetry. Both Lockwoods Folly Inlet and Shallotte Inlet have a noticeable impact on local longshore transport rate.

Net transport rates range between about zero and 300,000 cu yd/yr toward the west, though a local peak over 500,000 cu yd/yr occurs near Lockwoods Folly Inlet. Net transport becomes quite low along Ocean Isle Beach. Gross transport rates are around 500,000 cu yd/yr or greater in all locations. These gross tranport rates are substantially higher than those along most of the Area II coast.

Although this study included nearshore stations near grid boundaries, model results in the near-boundary regions are generally not reliable. For example, a station near the east boundary of Area III cannot possibly include effects of bathymetry in Area II, which would affect waves from easterly directions. Boundary effects account for differences in longshore transport rates between Areas II and III at their juncture.

Historical Conditions

Littoral transport results for historical bathymetry from the year 1872 differ from existing conditions around Cape Fear River entrance and Bald Head Island (Figures 36 and 37). Comparison of these patterns with existing conditions gives a perspective on impacts of the dredged navigation channel over many years. Westward and eastward transport rates for 1872 and existing bathymetry are superimposed in Figure 38. In the area west of Cape Fear River entrance, the most noticeable difference is the reduced eastward transport along most of Caswell Beach caused by the 1872 bathymetry. Differences along Long Beach are small. As discussed in Chapter 3, bathymetry offshore from this area is existing, since 1872 bathymetry did not extend out far enough to fill the grid.

Immediately east of the entrance, the 1872 bathymetry gives reduced westward transport. The low littoral transport rates in this area are a consequence of a large, very shallow shoal extending from shore in an east-west orientation. Beyond reference distance 130,000 ft, westward transport rates are significantly higher for the 1872 bathymetry in comparison to the existing condition. This increase can be attributed at least partially to a changed orientation of the Bald Head Island coast and nearshore bathymetry.

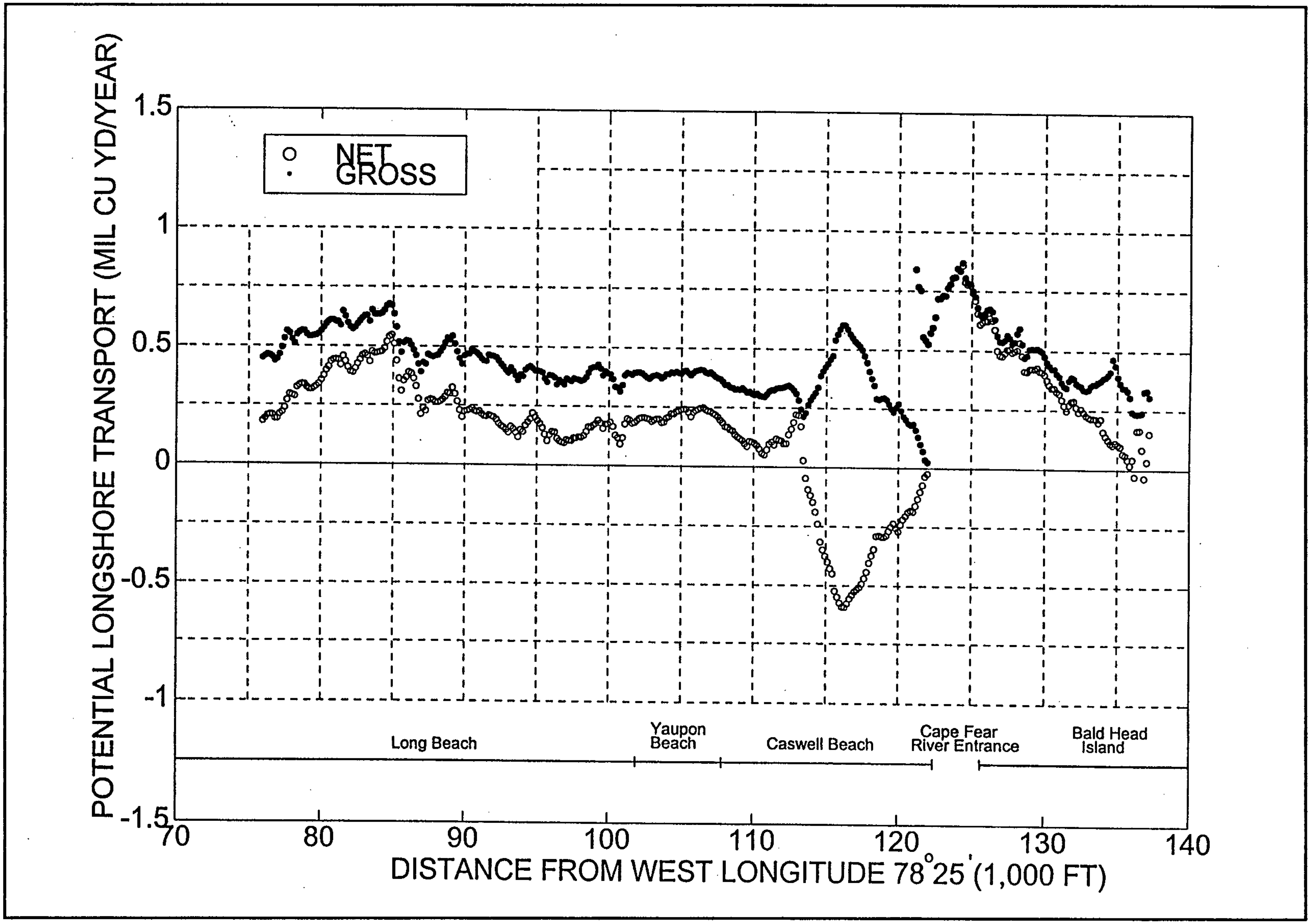

Figure 33. Net and gross *Q*, Area II, existing condition

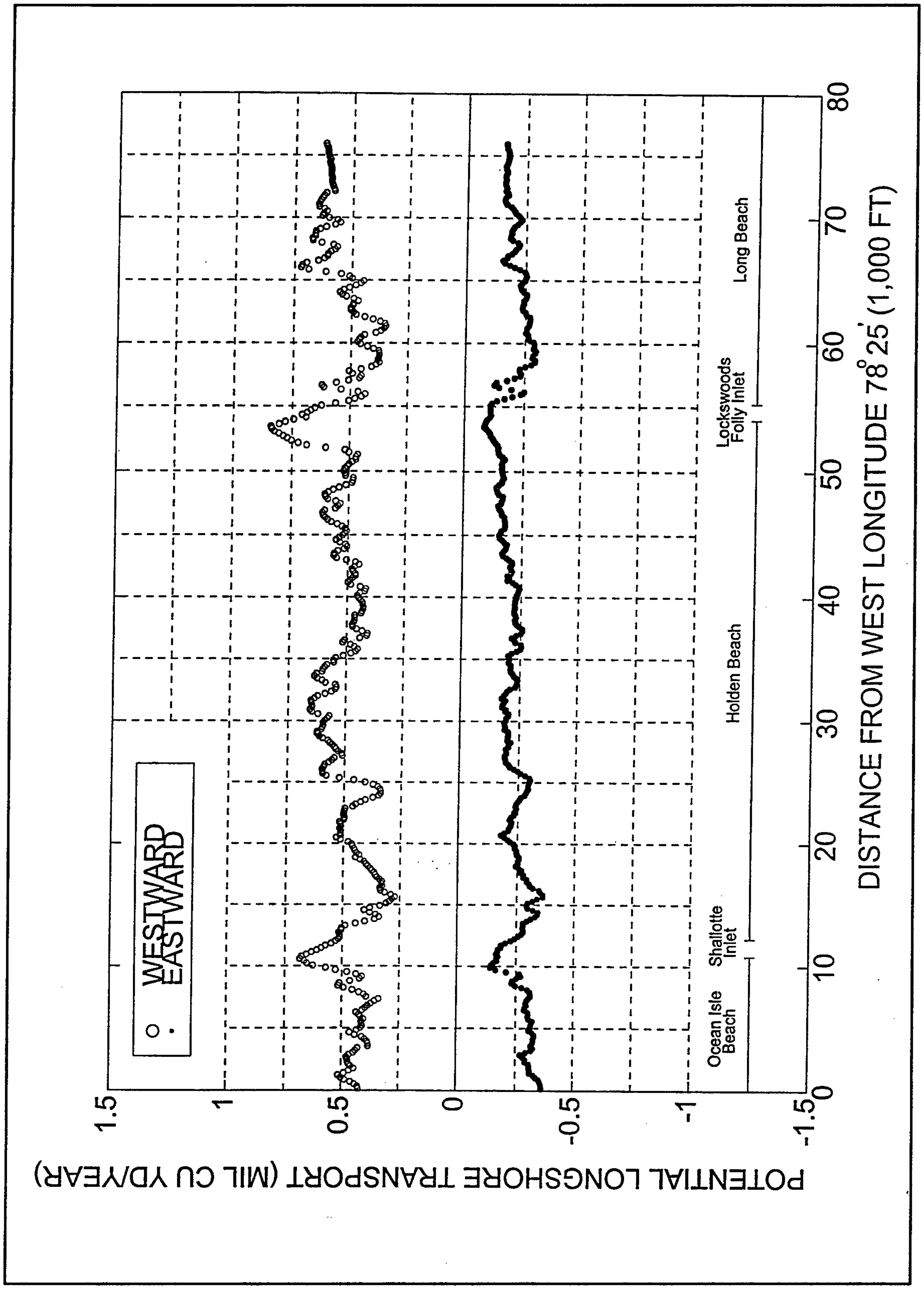

Figure 34. Westward and eastward *Q*, Area III, existing condition

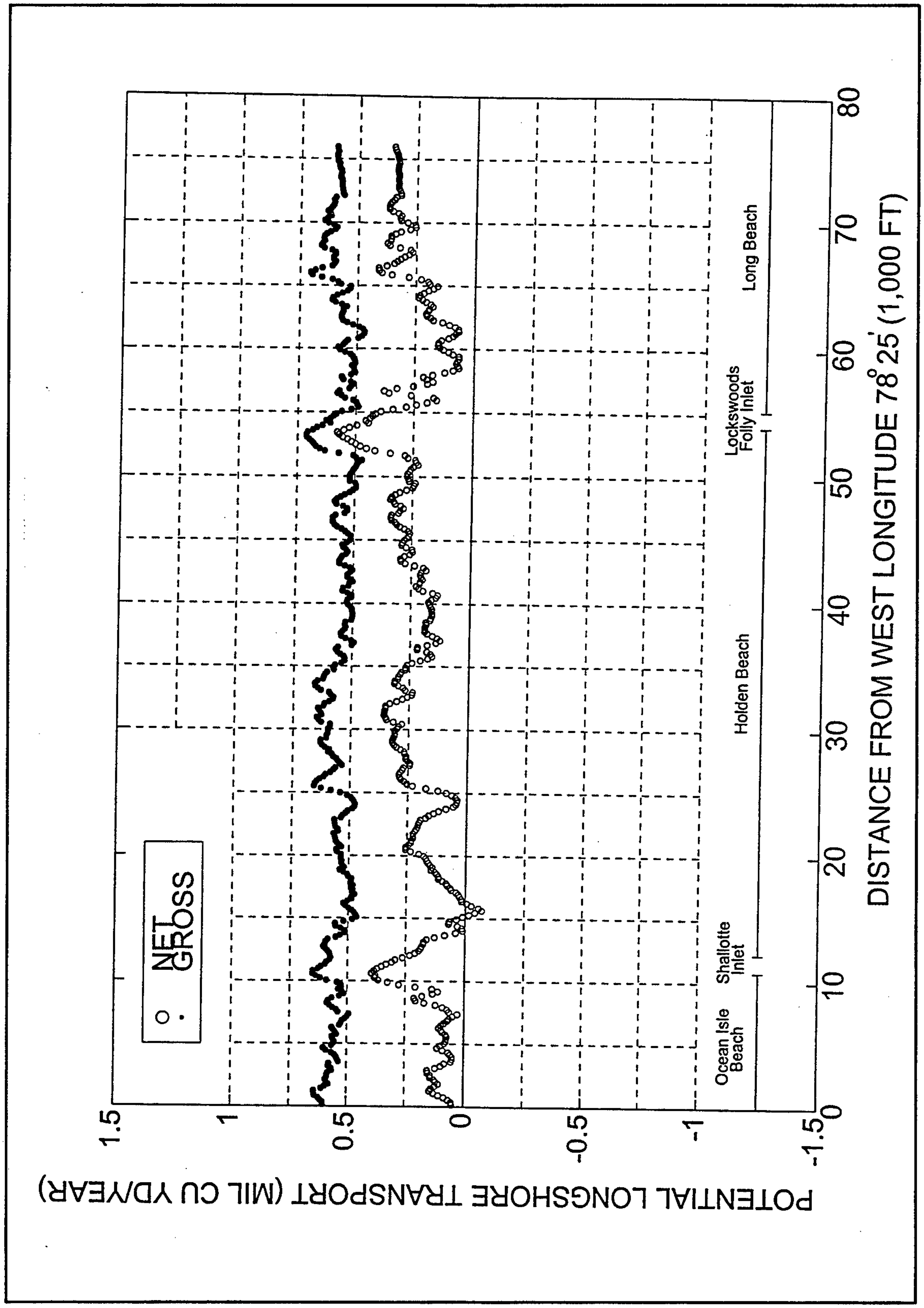

Figure 35. Net and gross *Q*, Area III, existing condition

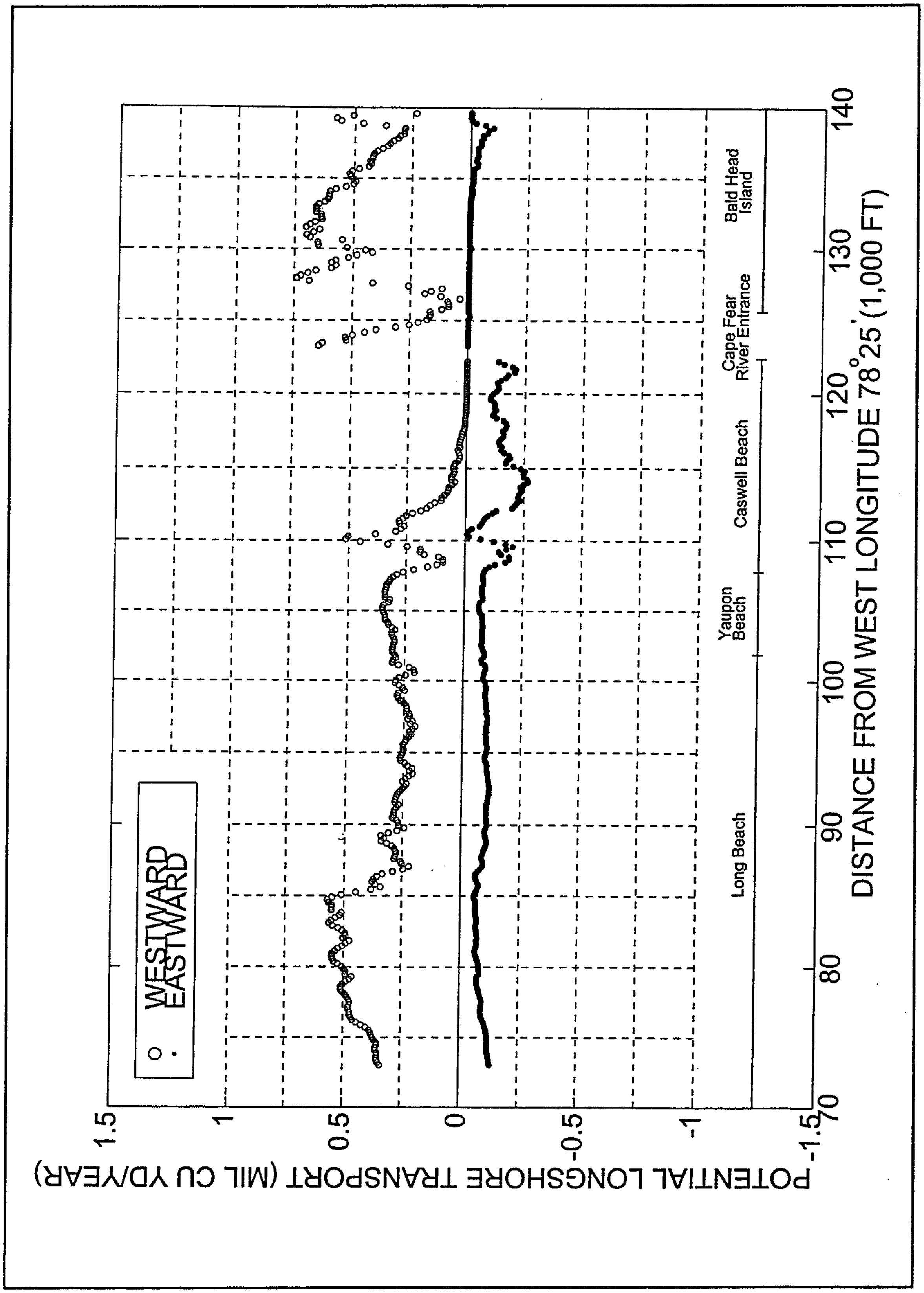

Figure 36. Westward and eastward *Q*, 1872 bathymetry

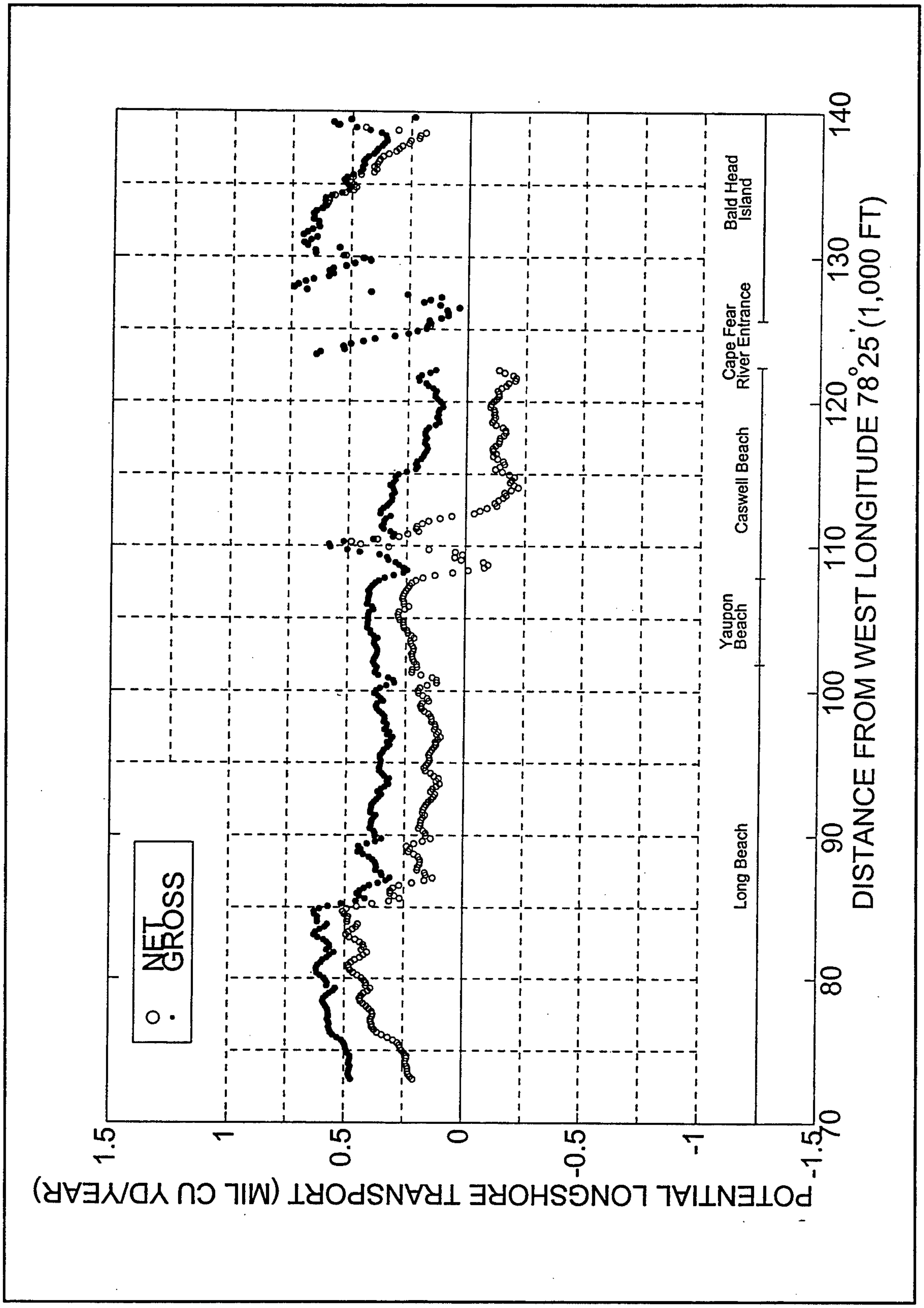

Figure 37. Net and gross *Q*, 1872 bathymetry

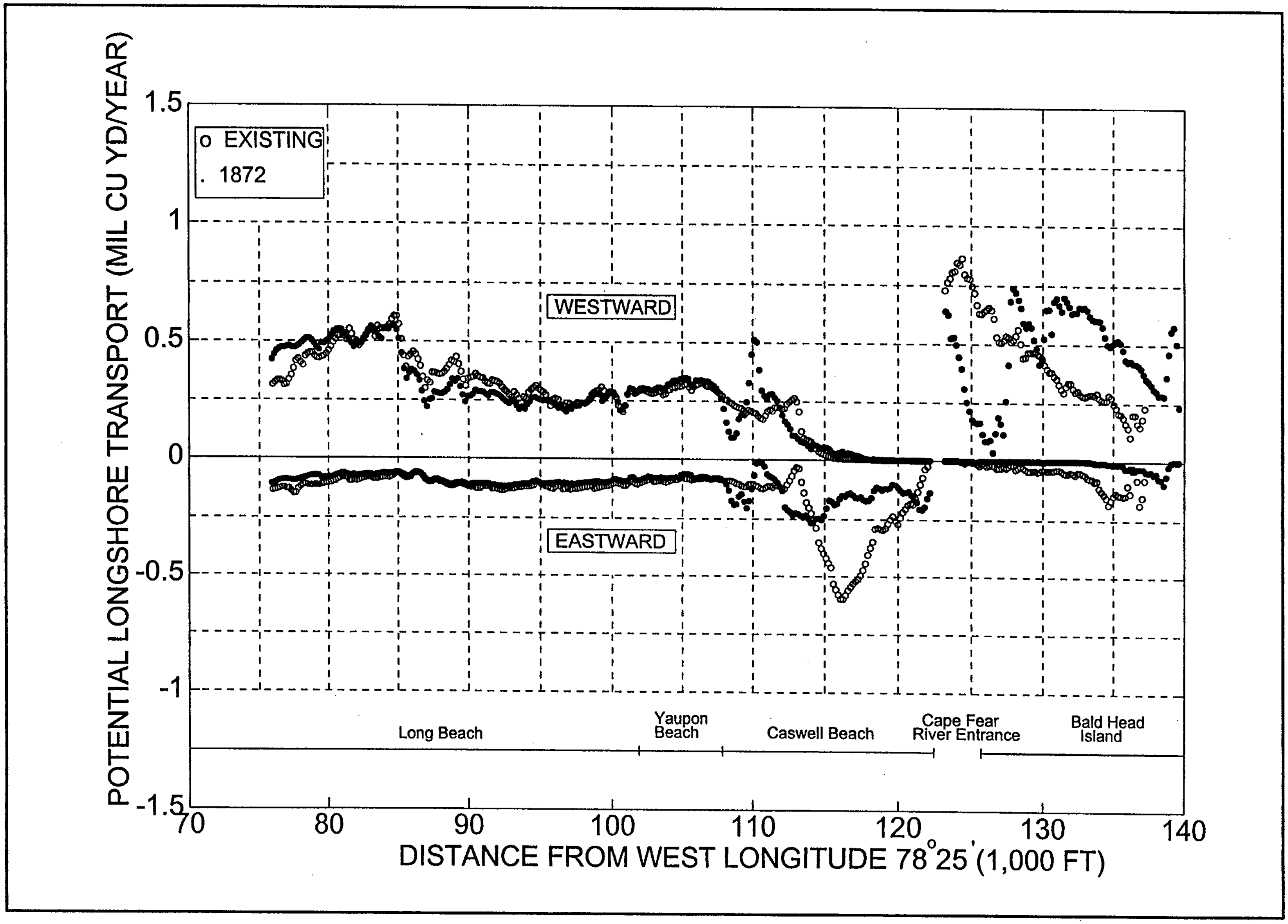

Figure 38. Westward and eastward *Q*, existing and 1872 conditions

Differences between net and gross transport rates in 1872 and existing conditions are shown in Figure 39. Some differences, such as those in the vicinity of distance marker 110,000 ft, are a consequence of localized shoal features which may have been transient even when bathymetry data were collected. The most significant difference trends in 1872 appear to be decreased eastward transport along eastern Caswell Beach, decreased westward transport along western Bald Head Island, and increased westward transport along central and eastern Bald Head Island. Key causes of the differences are the less developed shoal west of the entrance in the 1872 bathymetry, more developed shoal adjacent to shore on the east side of the entrance, and the changed shoreline and bathymetry orientation of Bald Head Island.

Proposed New Entrance Channel

Littoral transport rates for Plan 1 and 2 bathymetry are nearly identical to the existing condition, indicating that the presence of the plan channel has little impact on littoral transport (Figures 40 and 41). Superimposed westward/eastward transport rates and differences in net/gross rates clarify the small differences between Plan 1 and 2 and existing conditions (Figures 42 and 43). Plan conditions indicate a small decrease in transport rates along eastern Caswell Beach. A possible, very localized increase at the west end of Bald Head Island is also suggested.

Results for Plans 1 and 2 with adjusted ebb tide shoals to include anticipated longterm adjustments around the entrance if the plan channel were constructed show greater impacts on littoral transport rates (Figures 44 and 45). Superimposed westward/eastward transport rates and differences in net/gross rates indicate little change in eastward transport rates due to the modified shoals, but a tendency for decreased westward transport rates in some areas (Figures 46 and 47). The most sustained differences along the coast occur at a segment of Long Beach (between distance markers 85,000 and 93,000 ft) and at Yaupon Beach and western Caswell Beach, where westward transport rates drop by up to 70,000 cu yd/yr. Net transport rates in this area decrease correspondingly.

Differences along central and eastern Caswell Beach and Bald Head Island are more variable, but generally small. Transport rates along Bald Head Island indicate a tendency to be lower in the adjusted Plan 1 and 2 bathymetry in comparison to existing conditions.

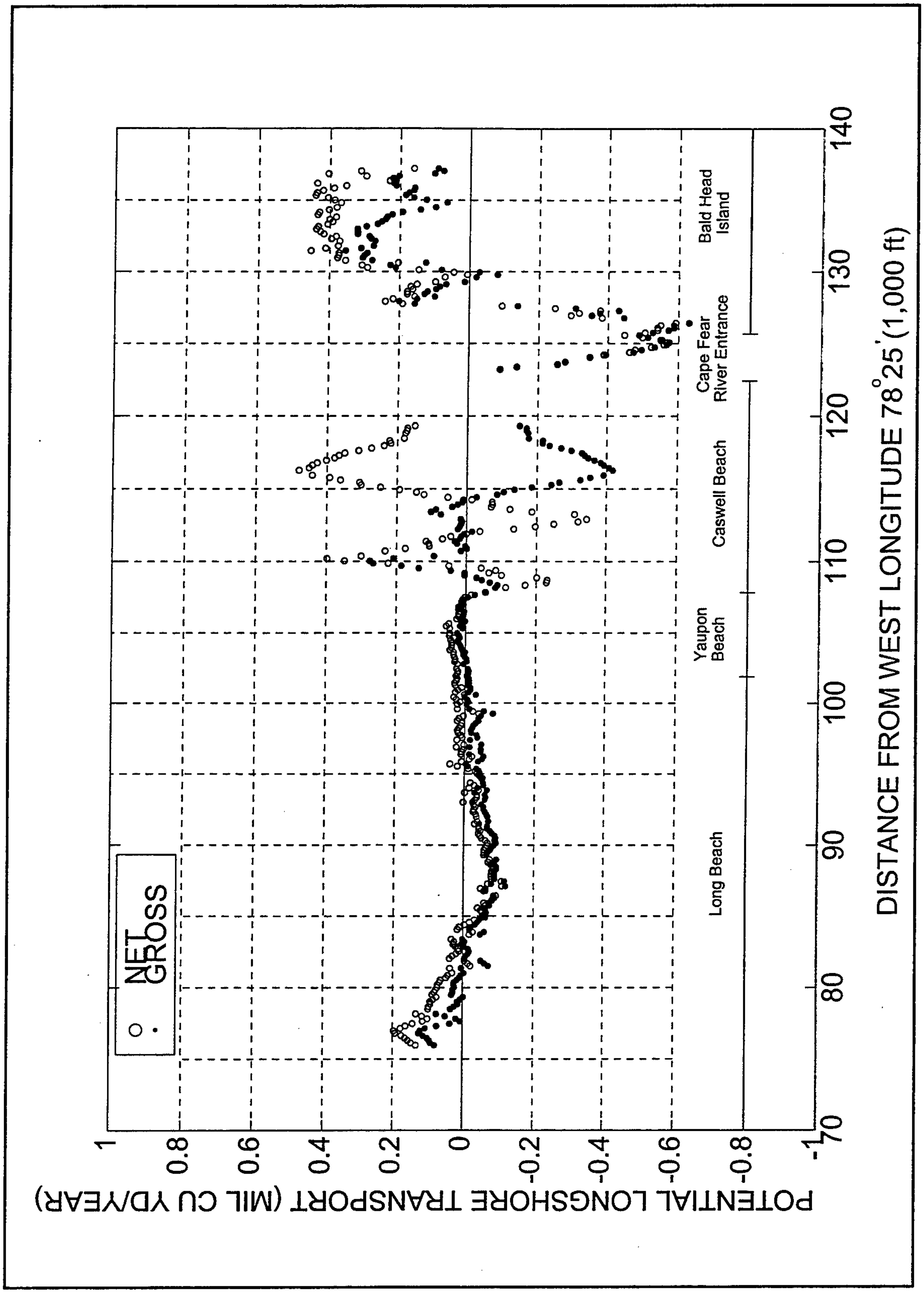

Figure 39. Net and gross *Q*, difference between 1872 and existing

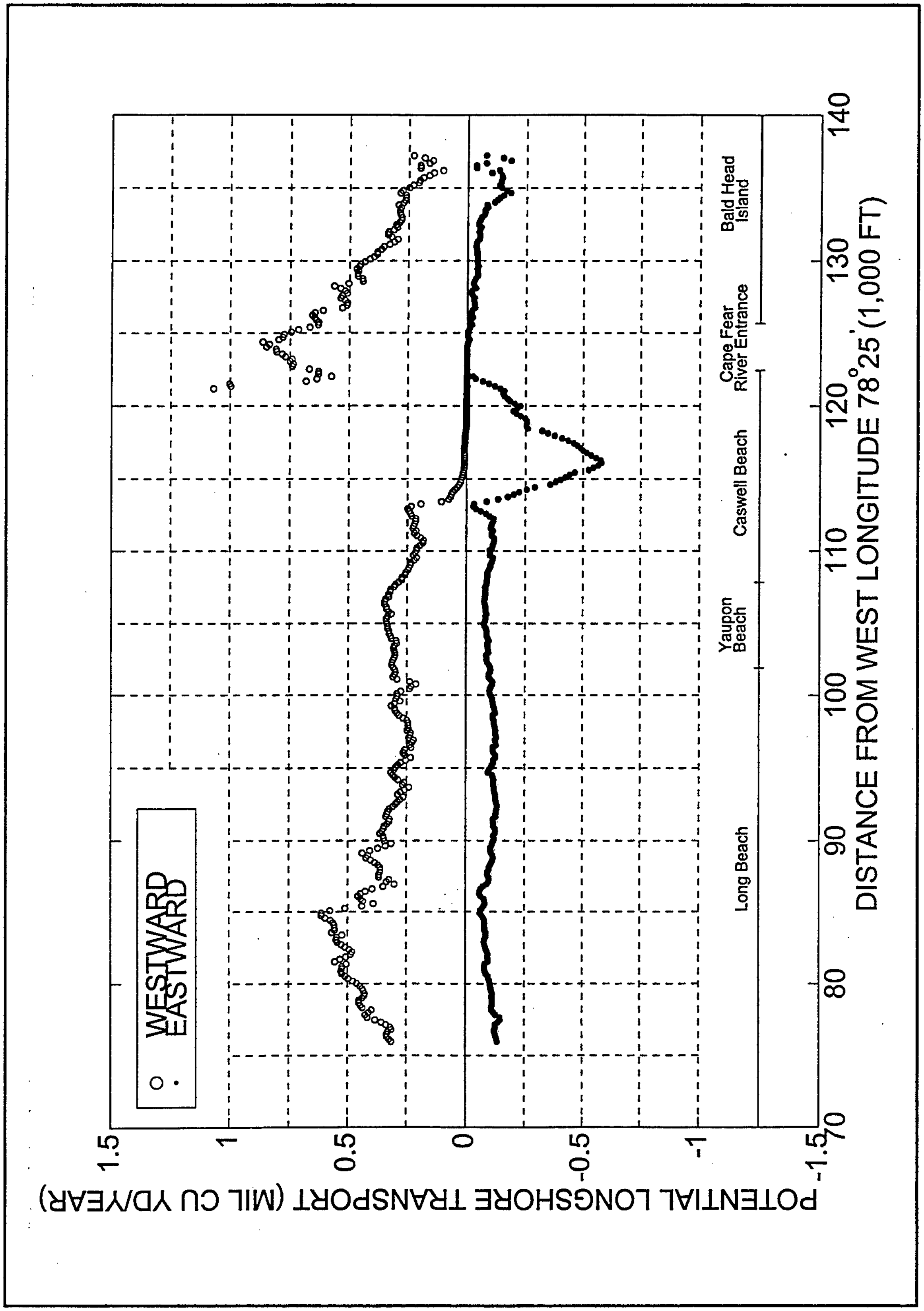

Figure 40. Westward and eastward *Q*, Plan 1 and 2 channel

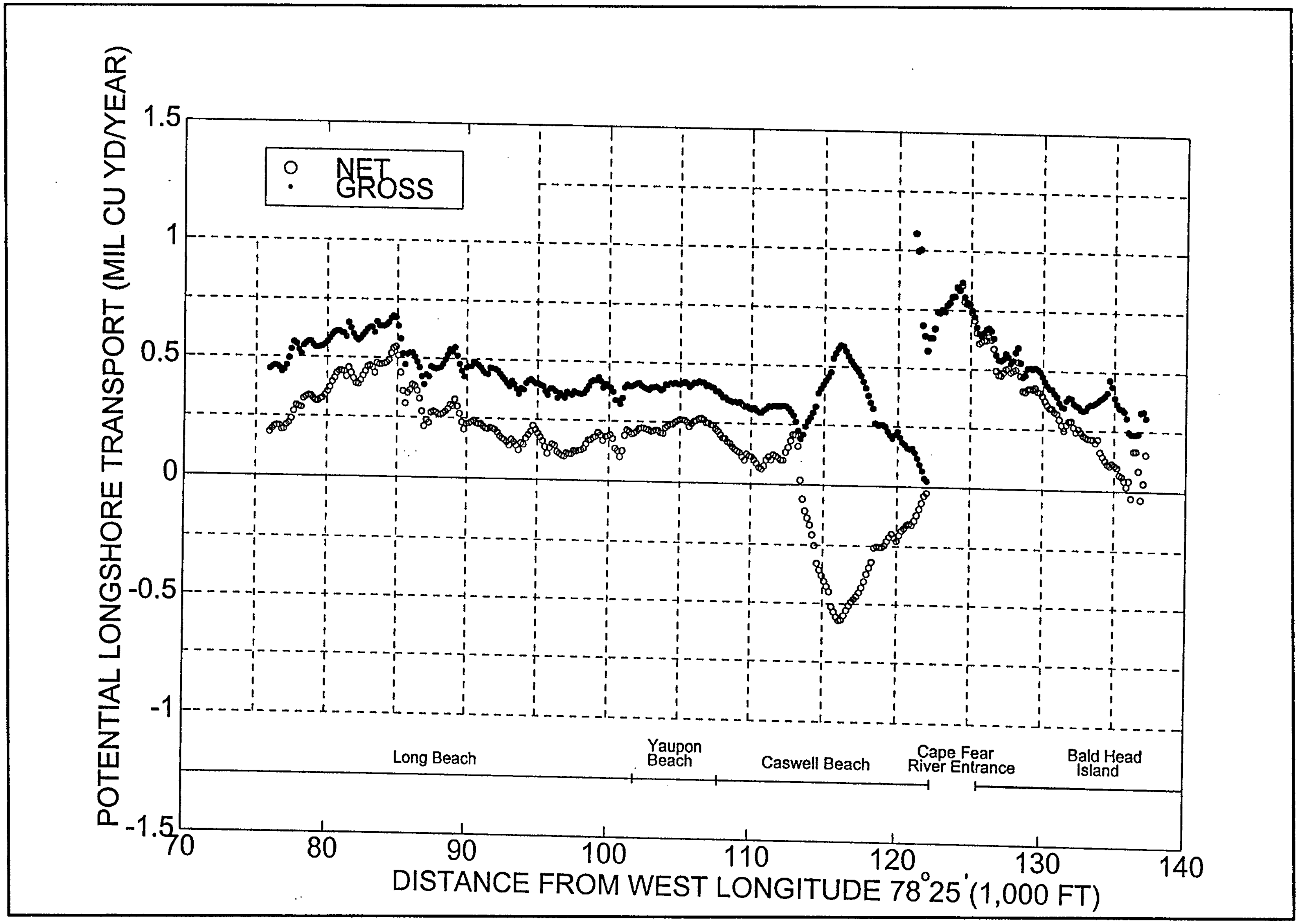

Figure 41. Net and gross *Q*, Plan 1 and 2 channel

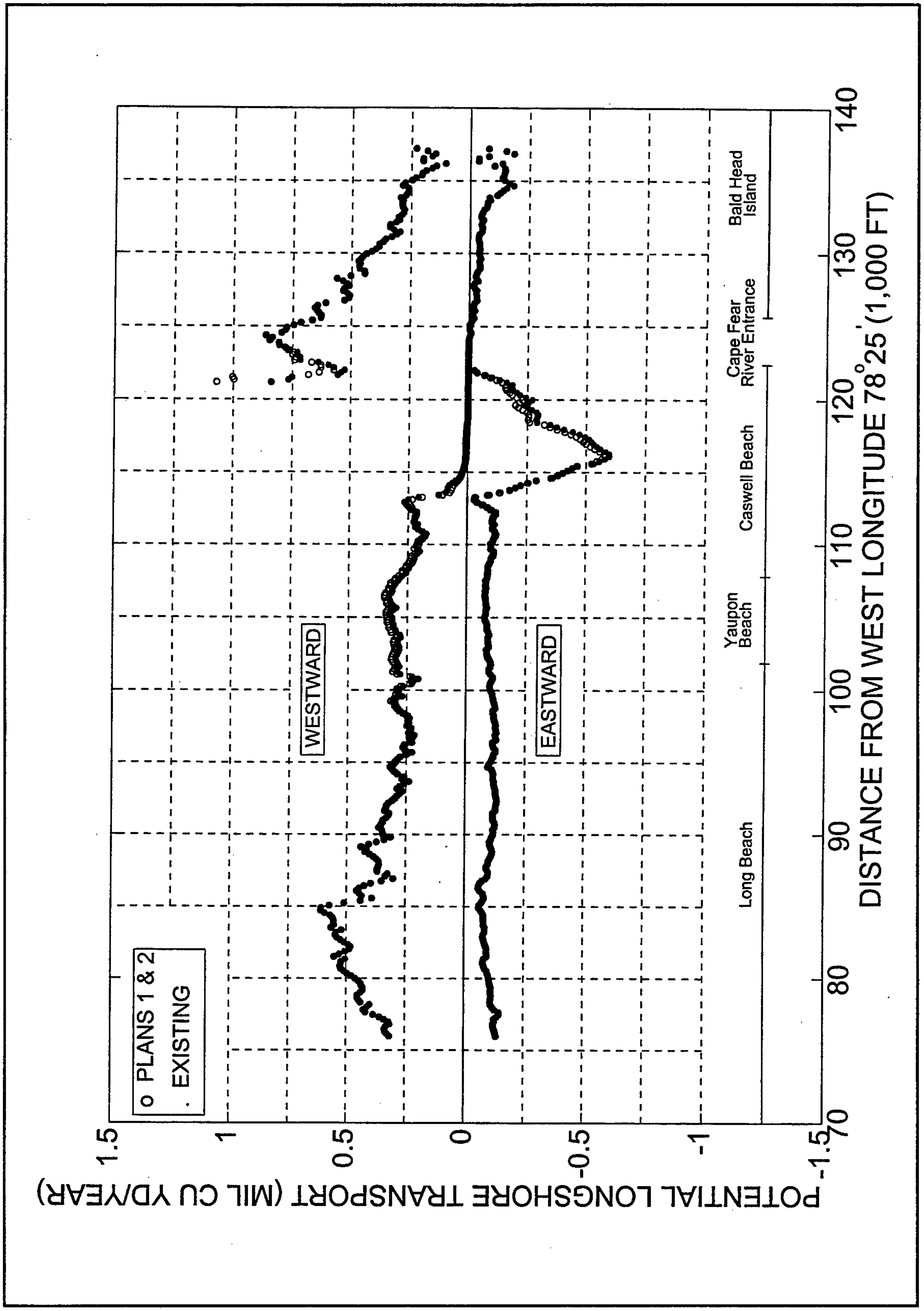

Figure 42. Westward and eastward *Q*, existing and Plan 1/2 conditions

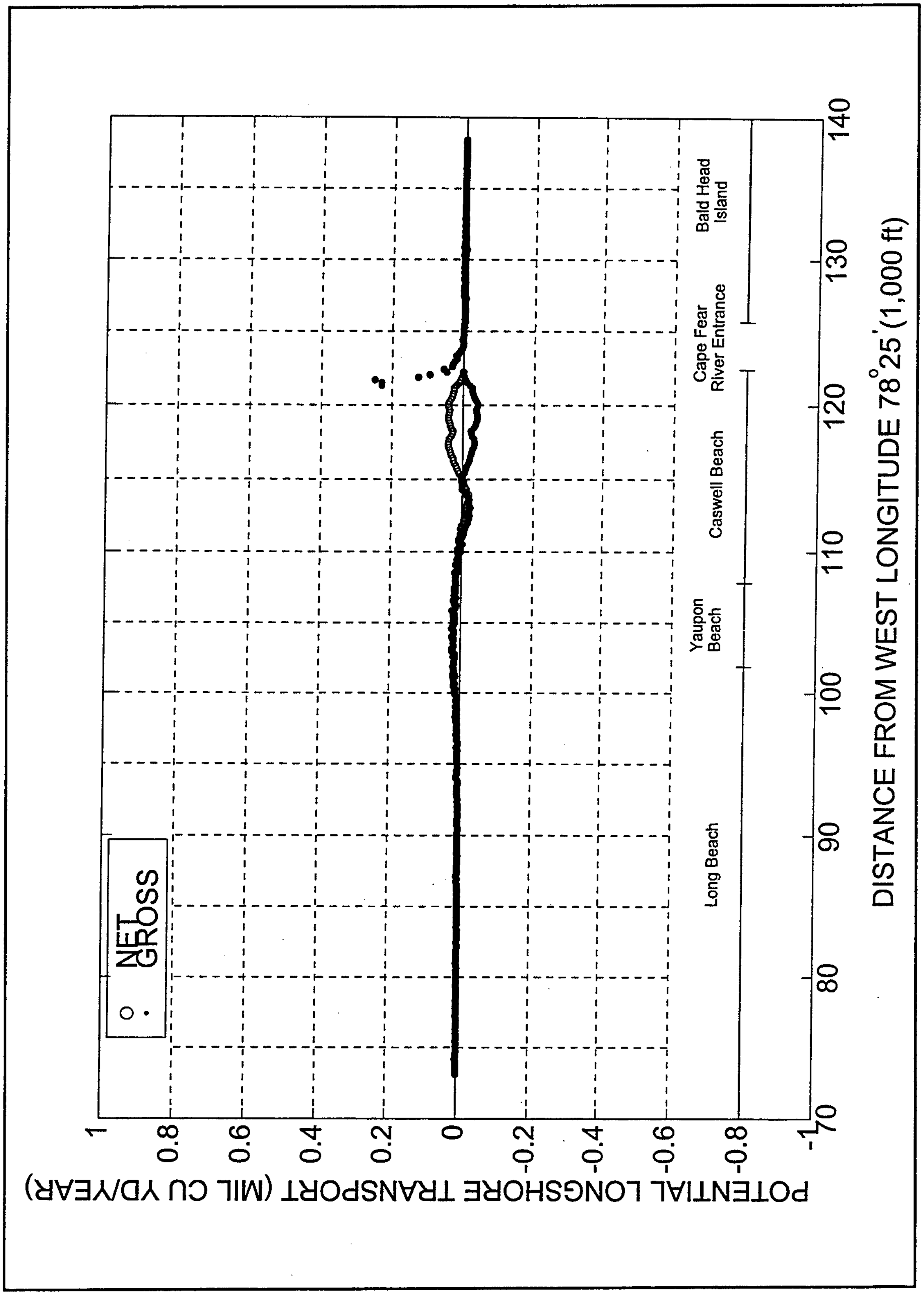

Figure 43. Net and gross *Q*, difference between Plan 1/2 and existing

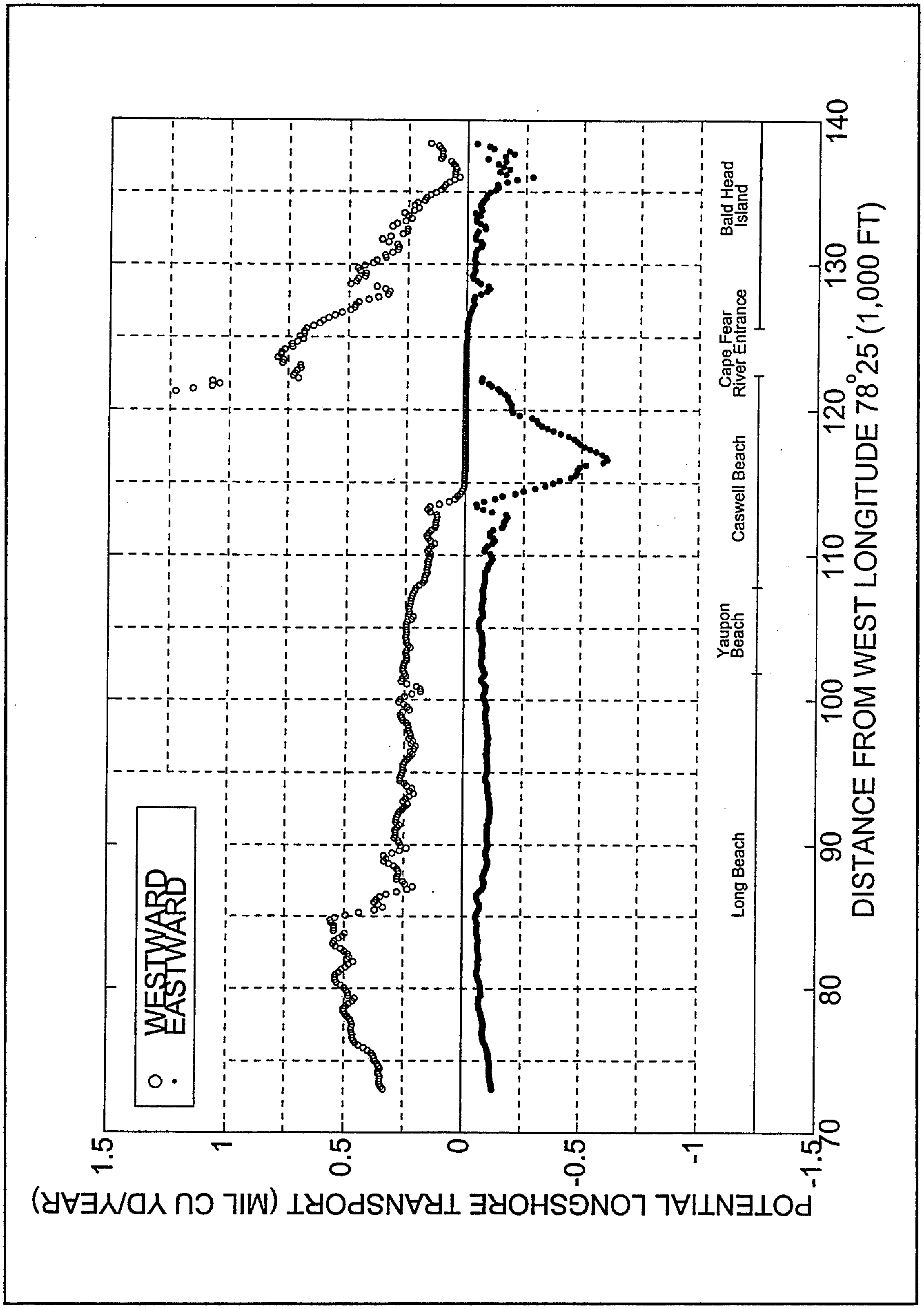

Figure 44. Westward and eastward *Q*, Plans 1 and 2 with adjusted ebb tide shoal

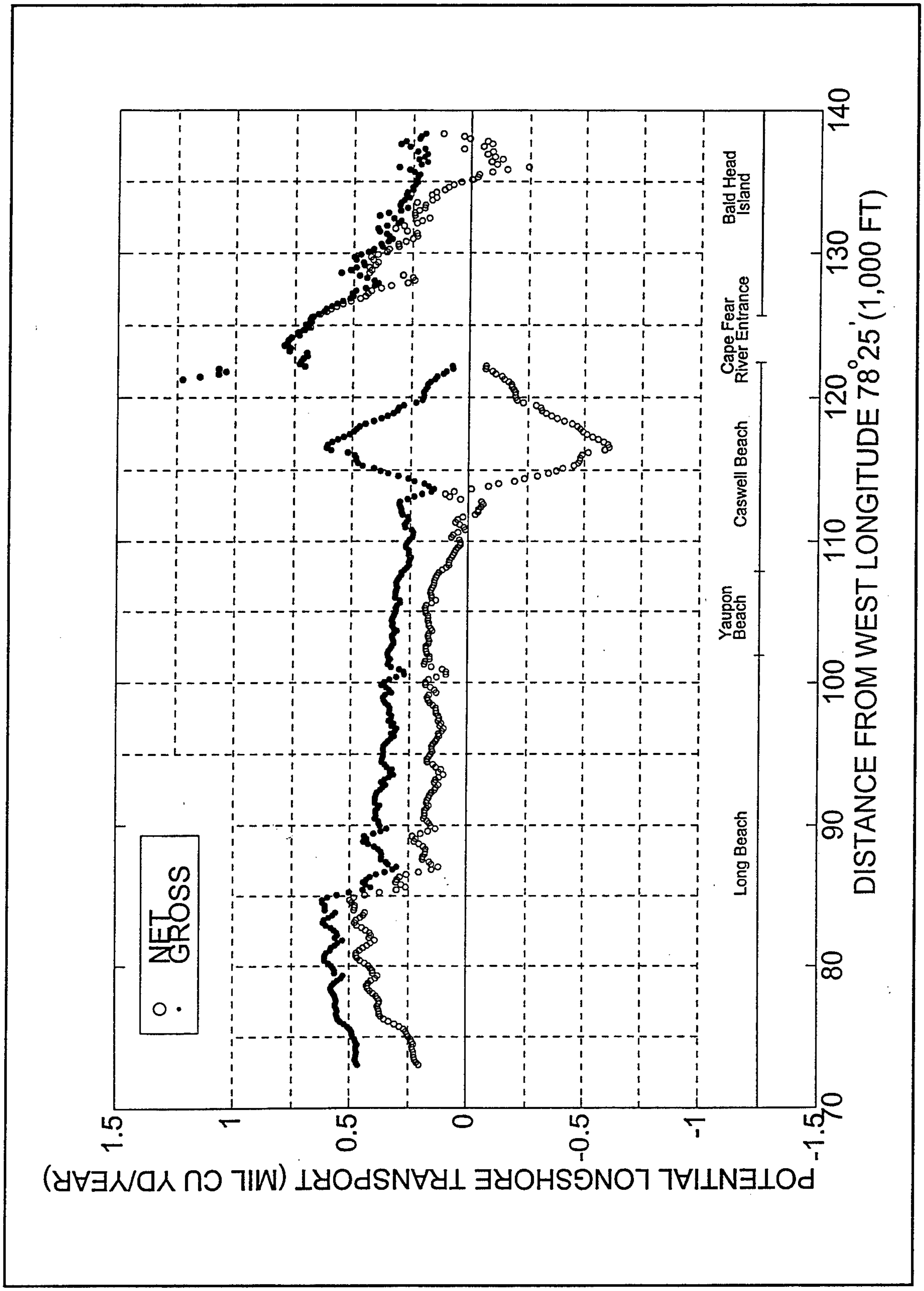

Figure 45. Net and gross *Q*, Plans 1 and 2 with adjusted ebb tide shoal

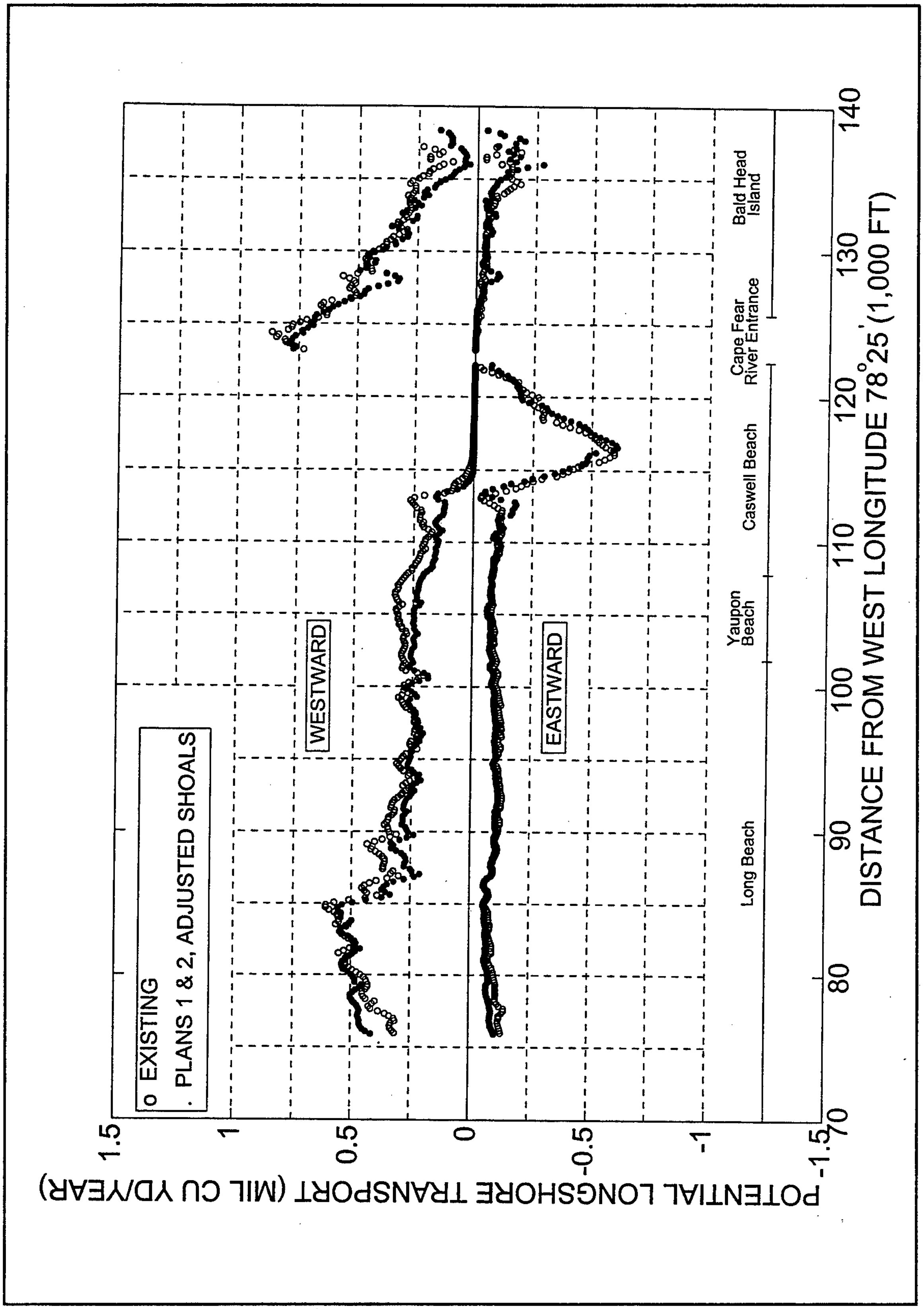

Figure 46. Westward and eastward *Q*, existing and Plan 1/2 with adjusted ebb tide shoal

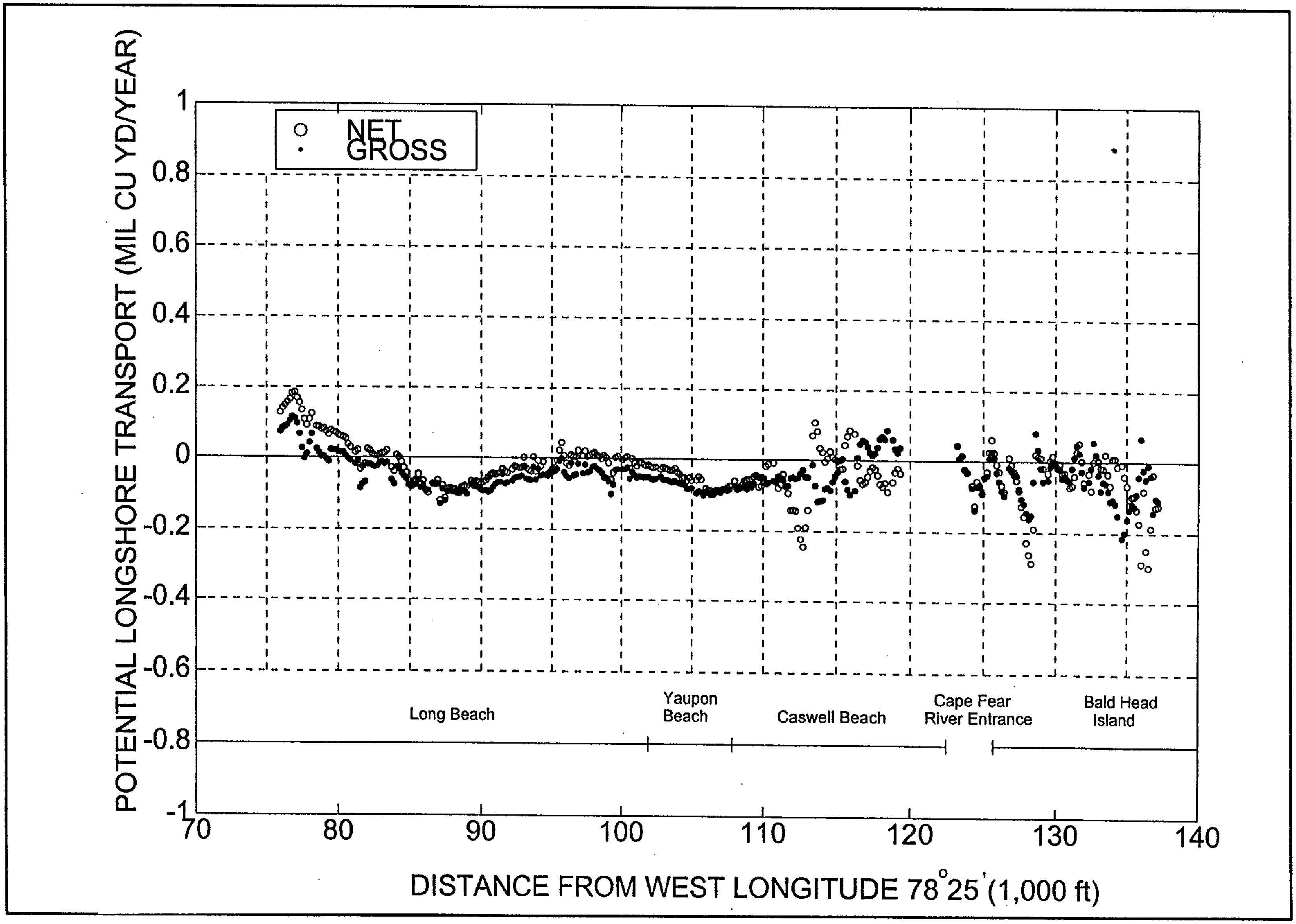

Figure 47. Net and gross *Q*, difference between Plan 1/2 with adjusted ebb tide shoal and existing

6 Conclusions

Numerical model studies have provided information to assist SAW in evaluating potential plans for modifying the Cape Fear River entrance channel and in preparing GRR reports. The offshore wave climate was evaluated, and WIS hindcasts from 1976-1995 were used as the incident wave climate. Wave transformation around Frying Pan Shoals and nearshore bathymetry was modeled with the spectral wave model STWAVE. Wave climate was estimated in existing and plan navigation channels, and along the Brunswick County, North Carolina, coast west of Cape Fear. Since potential areas for offshore disposal of dredged material are included in the wave model coverage, wave climate in the finally-selected ODMDS can be estimated from study results as needed.

Navigation channels included in the study are existing, Plans 1 and 2, and Plan 3. All of the channels considered are significantly sheltered from directions north of southeast by Frying Pan Shoals. The existing channel gains additional protection from the south and southeast because of ebb tide shoals south of the channel. Plan channels are more exposed to the south and south southeast.

Despite differences in exposure, wave climate in the plan channels is similar to the existing condition, indicating that Frying Pan Shoals provides the primary sheltering effect. Mean significant wave height in the outer plan channels is up to 8 percent higher than in the existing channel, but maximum significant height is lower. The increased depth in plan channels is a likely cause of the small reduction in maximum significant wave height. Maximum wave conditions come from 180-190 deg azimuth in all cases. Since plan channels have different orientation than the existing channel, ships in transit may experience high waves from a different direction relative to the ship. High waves from the south are expected to be less troublesome for navigation in plan channels than in the existing channel because waves will be more nearly aligned with the ship travel direction.

Nearshore wave climate was estimated for existing conditions between Cape Fear and the middle of Ocean Isle Beach to the west. Other bathymetric conditions studied between Cape Fear and the middle of Long Beach are historical 1872 bathymetry, Plans 1 and 2, and Plans 1 and 2 with adjusted ebb tide shoals representing a longterm equilibrium with the plan channel. Potential longshore annual transport rates were computed at approximately 55-m (180-ft) intervals along these coasts.

Littoral transport is significantly influenced by nearshore bathymetry, which is represented in considerable detail. In interpreting study results, conclusions should be based on characteristic littoral transport behavior rather than localized fluctuations due to transient shoal features represented in the particular bathymetric data set available. General conclusions from littoral transport studies are as follows:

a. Existing conditions. Littoral transport is predominantly westward along most of the study area. Potential net transport rates increase from near zero at Cape Fear to over 750,000 cu yd/yr at the west end of Bald Head Island. Net transport along most of Caswell Beach is eastward, a reversal of the dominant direction. From western Caswell Beach to Ocean Isle Beach, westward transport dominates ranging from about 100,000 to 200,000 cy yd/yr along Yaupon Beach and eastern Long Beach up to over 500,000 cu yd/yr along central Long Beach and back down to 150,000 cu yd/yr or less at Ocean Isle Beach. Gross transport rates are around 500,000-600,000 cu yd/yr along much of the study area, but lower around Yaupon Beach and eastern Bald Head Island.

b. Historical conditions. Littoral transport rates prior to establishment of a dredged navigation channel, as represented in the 1872 bathymetry, show significantly increased westward transport rates between Cape Fear and central Bald Head Island, and reduced rates along western Bald Head Island and most of Caswell Beach, in contrast to existing conditions. These results are a consequence of the Bald Head Island coast being rotated clockwise toward a more northwest-southeast orientation, a more developed shoal adjacent to the western part of Bald Head Island, and a less developed shoal along Caswell Beach. The net result is reduced transport into the entrance, but a strong transport of sediment along Bald Head Island into the shoal feature along the western part of Bald Head Island.

c. Proposed new entrance channel. The Plan 1 and 2 entrance channel alone has little impact on littoral transport along adjacent shores. When anticipated adjustment of ebb tide shoals in response to the changed channel location is included, the project has a perceptible impact on littoral transport rates. Eastward transport rates are relatively unchanged, but westward transport rates are reduced by up to 70,000 cu yd/yr along western Caswell Beach, Yaupon Beach, and eastern Long Beach. A similar trend for reduced westward transport is evident along Bald Head Island. The adjusted ebb tide shoals appear to afford increased sheltering of adjacent beach areas from incident wave energy.

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Appendix A
WIS Offshore Wave Climate

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT .0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 767
% OF TOTAL: 1.3

HEIGHT IN METERS	.0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	479	3	.	.	.	.	.	.	.	.	482
1.00-1.99	672	106	.	.	8	.	.	.	.	.	786
2.00-2.99	.	18	5	.	18	.	.	.	.	.	41
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	1151	127	5	0	26	0	0	0	0	0	

MEAN Hmo(M) = 1.1 LARGEST Hmo(M) = 2.6 MEAN TP(SEC) = 4.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 22.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 922
% OF TOTAL: 1.6

HEIGHT IN METERS	.0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	381	3	.	.	.	.	.	.	.	.	384
1.00-1.99	482	503	.	.	20	.	.	.	.	.	1005
2.00-2.99	.	124	46	.	15	.	.	.	.	.	185
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	863	630	46	0	35	0	0	0	0	0	

MEAN Hmo(M) = 1.3 LARGEST Hmo(M) = 2.9 MEAN TP(SEC) = 4.7

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 45.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M)
NO. CASES: 2030
% OF TOTAL: 3.5

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	364	56	.	.	.	.	.	.	.	.	420
1.00-1.99	128	2058	17	.	6	.	.	.	.	.	2209
2.00-2.99	.	398	410	6	15	.	.	.	.	.	829
3.00-3.99	.	.	10	.	.	.	.	.	.	.	10
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	492	2512	437	6	21	0	0	0	0	0	

MEAN Hmo(M) = 1.6 LARGEST Hmo(M) = 3.5 MEAN TP(SEC) = 5.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 67.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M)
NO. CASES: 1420
% OF TOTAL: 2.4

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	393	88	10	.	.	.	.	.	.	.	491
1.00-1.99	75	1469	61	.	13	.	.	.	.	.	1618
2.00-2.99	.	124	169	5	13	.	.	.	.	.	311
3.00-3.99	.	.	3	.	.	.	.	.	.	.	3
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	468	1681	243	5	26	0	0	0	0	0	

MEAN Hmo(M) = 1.4 LARGEST Hmo(M) = 3.3 MEAN TP(SEC) = 5.4

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 90.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 11108
% OF TOTAL: 19.0

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	361	660	925	1605	2731	2638	975	275	71	10	10251
1.00-1.99	42	814	843	901	1512	1996	1040	241	94	5	7488
2.00-2.99	.	11	193	126	189	189	152	85	59	.	1004
3.00-3.99	.	.	.	29	114	39	5	11	.	.	198
4.00-4.99	.	.	.	.	8	30	6	.	.	.	44
5.00-5.99	.	.	.	.	.	3	.	.	.	.	3
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	403	1485	1961	2661	4554	4895	2178	612	224	15	

MEAN Hmo(M) = 1.0 LARGEST Hmo(M) = 5.2 MEAN TP(SEC) = 11.4

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 112.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 7695
% OF TOTAL: 13.2

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	254	980	3761	2108	580	32	3	3	.	.	7721
1.00-1.99	32	585	1584	1839	484	77	17	22	8	.	4648
2.00-2.99	.	20	157	326	138	15	5	.	.	.	661
3.00-3.99	.	.	1	44	51	15	.	.	.	.	111
4.00-4.99	.	.	.	.	3	11	.	.	.	.	14
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	286	1585	5503	4317	1256	150	25	25	8	0	

MEAN Hmo(M) = 1.0 LARGEST Hmo(M) = 4.8 MEAN TP(SEC) = 8.3

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 135.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 16240
% OF TOTAL: 27.8

HEIGHT IN METERS	.0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	208	1386	9496	5318	920	107	32	8	8	1	17484
1.00-1.99	42	723	2903	3531	968	314	97	25	22	5	8630
2.00-2.99	.	8	278	485	337	126	80	25	6	.	1345
3.00-3.99	.	.	3	90	61	29	41	5	6	.	235
4.00-4.99	.	.	.	.	10	8	.	11	6	.	35
5.00-5.99	.	.	.	.	.	.	3	10	23	.	36
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	250	2117	12680	9424	2296	584	253	84	71	-6	

MEAN Hmo(M) = 1.0 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 8.6

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 157.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 4455
% OF TOTAL: 7.6

HEIGHT IN METERS	.0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	195	780	1028	429	109	35	8	6	6	1	2597
1.00-1.99	35	903	1425	655	220	99	25	17	20	6	3405
2.00-2.99	.	20	417	453	131	61	49	17	8	.	1156
3.00-3.99	.	.	5	169	77	25	37	5	3	.	321
4.00-4.99	.	.	.	15	25	15	3	1	10	.	69
5.00-5.99	.	.	.	.	6	30	1	15	.	.	52
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	230	1703	2875	1721	568	265	123	61	47	7	

MEAN Hmo(M) = 1.4 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 8.2

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 180.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 4584
% OF TOTAL: 7.8

HEIGHT IN METERS	.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	414	1007	378	63	.	.	.	.	.	.	1862
1.00-1.99	75	1629	1812	386	34	.	.	.	.	.	3936
2.00-2.99	.	34	737	763	63	3	.	.	.	.	1600
3.00-3.99	.	.	11	212	106	3	.	.	.	.	332
4.00-4.99	.	.	.	20	63	3	.	.	.	.	86
5.00-5.99	.	.	.	1	6	11	.	.	.	.	18
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	489	2670	2938	1445	272	20	0	0	0	0	

MEAN Hmo(M) = 1.6 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 7.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 202.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 2711
% OF TOTAL: 4.6

HEIGHT IN METERS	.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	549	936	66	.	.	.	.	.	.	.	1551
1.00-1.99	88	1765	585	10	10	.	.	.	.	.	2458
2.00-2.99	.	15	393	154	3	.	.	.	.	.	565
3.00-3.99	.	.	6	42	10	.	.	.	.	.	58
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	637	2716	1050	206	23	0	0	0	0	0	

MEAN Hmo(M) = 1.3 LARGEST Hmo(M) = 3.9 MEAN TP(SEC) = 5.9

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 225.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M)

NO. CASES: 1866
% OF TOTAL: 3.2

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	716	229	.	.	.	.	.	.	.	.	945
1.00-1.99	102	1682	231	1	5	.	.	.	.	.	2021
2.00-2.99	.	23	171	18	8	.	.	.	.	.	220
3.00-3.99	.	.	1	.	.	.	.	.	.	.	1
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	818	1934	403	19	13	0	0	0	0	-0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 3.0 MEAN TP(SEC) = 5.3

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 247.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M)

NO. CASES: 1170
% OF TOTAL: 2.0

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	604	59	.	.	.	.	.	.	.	.	663
1.00-1.99	73	1110	15	.	6	.	.	.	.	.	1204
2.00-2.99	.	100	13	.	17	.	.	.	.	.	130
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	677	1269	28	0	23	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.7 MEAN TP(SEC) = 4.9

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 270.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M)

NO. CASES: 1216
% OF TOTAL: 2.1

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	521	3	.	.	.	.	.	.	.	.	524
1.00-1.99	95	1119	5	.	22	.	.	.	.	.	1241
2.00-2.99	.	249	23	.	32	.	.	.	.	.	304
3.00-3.99	.	.	6	.	.	.	.	.	.	.	6
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	616	1371	34	0	54	0	0	0	0	-0	

MEAN Hmo(M) = 1.4 LARGEST Hmo(M) = 3.6 MEAN TP(SEC) = 5.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 292.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M)

NO. CASES: 723
% OF TOTAL: 1.2

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	313	1	.	.	.	.	.	.	.	.	314
1.00-1.99	318	494	.	.	15	.	.	.	.	.	827
2.00-2.99	.	66	6	.	20	.	.	.	.	.	92
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	631	561	6	0	35	0	0	0	0	0	

MEAN Hmo(M) = 1.3 LARGEST Hmo(M) = 2.5 MEAN TP(SEC) = 4.7

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 315.0 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 824
% OF TOTAL: 1.4

PEAK PERIOD (IN SECONDS)

HEIGHT IN METERS	.0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	313	.	.	.	.	.	.	.	.	.	313
1.00-1.99	550	479	.	.	6	.	.	.	.	.	1035
2.00-2.99	.	42	1	.	15	.	.	.	.	.	58
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	863	521	1	0	21	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.6 MEAN TP(SEC) = 4.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 337.5 DEGREES AZIMUTH

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 709
% OF TOTAL: 1.2

PEAK PERIOD (IN SECONDS)

HEIGHT IN METERS	.0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	354	1	.	.	.	.	.	.	.	.	355
1.00-1.99	602	193	.	.	11	.	.	.	.	.	806
2.00-2.99	.	35	.	.	13	.	.	.	.	.	48
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	956	229	0	0	24	0	0	0	0	0	

MEAN Hmo(M) = 1.1 LARGEST Hmo(M) = 2.6 MEAN TP(SEC) = 4.2

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD
FOR ALL DIRECTIONS

STATION: A2041 (33.8N, 78.0W / 9.0M) NO. CASES: 58440
% OF TOTAL: 100.0

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	6425	6199	15667	9524	4341	2814	1019	294	87	13	46383
1.00-1.99	3420	15638	9484	7327	3348	2488	1180	306	145	17	43353
2.00-2.99	.	1298	3027	2340	1035	396	287	128	75	.	8586
3.00-3.99	.	.	51	588	420	112	83	22	10	.	1286
4.00-4.99	.	.	.	35	111	70	10	13	17	.	256
5.00-5.99	.	.	.	1	13	46	5	25	23	.	113
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	9845	23135	28229	19815	9268	5926	2584	788	357	30	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 8.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT .0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 880
% OF TOTAL: 1.5

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	658	.	.	.	.	.	.	.	.	.	658
1.00-1.99	645	118	.	.	18	.	.	.	.	.	781
2.00-2.99	.	27	.	.	37	.	.	.	.	.	64
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	1303	145	0	0	55	0	0	0	0	-0	

MEAN Hmo(M) = 1.0 LARGEST Hmo(M) = 2.6 MEAN TP(SEC) = 4.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 22.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 876
% OF TOTAL: 1.5

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	503	.	.	.	.	.	.	.	.	.	503
1.00-1.99	489	376	.	.	20	.	.	.	.	.	885
2.00-2.99	.	71	1	.	35	.	.	.	.	.	107
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	992	447	1	0	55	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.8 MEAN TP(SEC) = 4.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 45.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M)

NO. CASES: 1350
% OF TOTAL: 2.3

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	477	6	.	.	.	.	.	.	.	.	483
1.00-1.99	154	1387	.	.	6	.	.	.	.	.	1547
2.00-2.99	.	241	22	.	13	.	.	.	.	.	276
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	631	1634	22	0	19	0	0	0	0	0	

MEAN Hmo(M) = 1.4 LARGEST Hmo(M) = 2.8 MEAN TP(SEC) = 4.9

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 67.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M)

NO. CASES: 1189
% OF TOTAL: 2.0

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	438	46	.	.	.	.	.	.	.	.	484
1.00-1.99	92	1261	5	.	6	.	.	.	.	.	1364
2.00-2.99	.	155	17	3	8	.	.	.	.	.	183
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	530	1462	22	3	14	0	0	0	0	0	

MEAN Hmo(M) = 1.3 LARGEST Hmo(M) = 2.9 MEAN TP(SEC) = 5.0

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 90.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 11971
% OF TOTAL: 20.5

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	386	826	1440	2318	2200	1771	956	280	35	1	10213
1.00-1.99	41	1009	1563	1842	1670	1033	658	275	53	5	8149
2.00-2.99	.	23	462	362	405	236	85	30	23	.	1626
3.00-3.99	.	.	10	77	155	68	23	5	6	.	344
4.00-4.99	.	.	.	10	37	32	6	1	.	.	86
5.00-5.99	.	.	.	.	11	11	13	6	.	.	41
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	427	1858	3475	4609	4478	3151	1741	597	117	6	

MEAN Hmo(M) = 1.1 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 10.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 112.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 18759
% OF TOTAL: 32.1

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	217	1125	9709	6718	1497	142	35	3	51	15	19512
1.00-1.99	35	730	2790	4888	1428	314	82	27	88	20	10402
2.00-2.99	.	17	299	662	422	177	83	30	20	.	1710
3.00-3.99	.	.	1	104	121	34	59	5	3	1	328
4.00-4.99	.	.	.	3	41	25	.	8	1	.	78
5.00-5.99	.	.	.	.	3	6	5	13	18	.	45
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	252	1872	12799	12375	3512	698	264	86	181	36	

MEAN Hmo(M) = 1.0 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 8.9

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 135.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 8830
% OF TOTAL: 15.1

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	208	1197	4739	1986	251	49	10	6	11	.	8457
1.00-1.99	39	715	2267	1548	359	102	18	20	23	6	5097
2.00-2.99	.	8	290	460	200	88	46	17	11	.	1120
3.00-3.99	.	.	6	164	58	32	42	3	8	.	313
4.00-4.99	.	.	.	6	18	8	.	.	8	.	40
5.00-5.99	.	.	.	.	5	29	1	13	10	.	58
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	247	1920	7302	4164	891	308	117	59	71	-6	

MEAN Hmo(M) = 1.1 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 8.3

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 157.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 3332
% OF TOTAL: 5.7

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	189	725	573	95	8	.	.	1	1	.	1592
1.00-1.99	29	912	1240	417	63	13	5	1	.	.	2680
2.00-2.99	.	27	450	467	87	10	.	.	.	.	1041
3.00-3.99	.	.	5	162	90	8	3	.	.	.	268
4.00-4.99	.	.	.	17	42	8	3	1	.	.	71
5.00-5.99	.	.	.	.	11	15	1	.	6	.	33
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	218	1664	2268	1158	301	54	12	3	7	0	

MEAN Hmo(M) = 1.5 LARGEST Hmo(M) = 5.7 MEAN TP(SEC) = 7.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 180.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 4318
% OF TOTAL: 7.4

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	414	1473	592	95	.	.	.	.	.	.	2574
1.00-1.99	70	1476	1719	390	41	.	.	.	.	.	3696
2.00-2.99	.	22	383	497	65	3	.	.	.	.	970
3.00-3.99	.	.	1	78	49	.	.	.	.	.	128
4.00-4.99	.	.	.	1	8	.	.	.	.	.	9
5.00-5.99	.	.	.	.	.	3	.	.	.	.	3
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	484	2971	2695	1061	163	6	0	0	0	0	

MEAN Hmo(M) = 1.3 LARGEST Hmo(M) = 5.6 MEAN TP(SEC) = 6.8

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 202.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) NO. CASES: 1968
% OF TOTAL: 3.4

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0- 4.9	5.0- 6.9	7.0- 8.9	9.0- 10.9	11.0- 12.9	13.0- 14.9	15.0- 16.9	17.0- 18.9	19.0- 20.9	21.0- LONGER	TOTAL
.00- .99	503	581	11	.	.	.	.	.	.	.	1095
1.00-1.99	100	1504	408	.	13	.	.	.	.	.	2025
2.00-2.99	.	29	169	30	13	.	.	.	.	.	241
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	603	2114	588	30	26	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.8 MEAN TP(SEC) = 5.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 225.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) — NO. CASES: 1536; % OF TOTAL: 2.6

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	651	189	.	.	.	.	.	.	.	.	840
1.00-1.99	131	1370	124	.	1	.	.	.	.	.	1626
2.00-2.99	.	15	118	8	15	.	.	.	.	.	156
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	782	1574	242	8	16	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.9 MEAN TP(SEC) = 5.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 247.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) — NO. CASES: 688; % OF TOTAL: 1.2

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	544	20	.	.	.	.	.	.	.	.	564
1.00-1.99	109	432	18	.	5	.	.	.	.	.	564
2.00-2.99	.	8	10	.	27	.	.	.	.	.	45
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	653	460	28	0	32	0	0	0	0	0	

MEAN Hmo(M) = 1.0 LARGEST Hmo(M) = 2.5 MEAN TP(SEC) = 4.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 270.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) — NO. CASES: 593 — % OF TOTAL: 1.0

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	619	.	.	.	.	.	.	.	.	.	619
1.00-1.99	304	51	3	.	6	.	.	.	.	.	364
2.00-2.99	.	3	1	.	23	.	.	.	.	.	27
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	923	54	4	0	29	0	0	0	0	-0	

MEAN Hmo(M) = .9 LARGEST Hmo(M) = 2.4 MEAN TP(SEC) = 3.8

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 292.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M) — NO. CASES: 555 — % OF TOTAL: .9

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	373	.	.	.	.	.	.	.	.	.	373
1.00-1.99	386	154	.	.	11	.	.	.	.	.	551
2.00-2.99	.	11	.	.	11	.	.	.	.	.	22
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	759	165	0	0	22	0	0	0	0	0	

MEAN Hmo(M) = 1.1 LARGEST Hmo(M) = 2.5 MEAN TP(SEC) = 4.1

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 315.0 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M)

NO. CASES: 793
% OF TOTAL: 1.4

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	304	.	.	.	.	.	.	.	.	.	304
1.00-1.99	549	426	.	.	5	.	.	.	.	.	980
2.00-2.99	.	42	.	.	29	.	.	.	.	.	71
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	853	468	0	0	34	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.5 MEAN TP(SEC) = 4.5

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD BY DIRECTION
22.5 DEGREES ABOUT 337.5 DEGREES AZIMUTH

STATION: A2042 (34.0N, 77.8W / 9.0M)

NO. CASES: 802
% OF TOTAL: 1.4

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	396	.	.	.	.	.	.	.	.	.	396
1.00-1.99	629	265	.	.	17	.	.	.	.	.	911
2.00-2.99	.	49	1	.	11	.	.	.	.	.	61
3.00-3.99	.	.	.	.	.	.	.	.	.	.	0
4.00-4.99	.	.	.	.	.	.	.	.	.	.	0
5.00-5.99	.	.	.	.	.	.	.	.	.	.	0
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	1025	314	1	0	28	0	0	0	0	0	

MEAN Hmo(M) = 1.2 LARGEST Hmo(M) = 2.8 MEAN TP(SEC) = 4.3

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD
FOR ALL DIRECTIONS

STATION: A2042 (34.0N, 77.8W / 9.0M)   NO. CASES: 58440
% OF TOTAL: 100.0

HEIGHT IN METERS	PEAK PERIOD (IN SECONDS) .0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-LONGER	TOTAL
.00- .99	6887	6194	17067	11214	3957	1962	1002	292	100	17	48692
1.00-1.99	3809	12191	10143	9087	3677	1464	764	325	165	32	41657
2.00-2.99	.	756	2227	2493	1409	516	215	78	56	.	7750
3.00-3.99	.	.	25	586	475	143	130	13	18	1	1391
4.00-4.99	.	.	.	39	148	75	10	11	10	.	293
5.00-5.99	.	.	.	.	32	66	22	34	35	.	189
6.00-6.99	.	.	.	.	.	.	.	.	.	.	0
7.00-7.99	.	.	.	.	.	.	.	.	.	.	0
8.00-8.99	.	.	.	.	.	.	.	.	.	.	0
9.00-9.99	.	.	.	.	.	.	.	.	.	.	0
10.0+	.	.	.	.	.	.	.	.	.	.	0
TOTAL	10696	19141	29462	23419	9698	4226	2143	753	384	50	

MEAN Hmo(M) = 1.1   LARGEST Hmo(M) = 5.7   MEAN TP(SEC) = 8.1

Appendix B
Wave Model Description

The WES spectral wind-wave growth and propagation model STWAVE (Steady-state spectral WAVE) (Resio 1987, 1988a, 1988b, Davis 1992), modified for wave-current interaction (Version 6_7), was chosen for wave transformation modeling in the vicinity of Wilmington Harbor Entrance Channel. STWAVE, which numerically solves the steady-state spectral energy-balance equation, was modified to solve the steady-state conservation of wave action:

$$\frac{\partial}{\partial x}\left(C_{ga_x} \frac{E(f,\theta)}{\omega_r} \right) + \frac{\partial}{\partial y}\left(C_{ga_y} \frac{E(f,\theta)}{\omega_r} \right) = \Sigma \frac{S}{\omega_r} \qquad (1)$$

where

E = spectral energy density
f = frequency of spectral component
θ = propagation direction of spectral component
C_{ga} = absolute group velocity of spectral component
x,y = spatial coordinates
S = energy source/sink terms
ω_r = relative angular frequency (frequency relative to the current)

The source terms include wind input, nonlinear wave-wave interactions, dissipation within the wave field, and depth- and steepness-limited breaking. The terms on the left-hand side of Equation 1 represent wave propagation (refraction and shoaling) and the source terms on the right-hand side of the equation represent energy growth or decay in the spectrum. The assumptions made in STWAVE are:

a. Mild bottom slopes.
b. Negligible wave reflection.
c. Spatially homogeneous offshore waves.
d. Steady waves and winds.
e. Linear refraction and shoaling.
f. Linear wave-current interaction.

g. Nonlinear wave-wave interaction.

STWAVE includes two breaking mechanisms: depth limited and steepness limited. The depth criterion limits the wave height-to-water depth ratio to 0.64. The steepness limit is expressed as

$$H_{mo_{max}} = 0.1\ L\ \tanh kd \tag{2}$$

where L is wavelength, k is wave number, and d is water depth (corrected for tide/surge).

STWAVE is a half-plane model, meaning that waves propagate only in directions headed from the seaward boundary into the grid interior. Typically waves propagate and/or winds blow toward a coast near the grid boundary opposite the seaward boundary. Waves reflected from the coast or waves generated by winds blowing offshore are neglected. Incident waves with dominant direction of more than about 60 deg from perpendicular to the seaward boundary are not accurately modeled because a significant fraction of the directionally spread energy is directed seaward and truncated by the model. For applications such as Wilmington Harbor Entrance Channel, where a wide range of wave directions is important, more than one STWAVE grid must be developed.

STWAVE is a finite-difference model which calculates wave spectra on a rectangular grid with square grid cells using a backward ray-tracing scheme. The inputs needed to execute STWAVE are:

a. Bathymetry and shoreline position.
b. Size and resolution of the grid.
c. 2D wave spectrum on the offshore grid boundary (optional).
d. Wind speed and direction (optional).
e. Current field (optional).
f. Water level.

The model outputs zero-moment wave height (H_{mo}), peak spectral period (T_p), and mean wave direction (θ_m) at all grid points, and the 2D spectrum at selected grid points.

Directional wave spectra for model input are typically obtained from validated theoretical spectral forms or field measurements. If incident wave parameters significant height, peak period, and peak direction are specified, ACES 2.0 software (Leenknecht and Tanner 1997) can be helpful for creating the 2D spectrum needed for STWAVE. The ACES 2.0 software generates a directional spectrum for given wave parameters and water depth, based on the TMA frequency spectrum (Bouws et al. 1985) with $\cos^n \theta$ form of directional spreading. Two parameters are specified regarding spectral shape: a spectral peak enhancement factor, γ, and the directional spreading parameter, n. Spectral shape parameters in this study were determined based on peak spectral period to give an approach equivalent to that described by Thompson et al. (1996) (Table B1). The ACES software requires that n be an even number.

Table B1
Spectral Shape Parameters Used in ACES 2.0

T_p (sec)	γ	n
4-10	3.3	4
11	4	8
12	4	10
13	5	12
14	5	16
15	6	18
16	6	20
17	7	22
18	7	26
19	8	28
20	8	30
21	9	32
22	9	36
23	10	38
24	10	38

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Edward F. Thompson, Lihwa Lin, Doyle L. Jones

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13. ABSTRACT *(Maximum 200 words)*

Numerical model studies were conducted to assist the U.S. Army Engineer District, Wilmington, in evaluating potential plans for modifying the Cape Fear River entrance channel and in preparing General Reevaluation Reports. The offshore wave climate was evaluated, and Wave Information Studies hindcasts from 1976-1995 were used as the incident wave climate. Wave transformation around Frying Pan Shoals and nearshore bathymetry were modeled with the spectral wave model STWAVE. Wave climate was estimated in existing and plan navigation channels and along the Brunswick County, North Carolina, coast west of Cape Fear. Since potential areas for offshore disposal of dredged material are included in the wave model coverage, wave climate in the finally selected offshore dredged material site can be estimated from study results as needed.

Nearshore wave climate and littoral transport were estimated for existing conditions between Cape Fear and the middle of Ocean Isle Beach to the west. Other bathymetric conditions studied in the more localized area between Cape Fear and the middle of Long Beach are historical 1872 bathymetry, a plan navigation channel, and the plan channel with adjusted ebb-tide shoals representing a long-term equilibrium with the relocated channel. Potential longshore annual transport rates were computed at approximately 55-m (180-ft) intervals along these coasts.

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