APPENDIX F – NEARSHORE HARDBOTTOM MITIGATION PLAN AND SHORELINE IMPACT ANALYSIS

Mitigation Plan for Broward County
Beach Erosion Control Project
Broward County, Florida
United States Army Corps of Engineers
Permit Application # 199905545 (IP-DSG)
May 12, 2003

I Project Background

Most of Broward County's shoreline are in a state of chronic erosion. The State of Florida has estimated that 21 of the 24 miles of Broward's beaches are critically eroded, and in some areas there is little beach left at high tide. To combat this situation, Broward County has been engaged in shore protection, beach restoration, and beach sand management since the early 1960's.

In 1970, the first beach restoration project was conducted in Pompano Beach, followed by similar projects at John U. Lloyd Beach State Recreation Area (1977 and 1989); Hollywood and Hallandale (1979 and 1991); and Pompano Beach and Lauderdale-By-The-Sea (1983). The projects, cost-shared by the U.S. Army Corps of Engineers, the State of Florida, Broward County, and the affected municipalities, involved dredging sand from offshore "borrow sites" and pumping the sand onto the target beaches.

The current Broward County Beach Management Program is a comprehensive plan to replace beach sand where it is needed, to stabilize the most eroded stretches of beach, and, by means of inlet sand bypassing, to "feed" those beaches which are eroding because of the presence of stabilized inlets. Current projections call for approximately 2.5 million cubic yards of sand to be placed on about 11.8 miles of shoreline. The beach in the nourished areas will be 50 to 100 feet wider after the project, and sand by-passing at Port Everglades is predicted to contribute a minimum of 44,000 cubic yards of sand into the Segment III beach system (Coastal Systems International, 1997).

The project is not expected to adversely impact offshore coral reefs, adjacent to borrow areas. The approximately twelve miles of widened beaches are predicted to bury approximately 13.5 acres of nearshore hardbottom during equilibration of the beach fill. This represents the gross area of impact within which only 10.1 acres is actually hardbottom. The remainder is sand bottom. The hardbottom substrate supports various combinations and complexities of benthic and fish communities, and are located in shallow, wave-dominated environments. In some cases, the habitats are subject to periodic covering and uncovering by beach material moved by storms or by previous beach nourishment projects. The County is endeavoring to minimize impacts to these habitats and intends to fully mitigate for unavoidable impacts. This net mitigation planned is 11.9 acres (net) within a 13.5-acre footprint.

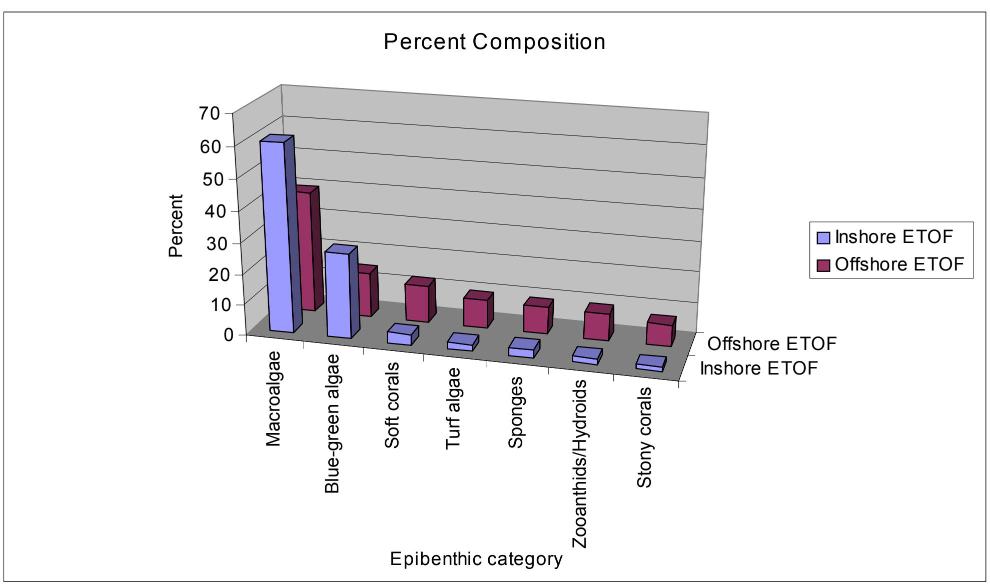
II Comparison of Impacted to Not-impacted Nearshore Reef Communities

The nearshore reef is generally characterized by low topographic relief with a biological community structure controlled by physical oceanographic conditions. These conditions include wave energy, turbidity, temperature extremes, and suspended sediment stresses. As a result, the hardbottom communities closest to the shore are of lower biological diversity and abundance than deeper water areas. Table 1 shows a comparison of hardbottom projected to be impacted by beach nourishment to those offshore of the estimated equilibrium toe of fill. Figure 1 compares the relative composition of the floral and faunal groups at the two areas. A detailed analysis of the biological data from the nearshore hardbottom areas is presented in the project EIS.

Table 1. Comparison of biological characteristics of hardbottom communities inshore (impacted by beach nourishment) to those offshore (not impacted) of the projected equilibrium toe of fill (ETOF).

Biological Characteristic	Inshore ETOF	Offshore ETOF
Average density of the dominant faunal species (#/m^2)	1.00	1.30
Number of stony coral species	6	7
Number of faunal species	10.25 Segment II 4.00 Segment III	19.60 Segment II 13.8 Segment III
Faunal diversity (Shannon Weaver)	1.66 Segment II 0.66 Segment III	2.42 Segment II 1.90 Segment III
Faunal density (#/m^2)	3.80 Segment II 1.23 Segment III	5.82 Segment II 5.66 Segment III

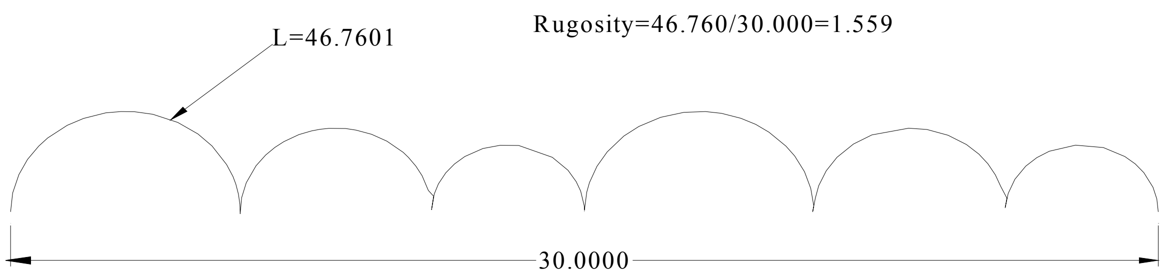
Figure 1. Comparison of the relative composition of the major floral and faunal groups between impacted (Inshore ETOF) and not impacted (Offshore ETOF) nearshore hardbottom areas.



III Mitigation Plan

The mitigation plan for the Broward County Beach Restoration project is based on a 1.2:1 mitigation ratio, providing 11.9 acres of substrate within a 13.5-acre footprint. Construction will take place in two phases, Segment III Mitigation (10.1 acres, gross; 8.9 acres, net) and Segment II (3.4 acres, gross; 3.0 acres, net). Each phase is contingent on receipt of all permits necessary for that phase's beach nourishment. A total of 21.8 acres of suitable sites have been identified to allow some flexibility in construction (Table 2, Figures 2-6). Burial of nearshore reef will be mitigated for by placement of limestone boulders in nearshore reef sand pockets. The individual boulders will be of large size (4-6 feet, diameter) for stability (Stability Analysis, Attachment 1) and placed in a single layer to avoid wave refraction that may affect natural sediment transport processes on the adjacent beach (Shoreline Change Analysis, Attachment 2). Boulders will be placed on shallow sediments (less than 3 feet thick) so that sand scouring does not result in total burial of the rocks. Partial settling will increase stability by anchoring the boulders in place. The criteria for selection and configuration of mitigation sites are 1) inshore of the nearshore hardbottom, 2) offshore of the predicted equilibrium toe of fill, 3) no shallower than the 15-foot depth contour, and 4) with a 50-foot buffer from all significant nearshore hardbottom.

The topography of the limestone boulder reefs will be of greater complexity than the natural impacted hardbottom which is typically low relief limestone pavement interrupted with pockets of higher complexity. The rugosity of the nearshore hardbottom to be impacted was measured by Dr. Richard Spieler, Nova Southeastern University, using the chain method. He found an average of 1.08 (n=199) (Dodge, 2002). Rugosity for the proposed mitigation was determined analytically by drawing an evendistribution of 4', 5', and 6' diameter boulders (touching at their midpoints) in AutoCad and draping a polyline over the boulders. This is illustrated in the following figure.



Even distribution of 6', 5', and 4' boulders in profile

The result is a rugosity estimate of 1.56. This represents a 44% increase in mitigation reef rugosity over the natural nearshore hardbottom. Texturally, limestone is a natural material and will provide a suitable replacement for the impacted nearshore reef substrate. It is anticipated that this plan will provide perpetual reef habitat that will be colonized by organisms similar to those found on the impacted natural reef.

The proposed time frame for construction of the boulder reefs is to begin deployments for Segment III Mitigation in Spring, 2003. Deployment will be carried out from April 1 through September 30. Areas not completed in 2003 will be completed in 2004, but it is anticipated that all deployments for Segment III Mitigation will be completed in the first year. Table 3 compares estimated time of nearshore reef impact to mitigation construction, illustrating that mitigation reefs will be functioning before impacts occur. Observations on artificial reefs constructed in Broward County indicate that juvenile fishes begin to settle on to reefs within days after construction.

Table 2. Locations and area of proposed sites suitable for mitigation.

Mitigation Area	Center Coordinates XY (NAD83)	Center Coordinates Lat/Long	Beach Segment	Reef Area (acres)
1	954611 683600	N 26 12.6884' W 80 05.3846'	II	1.83
2	954480 680863	N 26 12.2368' W 80 05.4121'	II	4.25
3	952181 664712	N 26 09.6066' W 80 05.8530'	II	3.00
4	951954 663363	N 26 09.3512' W 80 05.8965'	II	0.37
5	951037 655841	N 26 08.1107' W 80 06.0737'	II	0.48
6	950683 650626	N 26 07.2503' W 80 06.1450'	II	0.32
7	948333 624147	N 26 02.8823' W 80 06.6078'	III	2.97
7-8	948347 623621	N 26 02.7955' W 80 06.6059'	III	0.94
8	948310 623407	N 26 02.7602' W 80 06.6129'	III	0.67
9	948190 622604	N 26 02.6278' W 80 06.6358'	III	0.33
10	946923 601989	N 25 59.2265' W 80 06.8929'	III	1.86
11	946883 600302	N 25 58.9481' W 80 06.9023'	III	5.70
11b north	947084 600667	N 25 59.0081' W 80 06.8651'	III	2.25
11b south	946952 599834	N 25 58.8707' W 80 06.8902'	III	1.84
12	950551 643120	N 26 06.0115' W 80 06.1786'	II	10.11

Table 3. Projected time line of mitigation function and nearshore reef impacts from beach nourishment of Segment III.[1]

Months	Activity (Activity and Time from Beginning of Project)	Area of Reef Impact[2] (acres)	Area of Functioning Mitigation (acres)
0	mitigation construction begins	0	0
6	beach construction begins	0	0

Months	Activity and Time from Beginning of Project Activity	Area of Reef Impact[2] (acres)	Area of Functioning Mitigation (acres)
21	Hollywood/Hallandale impacts begin (Segment III)	2.5	13.5
22	JUL impacts begin (Segment III)	5.0	

[1]Schedule for Segment II Mitigation to be determined after permits are issued

[2] Assumptions: reef impact begins with equilibration of fill, approximately 1 year after placement
Beach construction begins March, 2003; mitigation construction April, 2003
Areas are for gross impacts and mitigation area

Artificial Reef Material

Limestone boulders of 4-6 feet diameter will be used for all construction. A minimum density of 131 lbs/cubic foot (pcf) gives a weight range of 2.2 to 7.4 tons per boulder. The estimated quantity of rock needed, assuming an even mix of 4, 5, and 6-foot boulders, is 7,400 tons/acre or 88,060 tons for 11.9 acres. Rocks will be placed in a single layer with no greater than 7 feet of spacing between the individual rocks.

Artificial Reef Construction

Several challenges are inherent in building artificial reefs in shallow waters around natural reefs. These include depth clearance for barge navigability, sensitivity to sea state, and barge anchoring. The magnitude of the project adds the problem of material supply and delivery to the deployment site. In addition, these factors can compound as in the case of sea state and water depth where wave height must be subtracted from the water depth to calculate minimum draft clearances. To allow some flexibility in construction a total of 36.9 acres of suitable sites have been identified (Figures 2-6 at end of document).

Minimum water depth at the proposed mitigation sites is 15 feet, which in calm weather conditions will allow a 600-ton barge to operate (7 feet, loaded draft). The shallow water depths will prohibit construction in any but calm weather conditions. Therefore, all construction will take place during the summer months.

Barges will be anchored during deployment with permanent moorings to allow for 4-point moorings for precise horizontal positioning. The challenge of anchoring is two-fold. Nearby hardbottom restricts anchor placement locations and shallow sediment depths create poor holding ground for anchors. As a result a 50-foot buffer will provide some westward anchoring areas shoreward of the nearshore reef. The buffer will also minimize the risk of accidental damage to natural hardbottom by misplacement of rocks. The permanent moorings (Figure 7) will be installed on sandy substrate and will consist of steel pilings driven into the bottom. The pilings will be cut-off approximately 2 ft above the sand surface and will be left in place after the project is completed.

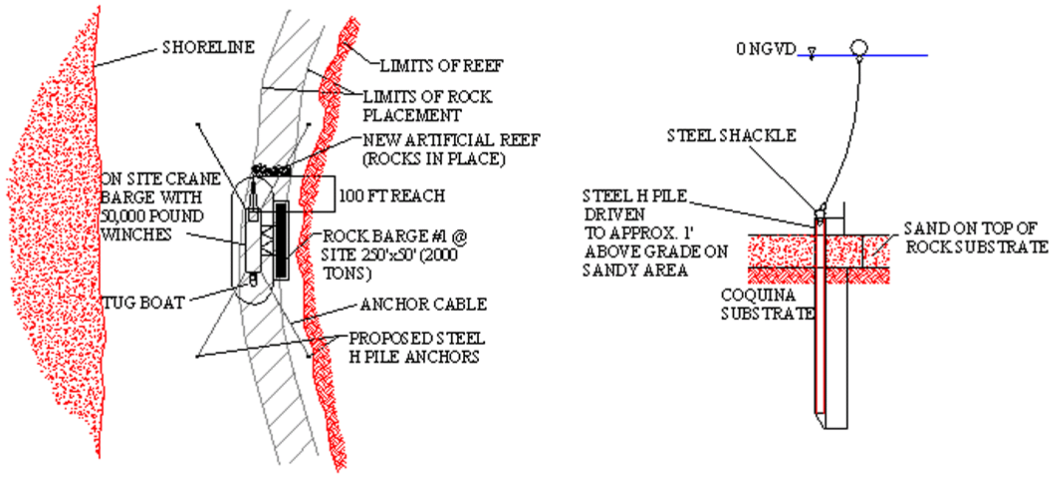


Figure 7. Permanent mooring system for rock deployment barge. Moorings will only be placed in sandy substrate.

Quality Assurance

1. No lines, cables or chain will be allowed to pass over hardbottom areas. If this proves necessary (for reef or existing mitigation) buoyant lines or floats will be used to prevent scraping the reef. Permanent moorings may be used for barges (if allowed in State and Federal permit conditions). These will be steel pilings driven into sand covered bottom. No anchors or moorings will be placed on hardbottom.

2. Rocks will be in a single layer but allowance is made for rocks landing in crevices between existing rocks as long as the vertical relief does not exceed 6 feet above the existing grade. A maximum spacing of 7 feet between some boulders is permitted, but the frequency of occurrence of this will not exceed 40%.

3. Limestone boulders will be clean and free of excessive soil or plant material.

4. Barges and tugs loaded drafts will not exceed 10 feet, and vessels will not operate in water depths less than 15 feet.

5. The County will be notified within 24 hours if reef damage occurs, and all construction operations shall cease until an assessment of damage is made.

6. Deployment operations will cease if seas exceed 4 feet, and all vessels must be released from moorings and relocated to deeper waters.

7. Deployment operations will take place between April 1 and September 30 unless approved by Broward County.

8. Transit corridors for barges will be identified to ensure adequate draft is available. The corridors will be located over sandy bottom to the greatest extent possible.

Transplantation of Stony Corals and Macroalgae

Stony corals will be relocated from nearshore impact areas to the mitigation reefs to avoid mortality from burial during equilibration of the beach fill. It is anticipated that 1000 to 2000 colonies of 15 cm diameter or greater will be transplanted onto approximately 5 acres of Mitigation. It is intended to move corals directly from the impact areas onto the mitigation reefs. However, unforeseen circumstances, such as delay of mitigation construction, may make this unfeasible in which case corals will be relocated to a cache site near the intended receiver site. At the earliest opportunity the corals will be moved from the cache site to the final transplant location.

The nearshore hardbottom areas offshore of Broward County Segment II are utilized by sea turtles as foraging grounds for macroalgae. One of the goals of mitigating for impacts to these areas is to provide suitable substrate for colonization by macroalgae. If monitoring of the mitigation in Segment II one year after construction shows that algal cover does not meet the goals established by the Florida Department of Environmental Protection, transplantation of macroalgae will be undertaken. It is intended that fragments of substrate with attached macroalgae will be transplanted to Mitigation Area 5 (0.48 acres, Figure 4 at end of document) in an experiment to see if this accelerates recruitment of macroalgae. The species that will be transplanted are those favored by foraging sea turtles.

IV Background of Reef Related Projects Carried Out by Broward County

Broward County has a relatively long history in the construction of artificial reefs. The goals of the program have been to restore depleted fish stocks by habitat creation and to relieve some of the user pressure (divers and fishers) on the natural reefs. In order to evaluate the success of previous reef constructions and to improve future methods we began the first steps in understanding the fundamental processes to control fish assemblages on reefs by establishing a long term research program. The Following (Table 4) is a list of studies that are completed or ongoing and a summary of results:

Table 4. Broward County Department of Environmental Protection reef research projects (Broward County, 2000; Sherman et al., 2002; and Spieler, 2000).

Year	Study Description	Results
1993-1995	Potential for using tire chips as aggregate in concrete artificial reefs	Tire aggregate is an appropriate material for reef construction
1995-1997	Fish assemblages and recruitment at shallow versus deep-water sites	found greater biomass and diversity of Juvenile fishes at deeper reefs suggesting that recruitment reefs should be placed in deeper water

Year	Study Description	Results
1997-1999	Attractants for settlement on artificial reefs	attractants (floating lines) did not enhance recruitment to reefs
1997-1999	Complexity versus void space in small artificial reefs	high complexity is more important than extensive void space for high fish diversity and biomass
1997-1999	Complexity and refuge size	shelter size is an important aspect of artificial reef design
1997-2001	Fish population assemblages on natural and artificial reefs in Broward County	ongoing; compares population and trophic structure on natural and artificial reefs/vessels
2000-2001	A socioeconomic study of the reef resources of southeast Florida and the Florida Keys	analyzes the economic value of artificial and natural reefs to local and state economies
2002	The development of a regional reef resource management plan for southeast Florida and the Florida Keys - contingent upon funding	a regional approach to evaluate needs and analyze strategies that can be used to manage artificial and natural reef resources

V Expected Outcomes of Mitigation Project

Preserving natural habitat is preferred to imposing any impacts from human activities. However, when impacts are unavoidable it is necessary to consider all available scientific data to design an optimized, yet economical, mitigation strategy. Based on studies carried out in Broward County waters over the past 20 years it is anticipated that the construction of artificial reef in the nearshore region will provide habitat that is both complex for fish recruitment and provides a substrate that is suitable for colonization by benthic invertebrates. The fact that the artificial reef will be more complex than the natural impacted substrate may result in an effective mitigation ratio greater than the actual proposed 1.2:1. Summaries of monitoring of mitigation projects are found following the references below and support the use of limestone boulders as mitigation for nearshore hardbottom impacts.

VI References

Broward County Department of Planning and Environmental Protection, 2000. *Artificial Reef Research in Broward County 1993-2000: A Summary Report*, Technical Report 01-05, Fort Lauderdale, Florida, unpaginated.

Coastal Systems International, Inc., 1997. *Port Everglades Inlet Management Plan Addendum,* prepared for Department of Natural Resource Protection, Broward County, Florida, 56p.

Dodge, R., 2002. HEA approach for calculating Broward County nearshore mitigation amount, white paper, draft, Saturday, October 5, 2002. Nova Southeastern University Oceanographic Center.

Sherman, R.L., D.S. Gilliam and R.E. Spieler, 2002. Effects of refuge size and complexity on recruitment and fish assemblage formation on small artificial reefs. *Proceedings of the Fifty-Third Annual Gulf and Caribbean Fisheries Institute,* Biloxi, Mississippi, USA, in press.

Spieler, R.E., 2000. *Effects of Module Spacing on the Formation and Maintenance of Fish Assemblages on Artificial Reefs*, Florida Fish and Wildlife Conservation Commission Grant Agreement OFMAS-132, Executive Summary, submitted to Broward County Department of Planning and Environmental Protection, 1p.

VII Summaries of Results of Similar Mitigation Projects

Cummings, S. L., 1994. *The Boca Raton mitigative artificial reef-5 ½ years later*. Proceedings of the 1994 National Conference on Beach Preservation Technology, Tampa, Florida, February 9-11, 252-284.

A 5 ½ yr study of limestone boulder reefs (for mitigation of a beach renourishment project) in a depth of 2-m off Boca Raton, Florida found that the reefs provided suitable mitigation for nearshore, low relief hard bottom habitat lost as a result of the 1998 Boca Beach Restoration Project. Compared to a nearby natural nearshore rock formation (Red Reef Rock), the Boca Raton artificial reef provided enhanced habitats for fishes and macroinvertebrates. In addition, the shore-detached groin and artificial reef provided a suitable replacement habitat for a majority of the algae found at the nearby natural hard bottom habitat. Cummings stated that the, "..higher relief provided more shelter and greater surface area for the attachment of sessile organisms. Additionally, the higher relief exhibited by the mitigation structures made them less prone to coverage by sand movements, thereby providing a more permanent habitat for marine organism." She also stated that the limestone used to construct the mitigation structures simulated the texture and calcareous nature of the natural nearshore hard bottom formations, whereas, the increased complexity provided increased surface area for colonization.

Miller, M.W. and Barimo, J., 2001. Assessment of juvenile coral populations at two reef restoration sites in the Florida Keys National Marine Sanctuary: indicators of success. *Bulletin of Marine Science*, 69(2): 396-405.

Mitigation for the groundings of two vessels, the Elpis and Maitland, in the Florida Keys was carried out using limestone boulders and concrete armor structures/limestone, respectively. This assessment on recruitment of stony corals to the mitigation structures indicates that "...coral recruits preferentially occurred on limerock substrates..."

Palm Beach County ERM, 2000. *Evaluation of mitigation reef constructed to offset impacts of Jupiter/Carlin shore protection project.* Interim Report, July 26, 2000, 20p.

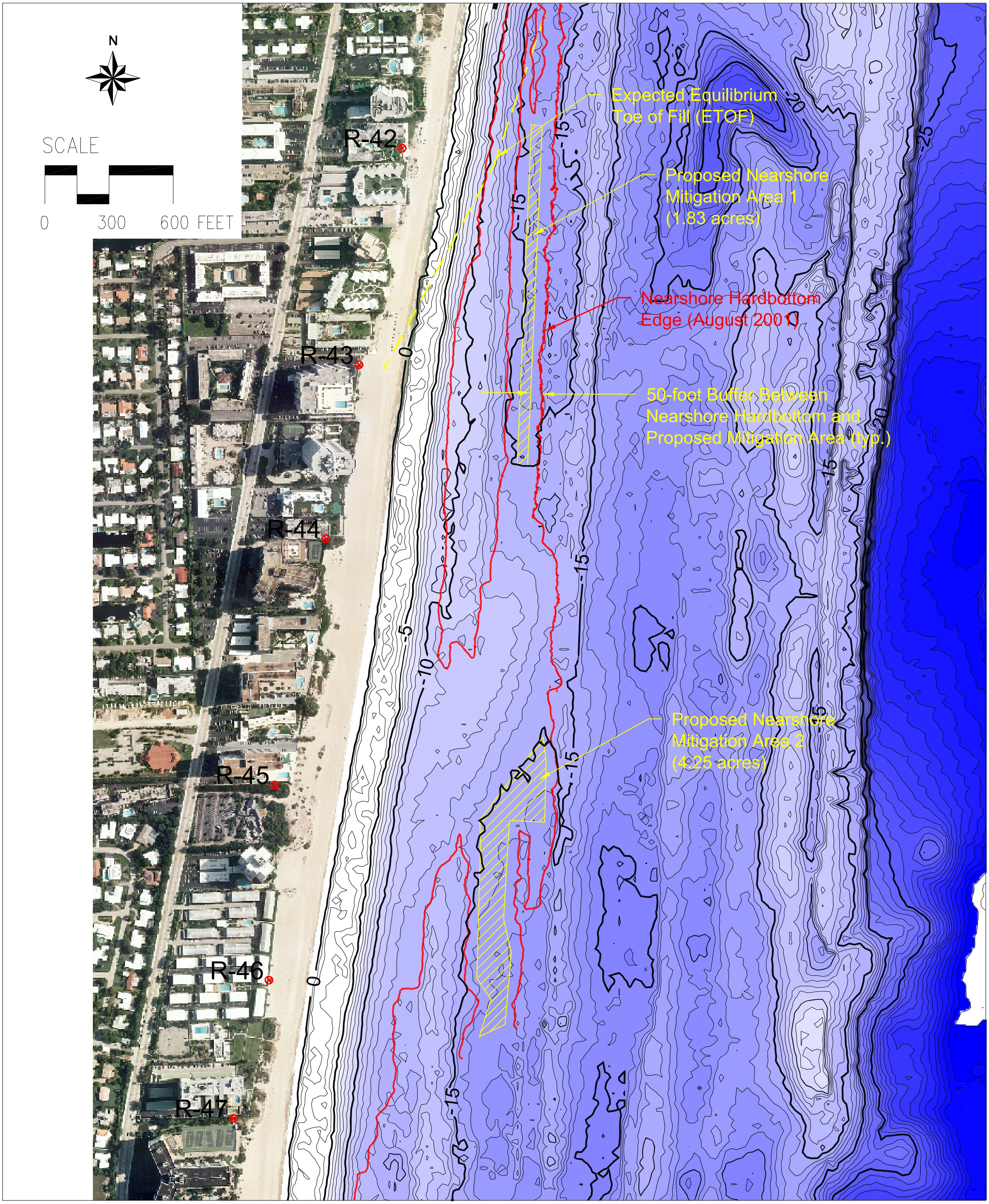
A Mitigation reef was constructed of limestone boulders and one of concrete rubble; depth=17-25'; average relief 2-3', max 5-6'. The monitoring study compared the mitigation reef to the impacted nearshore reef. After 18 months, worm rock encrusted a large proportion of the limestone boulders. The mean coverage by invertebrates and algal taxa on limestone was 60% and the concrete reef 40% (showed little signs of colonization by worm rock). Fish species increased from 26 to 37 on impacted nearshore reef, 35 to 56 on the limestone reef, and 25-57 on the concrete reef. Juvenile fishes were more abundant on the limestone reef than the concrete reef. Numbers of juveniles on rock and concrete sections of reefs were as great as, or greater than numbers on the adjacent natural reef. The authors concluded that the mitigation reefs adjacent to the shore protection project are presently providing suitable habitats for reef fish, invertebrates and algae. The rapid colonization of these structures by benthic inverts and algae indicates that they are placed within hydrodynamic and bathymetric regimes which are conducive to larval settlement and growth. The colonization of the mitigation reef by certain key nearshore reef indicator species such as worm rock and hairy blenny can be considered at least one measure of success. The appearance of a diverse fish fauna indicates that these habitats provide adequate shelter and food to support a healthy fish community. This fauna includes a large proportion of species commonly associated with nearshore reefs, as well as juvenile representatives of many species. The limestone boulder material appears to be particularly preferred by juvenile fishes, and was also colonized by invertebrates more rapidly than the concrete. This may be due in part to the shallower depth of the boulder section, which may favor the growth of worm rock, but is probably also a function of the affinity of many marine organisms for a limestone based substrate.

Spieler, R. E., 2000. *Biological assessment of artificial reef materials: concrete aggregates and quarry stone*. Contract #199.6915.000343, 2000 Annual Report, submitted to the City of Miami Beach.

This study compared fish and invertebrate assemblages on artificial reefs constructed of quarry rock (limestone boulders), gravel-concrete aggregate and tire-concrete aggregate structures over a 2-year period. The reefs were deployed in 7-m water offshore Miami Beach, Florida. They found no significant differences in fish fauna among the reef types, but there were more hard corals found on limestone boulder reefs than concrete materials.

Spieler, R. E., personal communication, 11/29/00. Nova Southeastern University Oceanographic Center

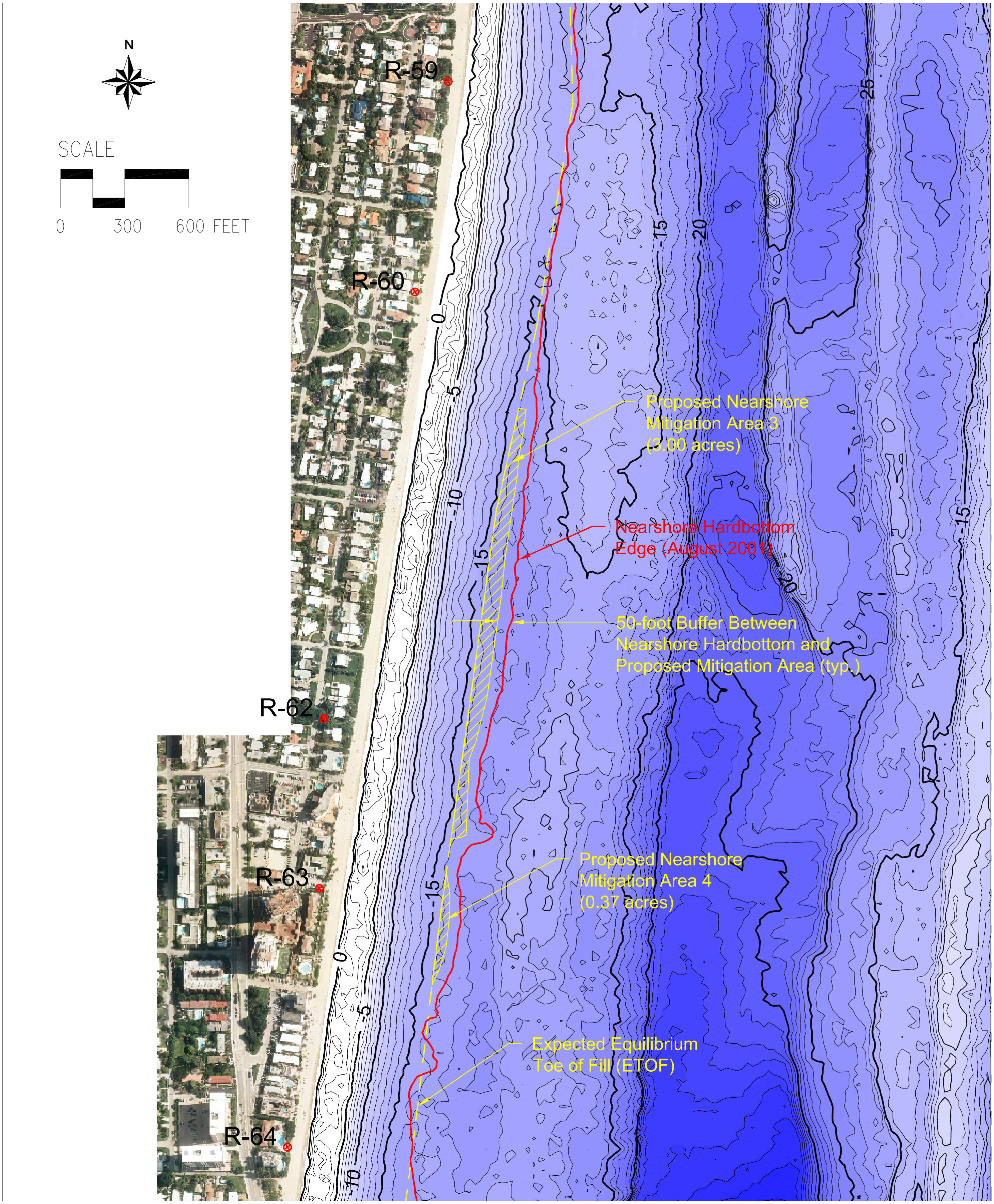
A comparison of fish richness and density of fishes found by Lindeman and Snyder (1998) with Nova Southeastern University's Miami Beach mitigation project study found: Lindeman: nearshore reef; 6-7 species, 38-40 individuals/30 sq meter = 0.2 species/sq m, 1.3 individuals/sq m Miami Beach: limestone boulders; 20 species, 750 individuals/64 sq meter = 0.3 species/sq m, 11.7 individuals/sq m



Broward County Federal Shore Protection Project
Proposed Nearshore Mitigation Areas
Segment II

Figure 2

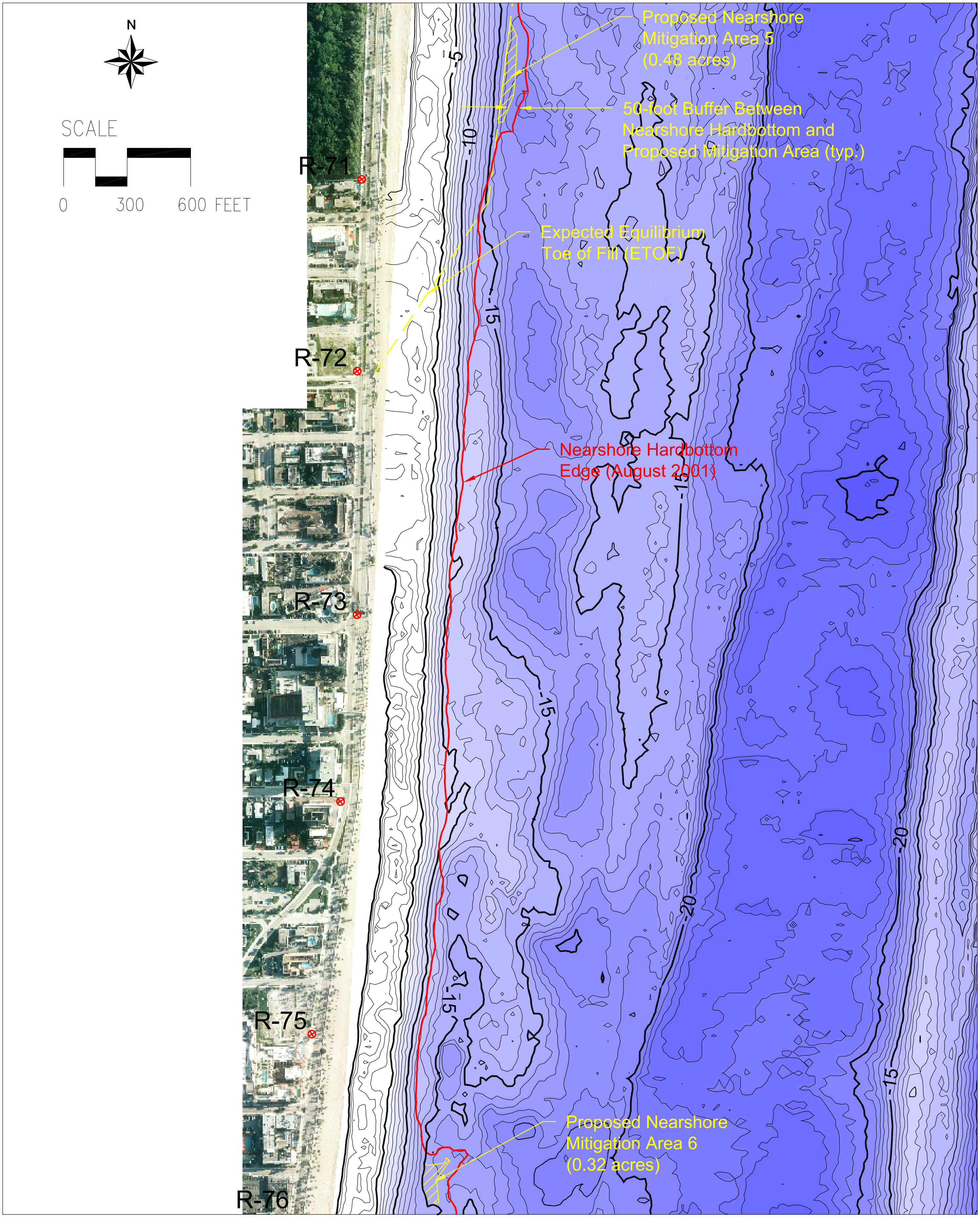
olsen associates, inc.



Broward County Federal Shore Protection Project
Proposed Nearshore Mitigation Areas
Segment II

Figure 3

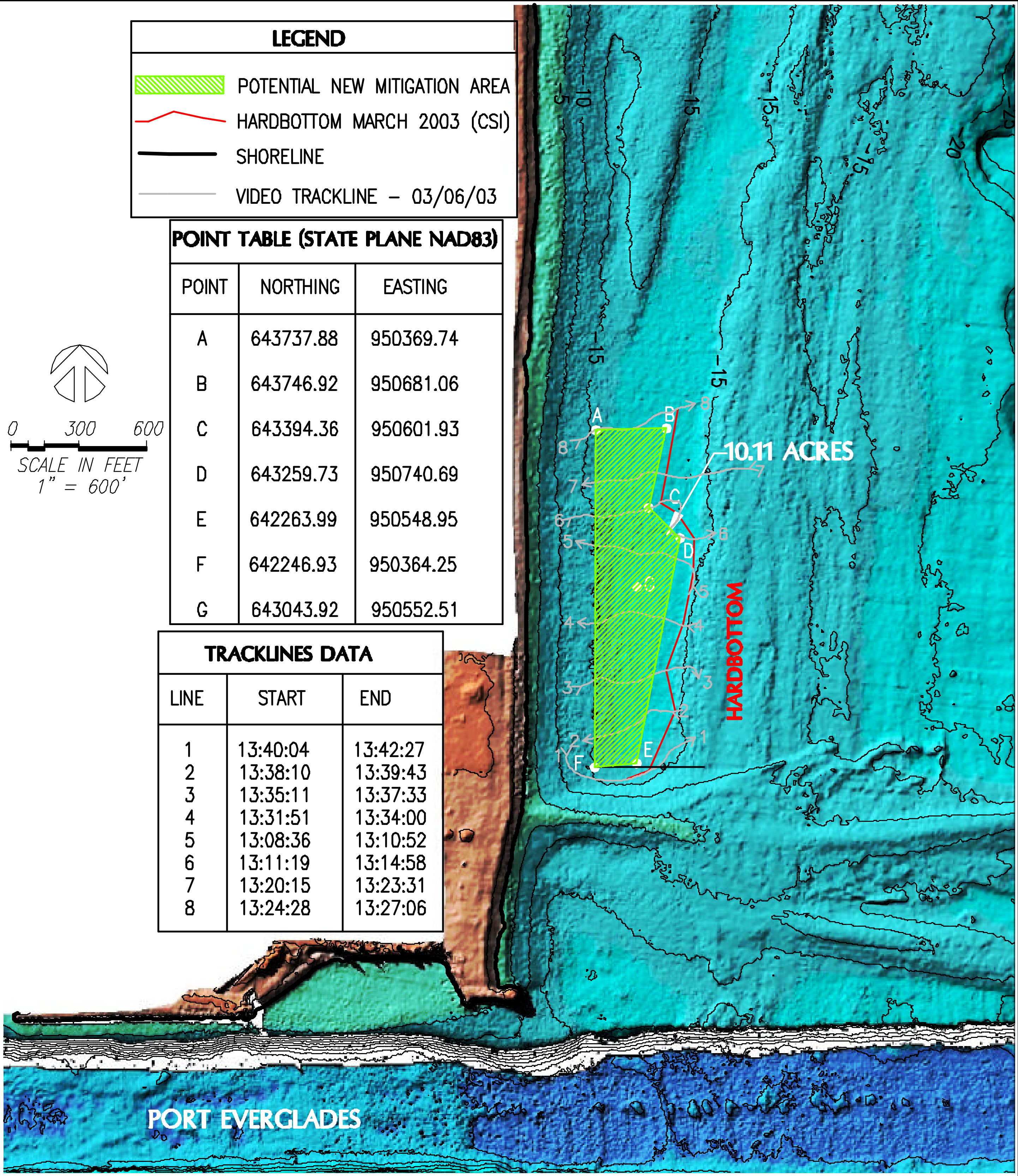
olsen associates, inc.



Broward County Federal Shore Protection Project
Proposed Nearshore Mitigation Areas
Segment II

Figure 4

olsen associates, inc.



LEGEND

- POTENTIAL NEW MITIGATION AREA
- HARDBOTTOM MARCH 2003 (CSI)
- SHORELINE
- VIDEO TRACKLINE – 03/06/03

POINT TABLE (STATE PLANE NAD83)

POINT	NORTHING	EASTING
A	643737.88	950369.74
B	643746.92	950681.06
C	643394.36	950601.93
D	643259.73	950740.69
E	642263.99	950548.95
F	642246.93	950364.25
G	643043.92	950552.51

TRACKLINES DATA

LINE	START	END
1	13:40:04	13:42:27
2	13:38:10	13:39:43
3	13:35:11	13:37:33
4	13:31:51	13:34:00
5	13:08:36	13:10:52
6	13:11:19	13:14:58
7	13:20:15	13:23:31
8	13:24:28	13:27:06

F/PROJECT/209800/PERMITSKETCHES/WORKING/Figure-4a.dwg

T.K. BLANKENSHIP
FL.REG.55910

BROWARD COUNTY
218 S.W 1st AVE.
FT. LAUDERDALE, 33301

COASTAL SYSTEMS INTERNATIONAL

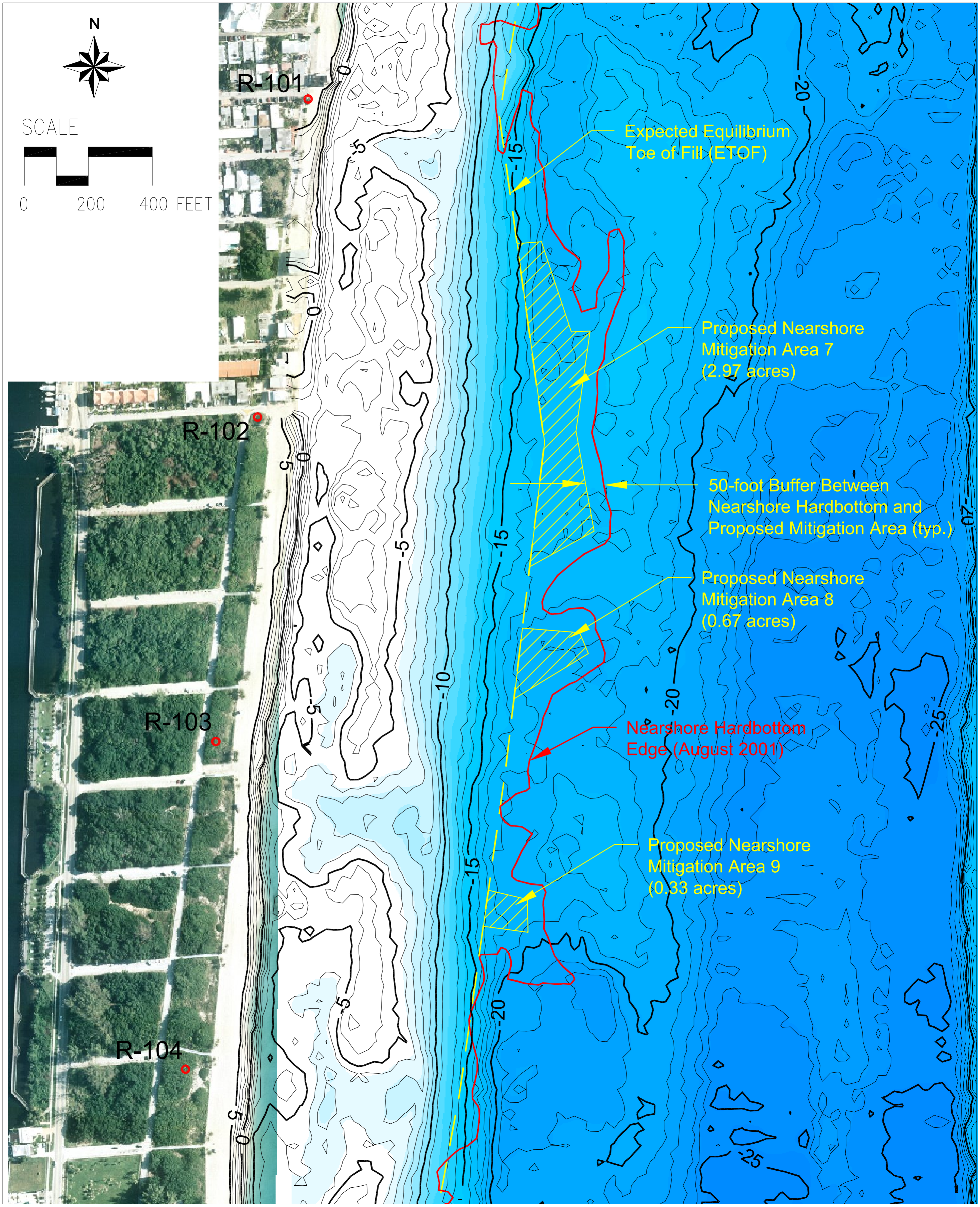
COASTAL SYSTEMS INTERNATIONAL, INC.
464 South Dixie Highway, Coral Gables, Florida 33146
Tel: 305/661-3655 Fax: 305/661-1914 www.CoastalSystemsInt.com
STATE OF FLORIDA EB #7087
Coastal, Environmental, Civil Engineering and Management

BEACH RESTORATION MITIGATION
MITIGATION AREA 12

SEGMENT II

JOB:	209800	DATE:	04/23/03
BY:	SR	SHEET	4a OF

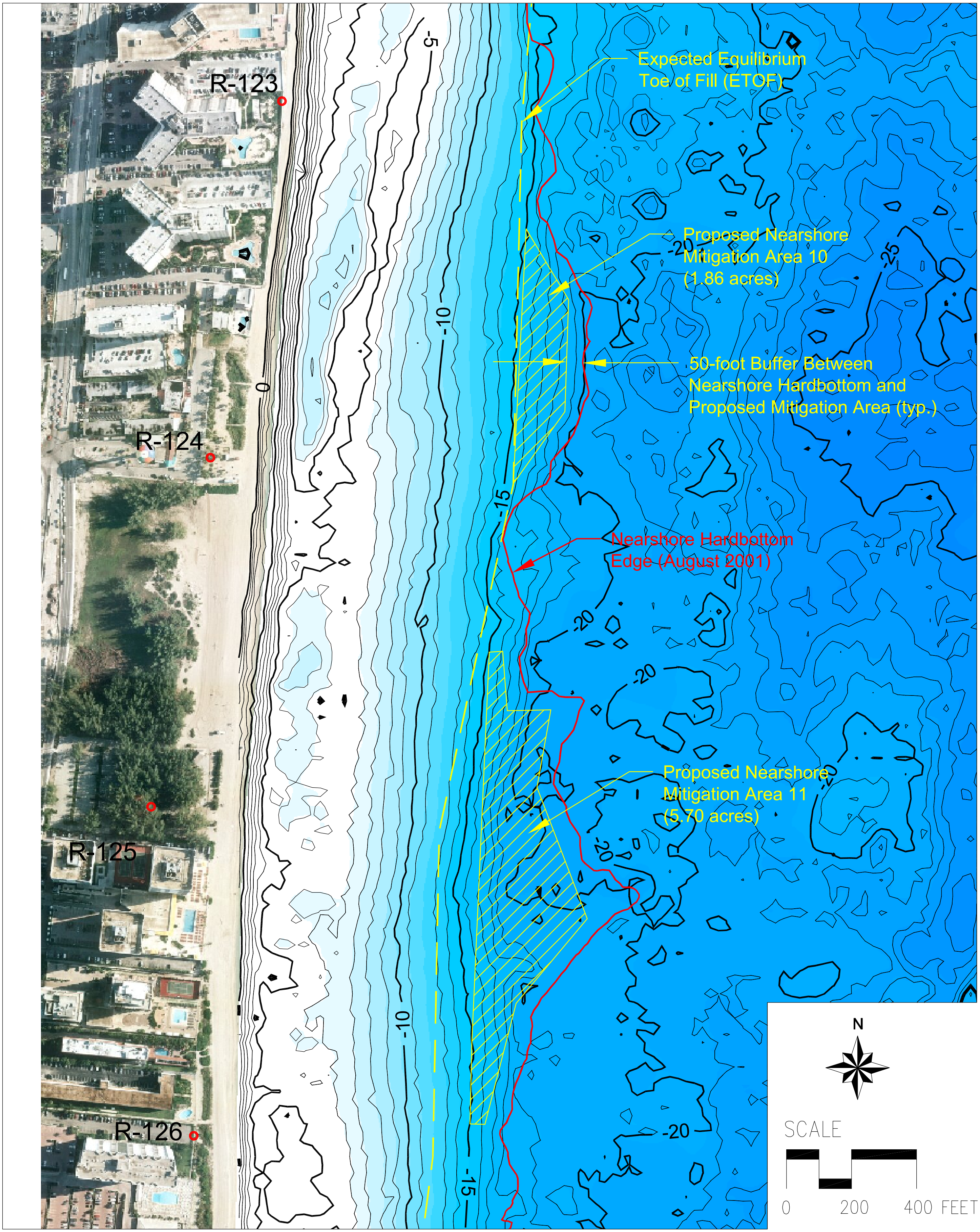
Figure 4a



Broward County Federal Shore Protection Project
Proposed Nearshore Mitigation Areas
Segment III

Figure 5

olsen associates, inc.



Broward County Federal Shore Protection Project
Proposed Nearshore Mitigation Areas
Segment III

Figure 6

olsen associates, inc.

MITIGATION ACREAGE TABLE			
MITIGATION AREA	PERMITTED ACRES	AVAILABLE ACRES	POTENTIAL NEW ACRES
AREA 7	2.97	2.92	0.94
AREA 8	0.67	0.67	0
AREA 9	0.33	0.32	0

POINT TABLE (STATE PLANE NAD83)		
POINT	EAST	NORTH
A	948447	623788
B	948260	623683
C	948238	623491
D	948416	623478
E	948428	623450
F	948425	623473
G	948374	623599
H	948448	623675
I	948445	623761

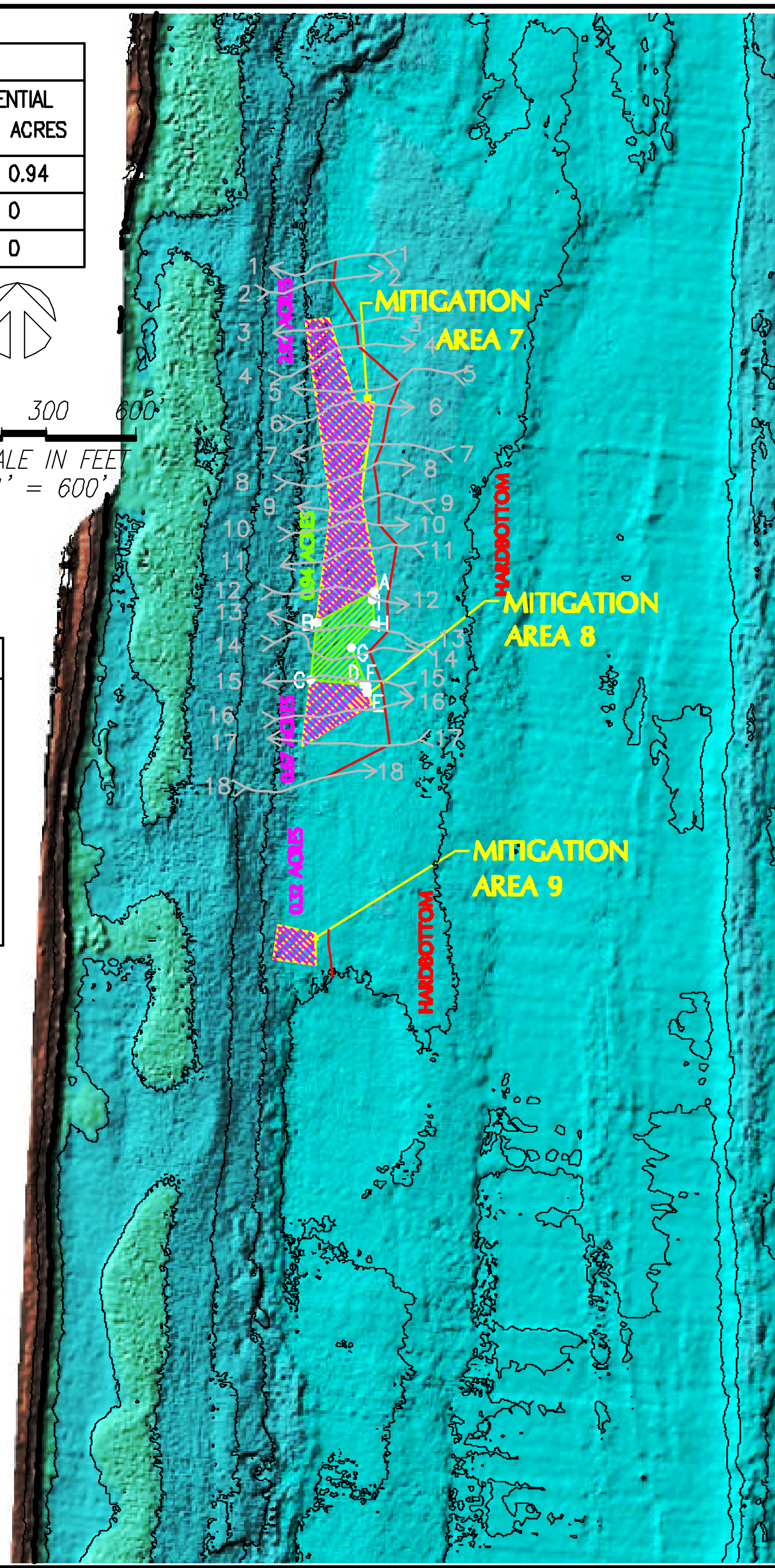
0 300 600'

SCALE IN FEET
1' = 600'

LEGEND

- PERMITTED MITIGATION AREA
- AVAILABLE AREA WITHIN PERMITTED AREA
- POTENTIAL NEW MITIGATION AREA
- HARDBOTTOM MARCH 2003 (CSI)
- SHORELINE
- VIDEO TRACKLINE 03/07/03

TRACKLINE DATA		
LINE	START	END
1	13:22:30	13:23:54
2	13:24:30	13:25:47
3	13:27:09	13:28:26
4	13:29:06	13:20:41
5	13:31:57	13:33:51
6	13:34:28	13:35:55
7	13:37:00	13:38:50
8	13:39:13	13:42:59
9	13:41:29	13:42:59
10	13:43:37	13:44:54
11	13:45:43	13:47:21
12	13:47:47	13:49:28
13	13:50:01	13:51:53
14	13:52:25	13:54:15
15	13:55:15	13:56:53
16	13:57:42	13:59:17
17	14:00:09	14:01:58
18	14:02:49	14:04:07



F/PROJECT/209800/PERMIT SKETCHES/WORKING/Figure-6a.dwg

T.K. BLANKENSHIP
FL.REG.55910

BROWARD COUNTY
218 S. W 1st AVENUE
FT. LAUDERDALE

COASTAL SYSTEMS INTERNATIONAL

COASTAL SYSTEMS INTERNATIONAL, INC.
464 South Dixie Highway, Coral Gables, Florida 33146
Tel: 305/661-3655 Fax: 305/661-1914 www.CoastalSystemsInt.com
STATE OF FLORIDA EB #7087
Coastal, Environmental, Civil Engineering and Management

BEACH RESTORATION MITIGATION
MITIGATION AREA 7-8

SEGMENT III

JOB:	209800	DATE:	04/23/03
BY:	SR	SHEET	6a OF

Figure 6a

PROJECT/209800/PERMIT SKETCHES/WORKING/MIT-AREA-11-B

POINT TABLE (STATE PLANE NAD83)

POINT	EASTING	NORTHING
A	946957.21	600890.31
B	947084.87	600843.05
C	947202.70	600775.45
D	947241.33	600702.92
E	947095.27	600484.55
F	947119.44	600378.08
G	947128.63	600367.23
H	947018.14	600393.15
J	946915.94	600659.79
K	947078.64	600628.77
L	946851.85	599995.90
M	946858.07	600003.28
N	947000.81	600016.91
O	947120.88	599736.67
P	946892.76	599686.36
Q	946820.65	599669.71
R	946755.75	599623.72
S	946938.32	599820.31

TRACKLINES DATA

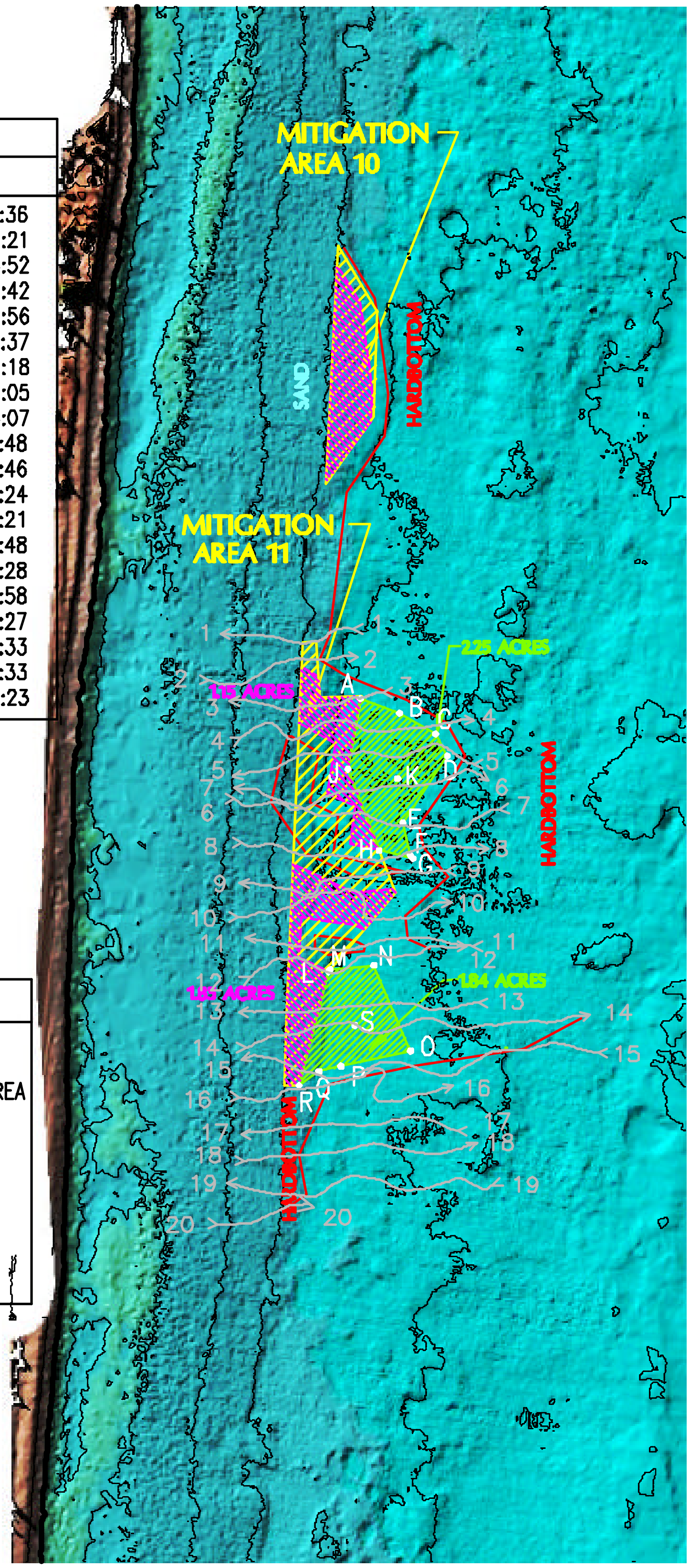
LINE	START	END
1	10:26:28	12:28:36
2	10:29:08	10:31:21
3	10:34:02	10:36:52
4	10:37:48	10:41:42
5	10:42:36	10:45:56
6	10:46:19	10:49:37
7	10:53:02	10:56:18
8	10:57:06	10:59:05
9	11:03:26	11:06:07
10	11:06:49	11:09:48
11	11:11:00	11:13:46
12	11:14:34	11:17:24
13	11:18:23	11:21:21
14	11:22:10	11:26:48
15	11:27:53	11:32:28
16	11:33:02	11:35:58
17	11:36:56	11:39:27
18	11:39:53	11:42:33
19	11:43:17	11:46:33
20	11:47:15	11:48:23

MITIGATION ACREAGE TABLE

MITIGATION AREA	PERMITTED ACRES	AVAILABLE ACRES	POTENTIAL NEW ACRES
AREA 11	5.70	3.0	4.09

LEGEND

- PERMITTED MITIGATION AREA
- AVAILABLE AREA WITHIN PERMITTED AREA
- POTENTIAL NEW MITIGATION AREA
- HARDBOTTOM MARCH 2003 (CSI)
- SHORELINE
- VIDEO TRACKLINES – 03/07/03



0 300 600
SCALE IN FEET
1" = 600'

T.K. BLANKENSHIP
FL.REG.55910

BROWARD COUNTY
218 S.W. Ist AVENUE
FT. LAUDERDALE, 33301

COASTAL SYSTEMS INTERNATIONAL, INC.
464 South Dixie Highway, Coral Gables, Florida 33146
Tel: 305/661-3655 Fax: 305/661-1914 www.CoastalSystemsInt.com
STATE OF FLORIDA EB #7087
Coastal, Environmental, Civil Engineering and Management

BEACH RESTORATION MITIGATION
MITIGATION AREA 11

SEGMENT III

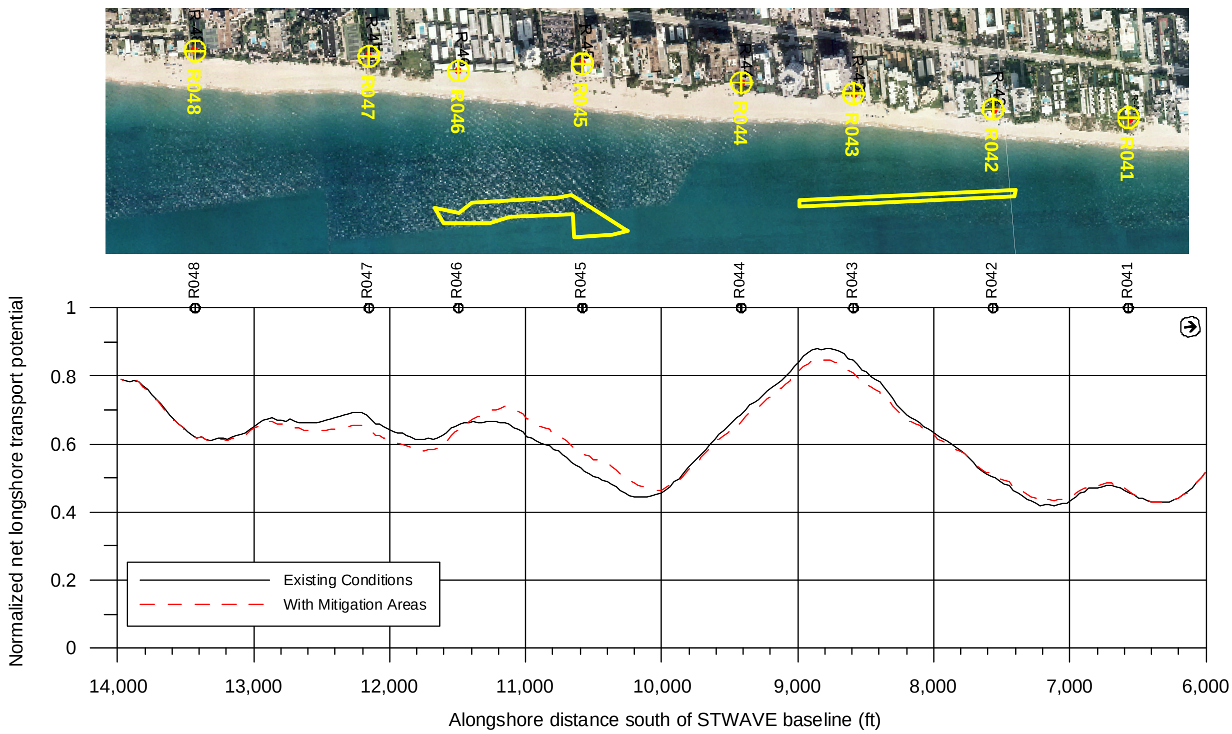
JOB:	209800	DATE:	04/23/03
BY:	SR	SHEET 6b OF	

Figure 6b

BROWARD COUNTY, FLORIDA
SHORE PROTECTION PROJECT

NEARSHORE HARDBOTTOM MITIGATION

Potential Shoreline Impact Analysis



Prepared for: Broward County, Florida

Prepared by: Coastal Planning & Engineering, Inc./
Olsen Associates, Inc. (J/V)

January 2002

Broward County Nearshore Hardbottom Mitigation Plan
Potential Shoreline Impact Analysis

February 2002

Table of Contents

Broward County Nearshore Hardbottom Mitigation Plan

Potential Shoreline Impact Analysis

February 2002

LIST OF TABLES

LIST OF FIGURES

Broward County Nearshore Hardbottom Mitigation Plan
Potential Shoreline Impact Analysis

February 2002

1.0 INTRODUCTION

As part of the Broward County Shore Protection Project, nearshore hardbottom mitigation areas will be created via the placement of limestone boulders in shallow water (15 to 20 ft water depths, typical) over broad, sandy areas in the central and southern portions of the County. The size of the boulders will be on the order of four feet and greater in nominal dimension and are expected to create two to three feet of residual relief following settlement into the sandy seabed. This report focuses on the potential impact these mitigation areas may have on the stability of the shoreline in their lee. Particular focus will be on the potential alteration of longshore sediment transport gradients and the potential formation of salients and/or tombolos and the attendant downdrift erosion.

Figure 1 depicts the locations of four areas identified for nearshore hardbottom mitigation. The locations and estimated acreage of each individual mitigation area proposed are listed, from north to south, in Table 1. The eleven proposed areas will provide sufficient space to construct up to 21.75 acres of nearshore hardbottom mitigation.

Results of these analyses indicate that the proposed mitigation configurations will have negligible effects on the average annual wave-induced longshore transport climate in the vicinity of each area. In a separate analysis, stability calculations relating to the potential sliding and rolling of the placed boulders indicate that the specified stone sizes (> 4-ft nominal dimension) are expected to be stable (Olsen Associates, 2002).

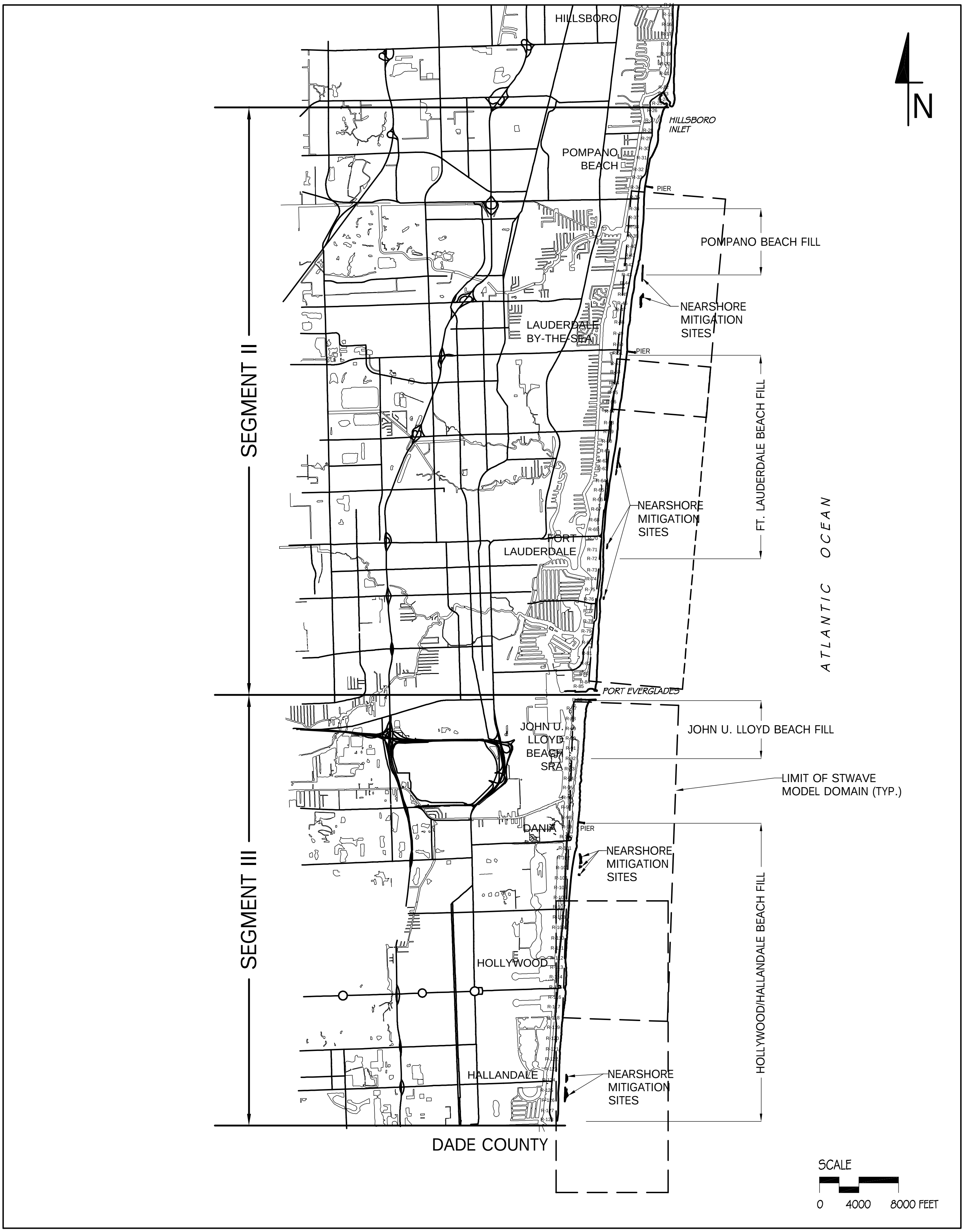


Figure 1 Location of mitigation areas and extent of STWAVE model domains.

Table 1 Area name, general location, and acreage associated with the eleven proposed nearshore hardbottom mitigation areas associated with the Broward County Shore Protection Project.

Mitigation Area	Acreage	General Location, STWAVE grid
#1	1.82	Lauderdale-by-the-Sea, Segment II North #1
#2	4.25	Lauderdale-by-the-Sea, Segment II North #2
#3	2.95	Ft. Lauderdale, Segment II South #1
#4	0.37	Ft. Lauderdale, Segment II South #2
#5	0.48	Ft. Lauderdale, Segment II South #3
#6	0.33	Ft. Lauderdale, Segment II South #4
Segment II Total	10.20	
Mitigation Area	**Acreage**	**General Location**
#7	2.97	Dania, Segment III North #1
#8	0.67	Dania, Segment III North #2
#9	0.33	Dania, Segment III North #3
#10	1.87	Hollywood/Hallandale, Segment III South #1
#11	5.70	Hollywood/Hallandale, Segment III South #2
Segment III Total	11.55	

These mitigation areas were selected based on the high-resolution LADS bathymetric data, aerial photography,and a 2001 survey of the nearshore hardbottom edge which show the extent of existing hardbottom areas offshore of Broward County. A 50-ft buffer was placed around significant hardbottom areas. Additionally, the predicted location of the toe of the equilibrated beach fill project was considered in order to place the structures seaward of the proposed project. Further guidance was based on the results of stability analyses (Olsen Associates, 2002) which suggested that mitigation areas should be sited in sandy bottom areas deeper than 15 ft mid-tide in areas sheltered by First Reef, the first mostly-contiguous reef feature offshore.

2.0 POTENTIAL SHORELINE IMPACTS

The proposed nearshore hardbottom mitigation plan calls for the placement of limestone boulders over broad sandy areas in the nearshore region in mean water depths of between 15 and 20 ft. This action will raise areas of the seabed by as much as 4 ft or more initially, depending on the sizes of the stones placed. The primary concern relating to potential shoreline impacts is the alteration of the existing wave climate in the nearshore region. The increased seabed elevation may trigger wave breaking over the placed boulders in a more seaward location, thus creating a sheltered area in the lee of (landward of) the mitigation area. This would produce a region of reduced longshore sediment transport potential along the shoreline which can cause deposition of sand and ultimately lead to the formation of shoreline features known as salients or tombolos (see Figure 2). While the area of the salient or tombolo benefits from the deposition of sand, the adjacent areas, particularly those downdrift of the feature, frequently experience a deficit of sand due to the shoreline perturbation and thus begin to erode. In the case of tombolo formation, the downdrift erosion can become substantial.

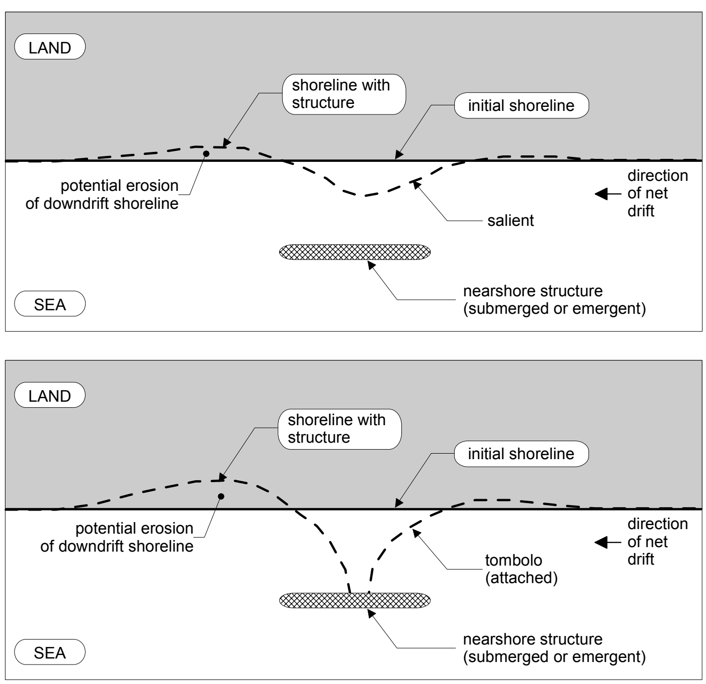


Figure 2 Schematic of shoreline alteration leeward of nearshore structures. The formation of salients or tombolos can produce erosion on adjacent shorelines.

In the present application, the limestone boulders would be placed in 15 to 20 of water (at mid-tide condition). The submerged boulders would initially occupy only as much as one-third of the total water column at mid-tide. This represents a minor obstruction to the wave field and is not expected to significantly reduce wave heights leeward of the mitigation areas. For example, Figure 3 illustrates the variation of the effectiveness of submerged and emergent breakwaters as a function of the structure elevation relative to the local water depth and the incident wave height (USACE, 1984, after Goda, 1969). The ratio of the wave height landward of the structures ($H_{transmitted}$, or H_t) to the incident wave height on the seaward side ($H_{incident}$, or H_i), is known as the transmission coefficient, or K_t.

Applying the plots in Figure 3 to the present situation at mid-tide, the quantity $(h-d_s)$ is approximately -10 ft, worst case (5 ft stone in 15 ft water depth). While a 10-ft incident wave is a rare occurrence at these sites, it is certainly possible. That wave height produces a value of $(h-d_s)/H_i$ of -1.0. According to Figure 3, the transmission coefficient is between 0.70 and 0.84, meaning that the incident waves would be reduced in height by between 16 and 30%, which is a meaningful reduction. However, the previous example calculation did not include the effect of a storm surge level which would reduce the effectiveness of the structure. For smaller waves, the transmission coefficient quickly approaches 1.0 (the situation moves to the left on the x-axis of Figure 3). For example, for a 5-ft incident wave in the same situation, the expected K_t values range between 0.95 and 1.00, indicating almost no influence of the stones on the incident waves.

For this reason, it is highly unlikely that sand would accrete in sufficient volumes leeward of the mitigation areas to create a tombolo. The degree of alteration that may initially occur due to construction of the mitigation areas is expected to take the form of mild salient-type variations alongshore (milder than that illustrated in Figure 2).

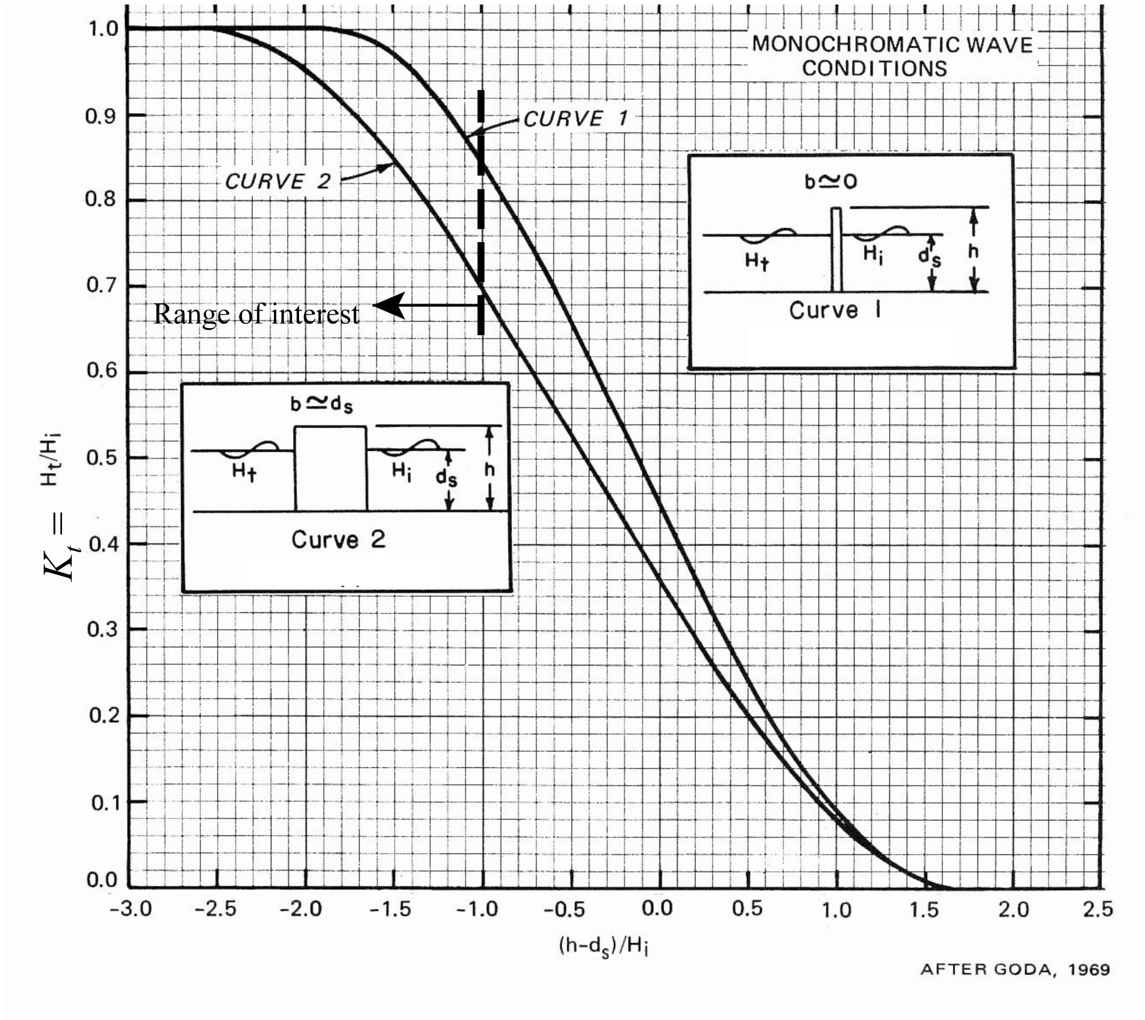


Figure 3 Typical transmission coefficients for narrow-crested and broad-crested breakwaters (modified from USACE, 1984, after Goda, 1969). In the figure, *b* represents the width of the structure in the cross-shore direction. Monochromatic wave conditions refer to a wave field with a single wave period (as opposed to a wave spectrum, which has a combination of many waves of different periods and possibly different directions).

3.0 WAVE CONDITIONS

Wave conditions for central and southern Broward County were compiled from two primary sources. The first source is the USACE Wave Information Study (Hubertz et al. 1993). This dataset provides wave height and wind magnitude and direction hindcast predictions for the area for the period 1976-1995 in three-hour intervals. The second source of wave data comes from a University of Florida field study by Dompe and Hanes (1992). Dompe and Hanes (D&H92) present significant wave height, period, and directional information for the period January 1990 to May 1992 for two wave gages. These gages were installed along a cross-shore transect in 17 ft (5.2m) and 35 ft (10.7m) water depths. The D&H92 dataset provides an excellent opportunity to adjust the WIS dataset for the local wave climate.

Figures 4a and 4b present wave rose data calculated from WIS stations 9 and 10 offshore of Broward County. Data from Station 9 are hindcast for deepwater conditions (roughly720 ft) offshore of the Hollywood/Hallandale area. Station 10 provides hindcast data in the Lauderdale-by-the-Sea/Pompano Beach area, also in deep water. The wave roses in Figures 4a and 4b clearly illustrate that the majority of occurences originate from the northeast quadrant, indicating, at least in part, the sheltering effect of the Bahama Bank. Both hindcasts produce very similar results, with Station 10 reporting slighter higher occurrences of NE waves due to its increased exposure to the open Atlantic Ocean.

Of interest in the present analysis is a comparison of the WIS hindcast data to the measured field data collected by D&H92. The D&H92 dataset is somewhat intermittent, so several discrete time periods were culled from that data and compared to the WIS data. Figure 5 provides a comparison of the significant wave heights reported during the month of March, 1990, by the WIS hindcast and the two wave gages. The reduction in wave height across the nearshore reef system of Broward County is readily apparent in the plot, which demonstrates remarkable agreement throughout the month over a range of wave conditions. Although not shown herein, the period and direction data also demonstrate good agreement and in many instances demonstrate the refraction of oblique waves across the profile.

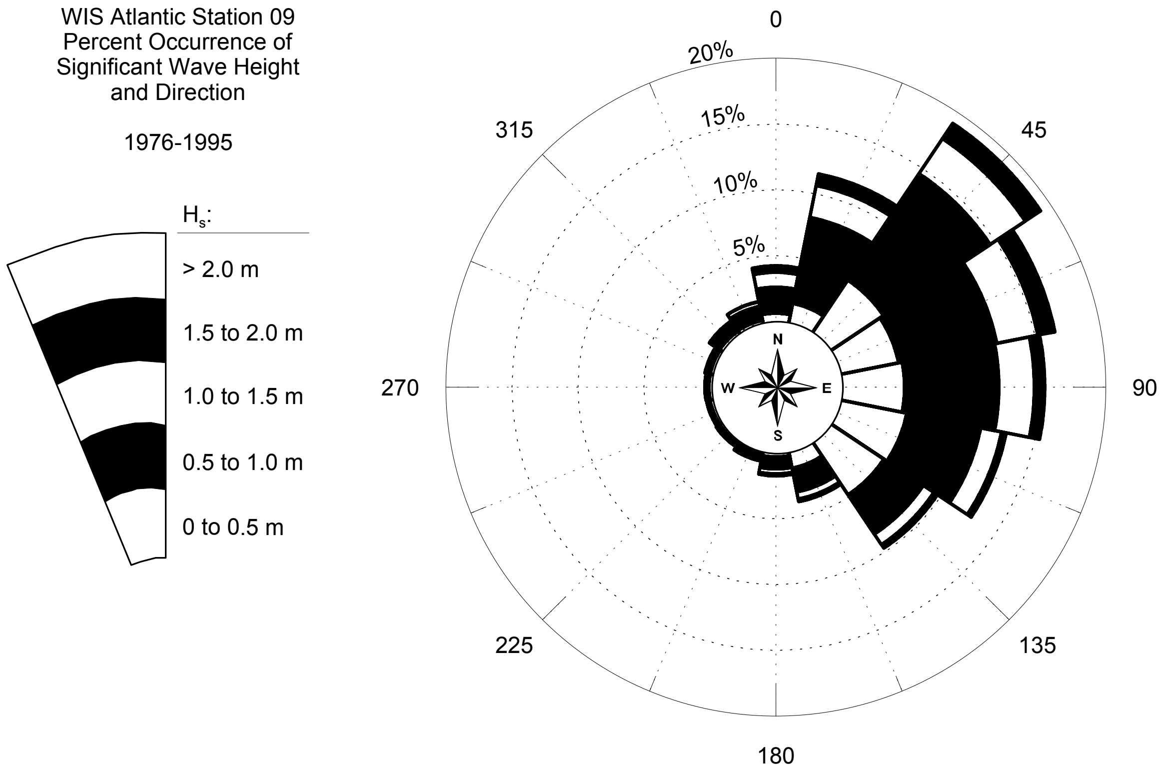


Figure 4a Wave rose generated from WIS Hindcast Station 9 offshore of south Broward County illustrating the percent occurrence of deepwater significant wave heights and directions (720 ft depth).

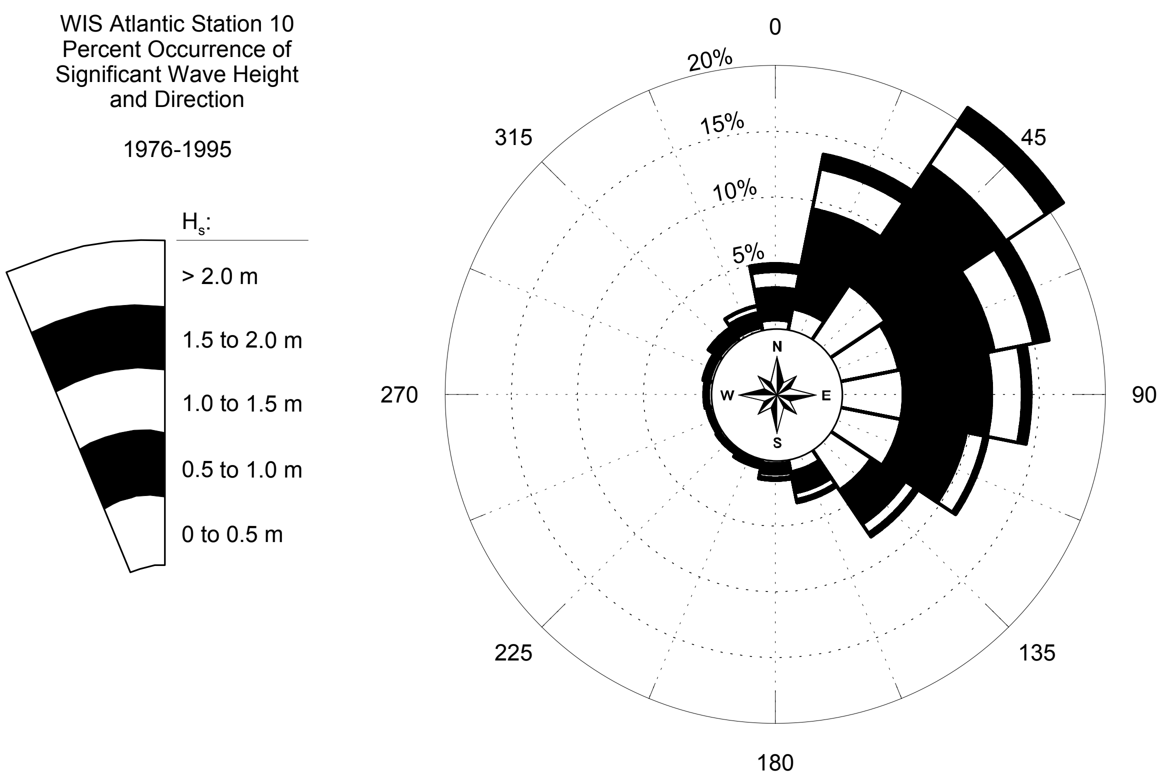


Figure 4b Wave rose generated from WIS Hindcast Station 10 offshore of north-central Broward County illustrating the percent occurrence of deepwater significant wave heights and directions (600 ft depth).

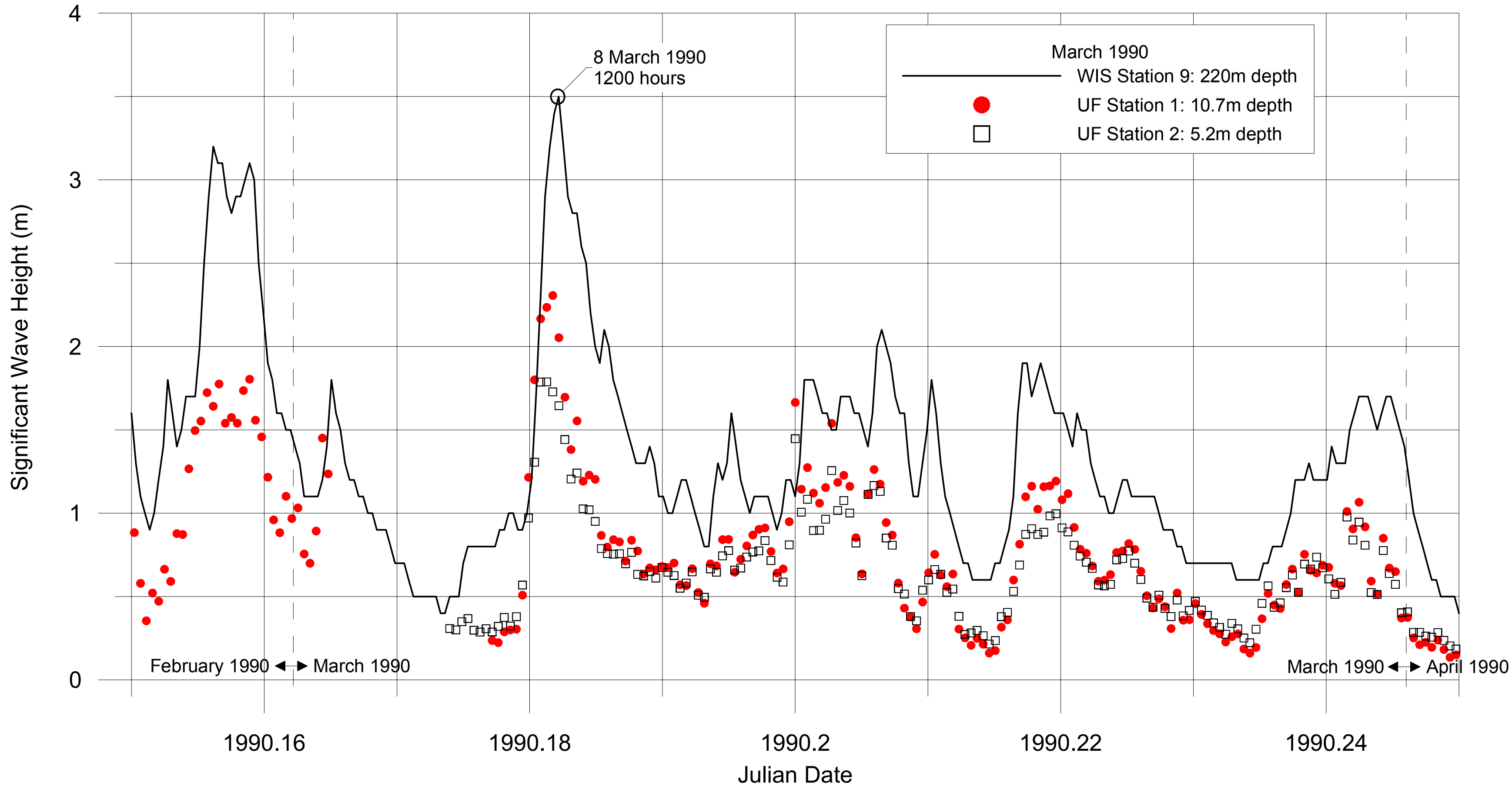


Figure 5 Comparison of WIS Hindcast Station 9 in deep water to Dompe and Hanes (1992) wave gage data in 10.7m and 5.2m water depths for the month of March, 1990. Both datasets are reported in SI units (1.00m = 3.28 ft).

Inspection of Figure 5 suggests that the hindcasted WIS wave height data is typically on the order of two times higher than the significant wave height reported at the first University of Florida (UF) wave gage of D&H92. A portion of this difference can be attributed to natural friction effects and wave breaking across the irregular reefs between the offshore region and the nearshore wave gage. The remainder of the difference is hypothesized to be an overprediction of the WIS hindcast data. To investigate this potential discrepancy, individual wave cases were modeled using the STWAVE refraction-diffraction model (described in Section 4.0). Figure 6 depicts the results of one such model run. STWAVE does not incorporate bottom friction, therefore, the reduction in wave height across the reefs is due to both spreading of wave components in the wave spectrum and wave breaking of portions of the wave spectrum in various depths. The overprediction of the WIS hindcast is shown in the figure, as the nearshore wave heights are overestimated by as much as 50% compared to the D&H92 data[1]. For this particular example, a reduction of the WIS hindcast significant wave height of 30% produces good agreement with the corresponding D&H92 data.

Applying the same comparative technique to other corresponding wave conditions indicates that reductions of the WIS significant wave heights of 25% to 35% produces improved agreement with the measured data (greater % reductions apply to larger hindcast wave heights). Using these values as a guideline, the WIS data were analyzed to produce a set of wave conditions representative of the average annual conditions in Broward County. In total, 19 conditions were generated from the data shown in Figures 4a and 4b. Significant wave heights were then reduced under the guidelines mentioned above. The resulting wave conditions used in the shoreline impact analysis are summarized in Table 2.

1

It is assumed that the measured data of Dompe and Hanes (1992) are the representative data.

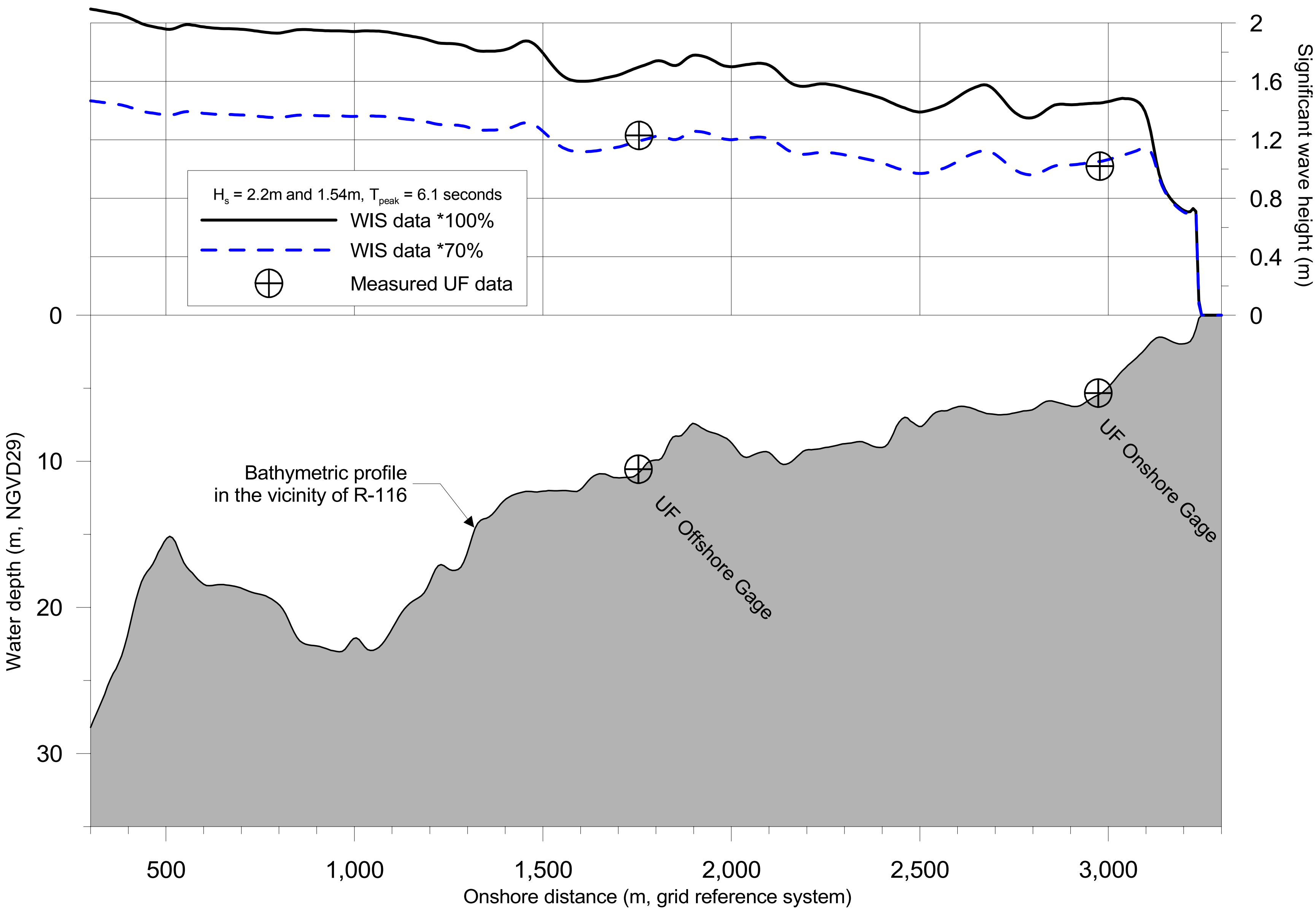


Figure 6 Example comparison of measured UF gage data (Dompe and Hanes, 1992) to hindcast WIS Station 9 data (March 1990).

Table 2 Representative average annual wave conditions for Broward County, FL, based on WIS Hindcast Data (e.g. Hubertz et al., 1993).

Case	Percent Occurrence	Raw Significant Wave Height (m)	Adjusted Significant Wave Height (m)**	Period (seconds)	Incident Direction (wrt due East, degrees)
1	4.69	0.83	0.62	7.4	44.5
2	1.77	1.62	1.13	7.6	44.5
3	1.50	2.72	1.66	6.8	44.5
4	5.36	0.84	0.63	4.7	44.4
5	1.66	1.53	1.07	5.0	43.9
6	1.05	0.80	0.60	6.4	24.8
7	1.21	2.59	1.61	6.2	23.4
8	3.08	1.59	1.11	5.6	23.1
9	6.39	0.85	0.64	4.5	22.5
10	0.37	0.85	0.64	6.2	2.3
11	0.65	2.60	1.61	6.2	0.9
12	2.40	1.55	1.09	5.6	0.7
13	6.45	0.84	0.63	4.4	0.1
14	0.30	2.61	1.61	6.2	-21.1
15	4.99	0.83	0.62	4.3	-21.4
16	1.39	1.54	1.08	5.5	-21.9
17	0.31	2.67	1.64	6.3	-43.1
18	0.68	1.53	1.07	5.0	-43.5
19	3.09	0.82	0.62	4.4	-43.9

Wave conditions reflect the average of the onshore directed waves from WIS Atlantic stations 9 and 10. Both the WIS dataset and the STWAVE refraction/diffraction model use metric units. ** Wave heights adjusted based on the data of Dompe and Hanes (1992).

4.0 METHODS, RESULTS, & DISCUSSION

To investigate the potential alteration of the longshore sediment transport climate due to the construction of the proposed nearshore hardbottom mitigation areas, the STWAVE refraction/diffraction model (Smith et al., 2001) was applied using the wave conditions described in the previous section. STWAVE was used to determine the alongshore wave breaking conditions at the four sites outlined in Figure 1, which encompass the 11 mitigation areas. The STWAVE model is a numerical finite-difference model intended to describe the steady-state wind-growth and propagation of water waves in the nearshore region. The acronym STWAVE stands for STeady-state spectral WAVE model. The governing equations for the model are derived from the wave-action balance equations. The model simulates the refraction, diffraction, and wind-generated growth of water waves over irregular bathymetries. The effects of wave breaking and wave-current interactions can be simulated in the model. In the present application, wave-current effects are not modeled.

The four areas identified in Figure 1 were digitized into a regularly spaced grid pattern of water depth data (bathymetry). The resolution of the bathymetric grid supplied to STWAVE was 10 m x 10 m (32.8 ft by 32.8 ft). Figures 7 through 10 illustrate the bathymetric grid data and depict the location of the mitigation areas in each model grid. The FDEP monuments are shown for reference. Each of the 19 wave cases in Table 2 were transformed into a wave spectrum for use in STWAVE.

Each of the grids shown in Figures 7 through 10 were modified to include the new relief of the proposed mitigation areas. The water depths in the areas highlighted in the figure were decreased by 1.22 m (4.0 ft) to simulate the presence of the mitigation stones. In total, 19 wave cases were run over 8 grids (4 areas, with and without mitigation areas in them) for a total of 152 STWAVE simulations. Results from the STWAVE simulations were analyzed to determine potential changes in the wave field and to the longshore sediment transport climate due to the mitigation areas.

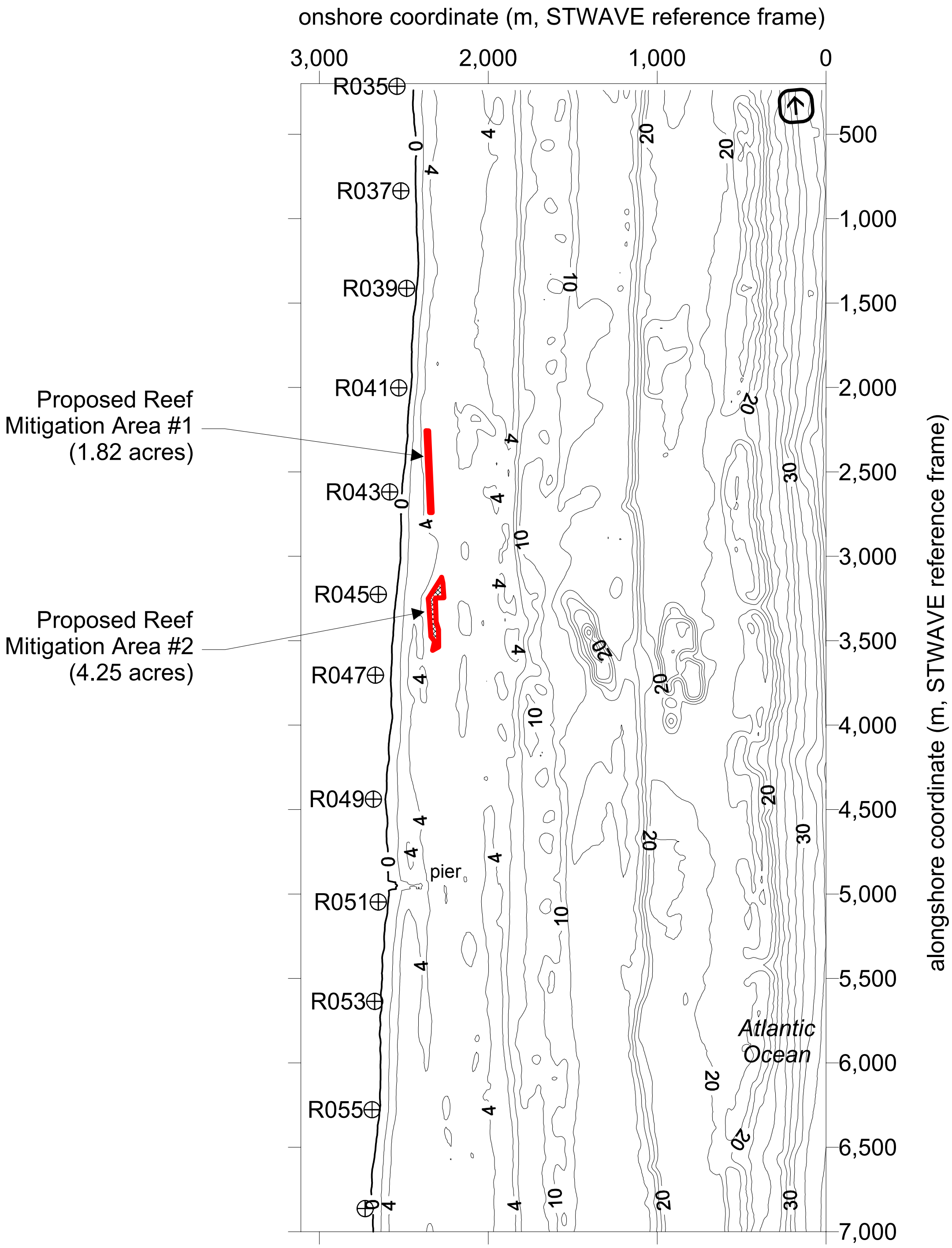


Figure 7 STWAVE grid depicting the reef mitigation areas and bathymetric contours in the Lauderdale-by-the-Sea area (areas #1 and #2). Coordinates and orientation apply to the STWAVE model input requirements. Contours indicate water depth in meters relative to NGVD29.

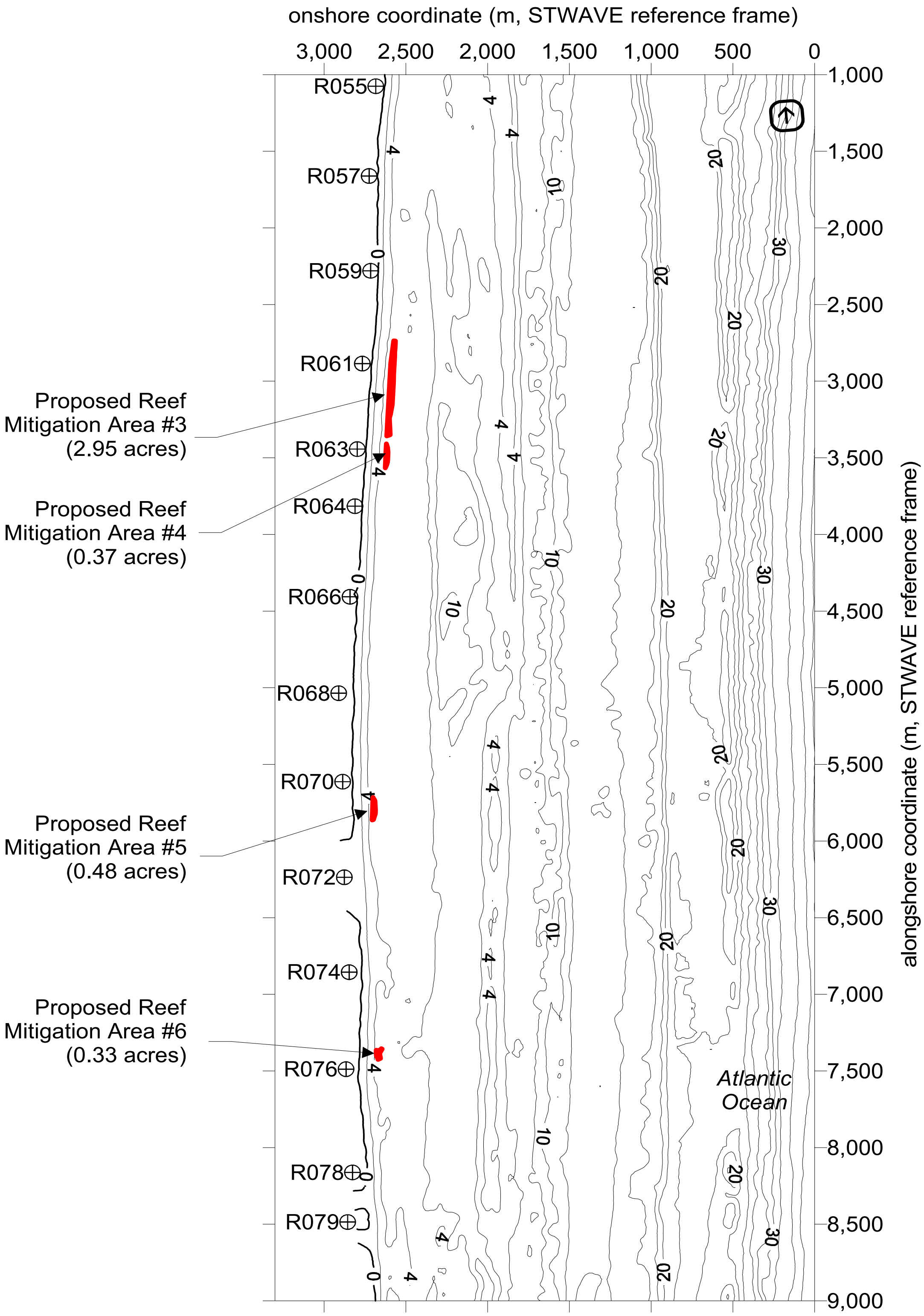


Figure 8 STWAVE grid depicting the reef mitigation areas and bathymetric contours in the Ft. Lauderdale area (areas #3 through #6). Coordinates and orientation apply to the STWAVE model input requirements. Contours indicate water depth in meters relative to NGVD29.

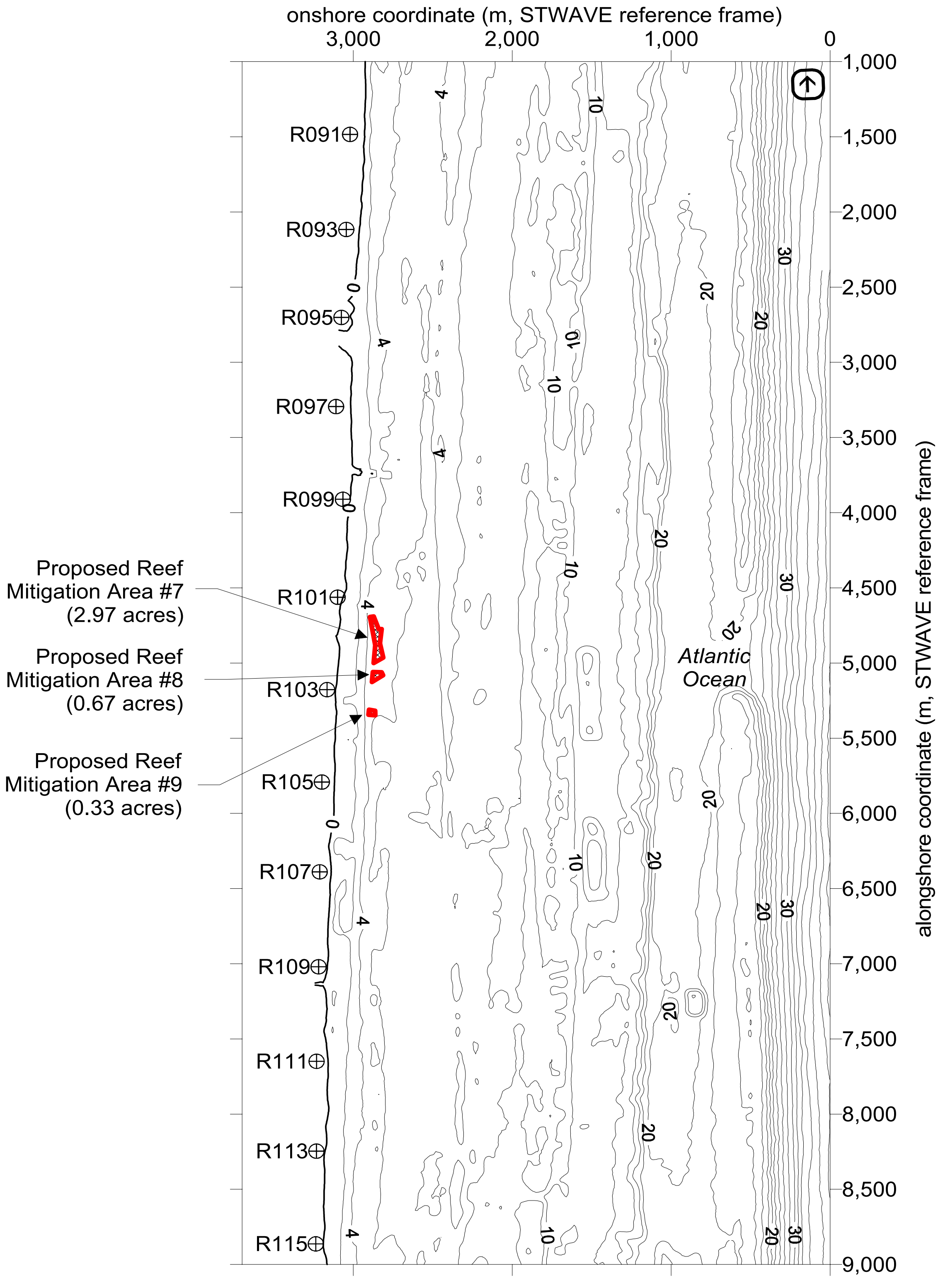


Figure 9 STWAVE grid depicting the reef mitigation areas and bathymetric contours in the Dania area (areas #7, #8, and #9). Coordinates and orientation apply to the STWAVE model input requirements. Contours indicate water depth in meters relative to NGVD29.

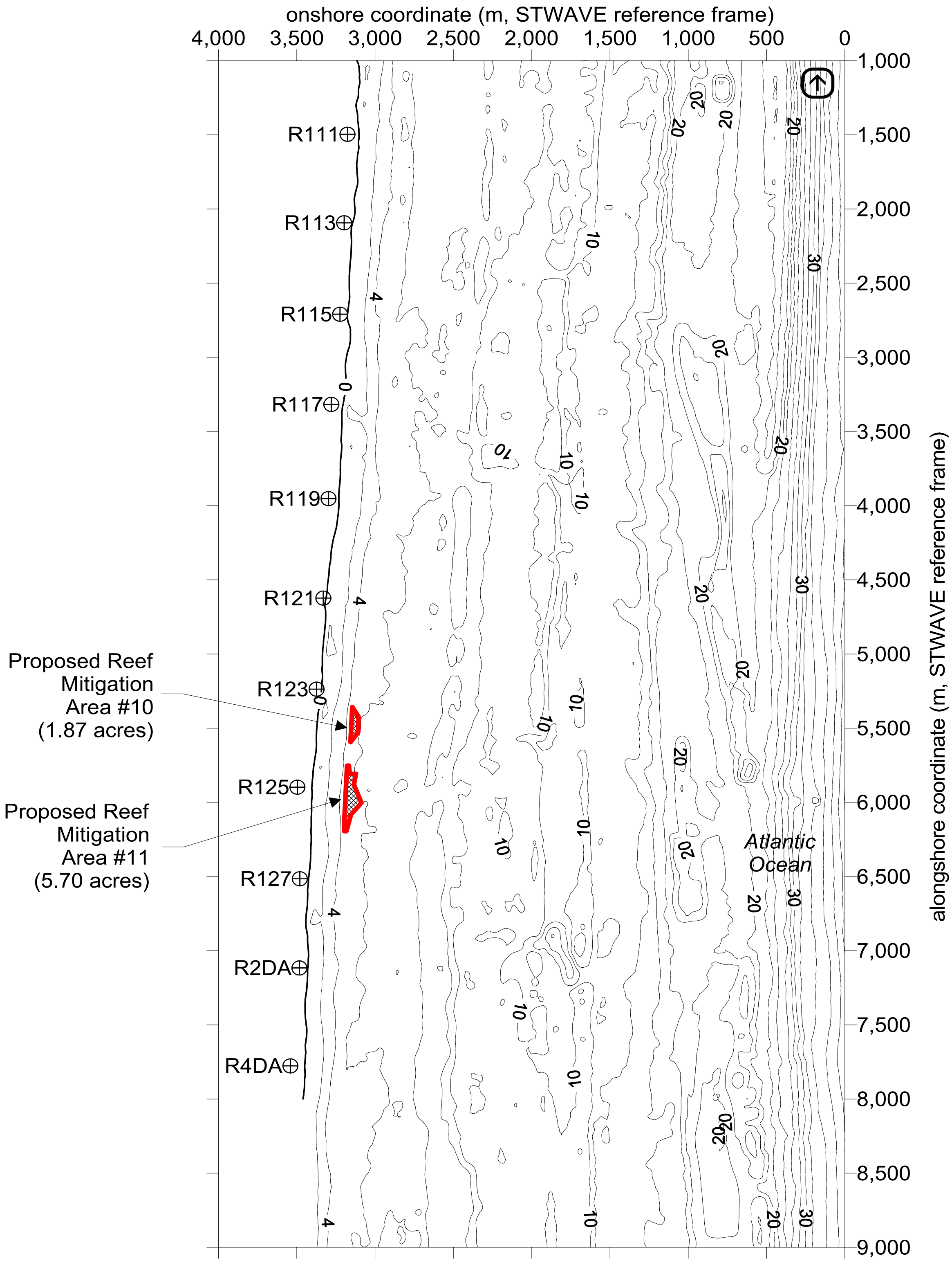


Figure 10 STWAVE grid depicting the reef mitigation areas and bathymetric contours in the Hollywood/Hallandale area (areas #10 and #11). Coordinates and orientation apply to the STWAVE model input requirements. Contours indicate water depth in meters relative to NGVD29.

While the WIS data and the STWAVE model use SI units exclusively, the following results have been converted to English units to agree with the unit system applied in the Broward County Shore Protection Project (USACE, 2001).

It is important to note that the STWAVE and corresponding transport potential results discussed herein are based on alterations caused by the ***initial*** construction of the mitigation areas. The initial conditions include uniform seabed relief of four feet caused by the limestone boulders. Settlement of one to two feet is ultimately expected, which would significantly reduce the alteration of the wave field and corresponding transport patterns. Additionally, the seabed relief ultimately created will be much more irregular, which is hypothesized to dampen the results shown herein (i.e, the STWAVE model likely overestimates the actual impacts that would occur). Thus the results discussed herein may be viewed as a worst case scenario.

4.1 Lauderdale-by-the-Sea Mitigation Areas (Areas #1 and #2)

Figure 11 depicts the changes in the average annual wave climate in the vicinity of FDEP monument R-45. Two mitigation areas totaling 6.07 acres are proposed for an area just seaward of the 15-ft contour. The upper frame of Figure 11 depicts the existing average annual wave conditions in the area. The middle frame shows the same information with the mitigation areas in place. On *average*, waves are on the order of 1.0 to 1.2 ft in height in the Broward County nearshore area, reflecting the typically mild conditions. The construction of the mitigation areas is expected to produce small areas where the average wave height increases by slightly more than 0.10 ft, and areas where the wave heights decrease by less than 0.1 ft. The increases and decreases are due principally to the focusing and diverging of waves due to refraction near the ends or corners of the mitigation areas. The orientation of the areas affected indicates the predominance of wave energy from the northeast, a situation that produces the net average annual southerly directed transport in Broward County. Landward of the mitigation areas, simulations indicate very little change in wave height in water depths shallower than approximately seven feet, suggesting that typically there would be no change in breaking wave height. However, the focusing and diverging of waves over the mitigation areas may induce changes in wave breaking angle, which also affects changes in the longshore sediment transport.

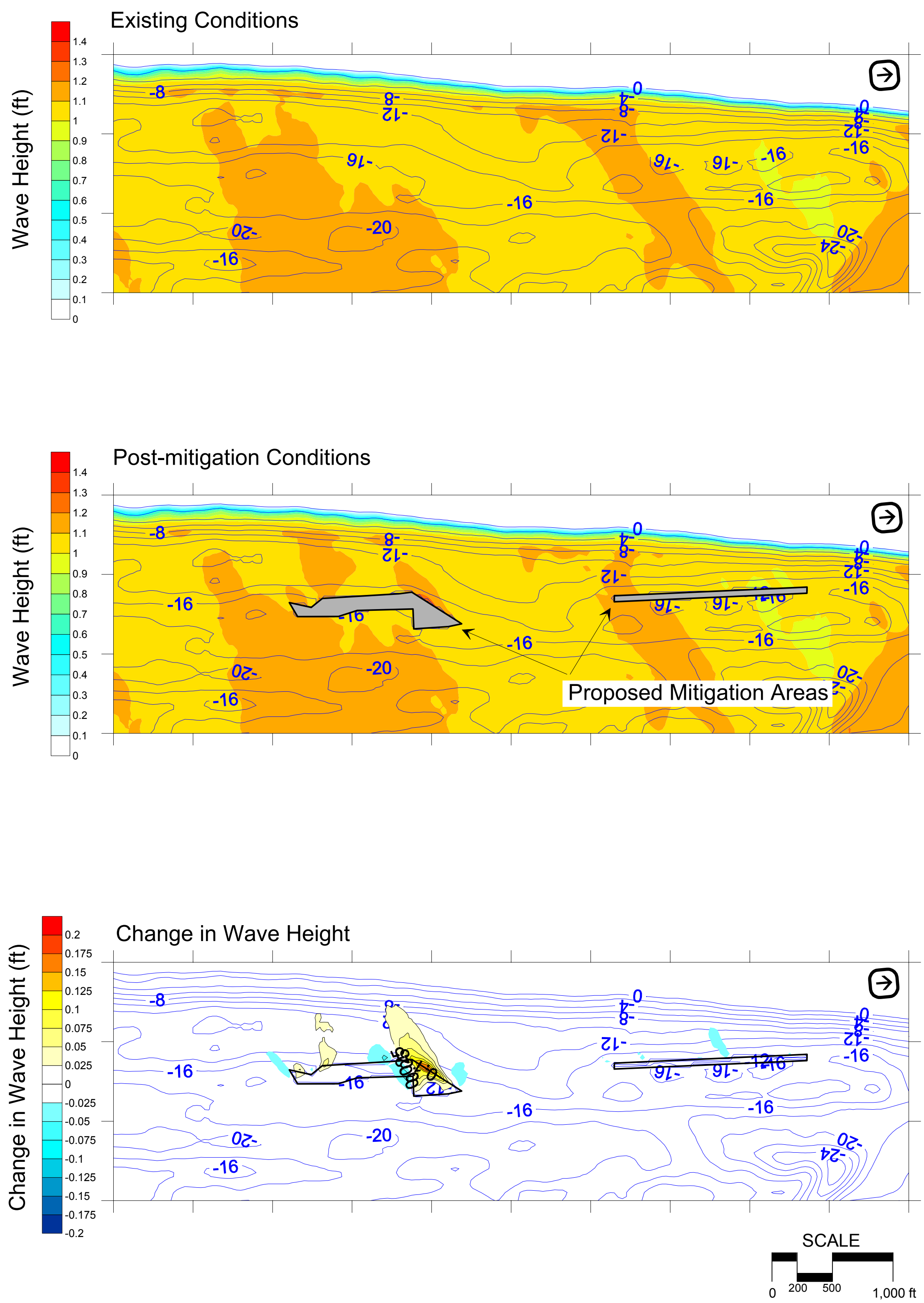


Figure 11 Changes in the average annual wave climate in the Lauderdale-by-the-Sea areas (FDEP R-45). The bottom frame indicates the change in wave climate over the proposed mitigation areas.

Figure 12 illustrates the expected changes in the net average annual longshore transport climate created by the construction of the mitigation areas. For each simulation, breaking wave conditions were calculated at each alongshore grid column. Smith et al (2001) provide a method for predicting breaking conditions for wave spectra. These conditions, breaking wave height and angle, were applied to the well-known CERC formula (e.g. USACE, 1984) to compute the longshore sediment transport potential. Inspection of the alongshore gradients in longshore sediment transport potential reveals information regarding expected areas of erosion and accretion (as will be explained in the following discussion). Moving north to south, areas where the southerly directed net transport is increasing would be expected to be erosional, on average. Conversely, areas where the southerly directed net transport is decreasing would typically be accretional. The refraction/diffraction patterns and sheltering caused by nearshore structures creates distinct changes to the longshore sediment transport potential, creating areas of increased erosion and deposition (e.g. Figure 2).

The results in Figure 12, all positive values indicating southerly directed transport, have been normalized by a standard value of transport potential. This normalization, which applies consistently to all the STWAVE grids applied herein (see Figures 7 through 10), was performed for two reasons. First, the absolute magnitude of the transport potential does not provide information regarding potential areas of erosion and accretion. Second, the CERC formula is typically thought to overestimate the magnitude of transport (e.g. Bodge and Kraus, 1991).

Inspection of Figure 12 suggests that the construction of the mitigation areas would produce only minor variations in the transport potential in the initial period following construction. The patterns of increasing and decreasing potential can be traced to the northern and southern limits of each area, where the majority of the wave field alteration occurs. From north to south, the first mitigation area creates a barely discernable increase in the net transport potential along the first roughly 1,000 ft of shoreline in its lee, followed by a longer (2,000 ft) area of decreased transport. This pattern generally applies to all the mitigation areas studied; for each area the northern segment of shoreline experiences an increase in transport, while the southern segment experiences a decrease.

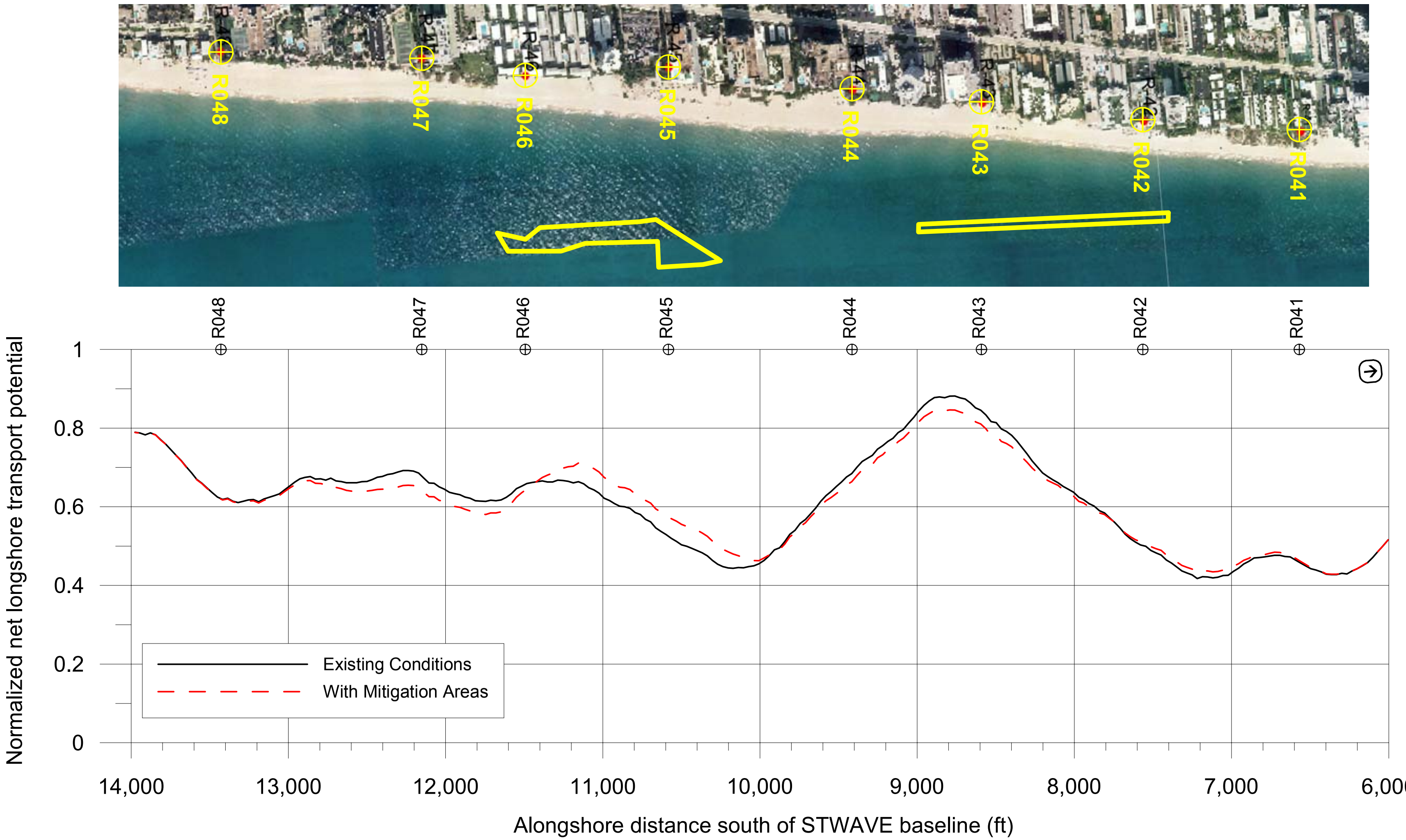


Figure 12 Normalized net transport potential in the Lauderdale-by-the-Sea area (Areas #1 and #2). Plot indicates the location of the proposed mitigation areas and the alongshore variations in the net southerly directed transport potential with and without mitigation.

The southern mitigation area is predicted to initially create an area of increased transport potential over a 1,400-ft segment of shoreline beginning just north of the mitigation limit. This segment corresponds with the area of increased wave height see in Figure 11. A corresponding area of decreased potential is predicted for the shoreline segment immediately southward thereof.

Overall, initial changes in the transport potential are predicted to be on the order of 10% or less (increases and decreases). As discussed previously, however, it is the gradients in transport (i.e. the slope of the curves in Figure 12) that produce areas of erosion and accretion. Inspection of the transport curve in Figure 12 suggests that only very short segments of the shoreline may experience slightly elevated erosion rates initially. For example, in the vicinity of R-41 and R-44.5, the value of transport changes more rapidly with the mitigation areas than without, suggesting that short segments of the shoreline might be more erosional. Conversely, at R-42 to R-43 and at R-46, the slope of the curve is milder suggesting that R-42 to R-43 would be less erosional and R-46 would experience increased deposition. It is important to note that these results represent average annual wave conditions. The behavior of the shoreline during a storm event or within a particular season may not correspond to the results shown in Figure 12 (refer to section 4.5).

4.2 **Ft. Lauderdale Mitigation Areas** (Areas #3 through #6)

Figure 13 depicts the changes in the average annual wave climate in the vicinity of the northern mitigation areas in Ft. Lauderdale, and Figure 14 plots the corresponding changes in the average annual net transport potential. Two mitigation areas, Areas #3 and #4, totaling 3.32 acres are proposed for an area near R-62 just seaward of the 15-ft contour. Patterns similar to the previous case are seen for each mitigation area, although the changes expected in the Ft. Lauderdale area are somewhat reduced due to the narrow cross-shore width and generally shore-parallel orientation dictated by the chosen design (compared to Figures 11& 12). Wave height changes are predicted to be only a few hundredths of a foot, and the patterns of these increases and decreases are similar to the previous example, with the northern edges of the mitigation areas experiencing the greatest increases.

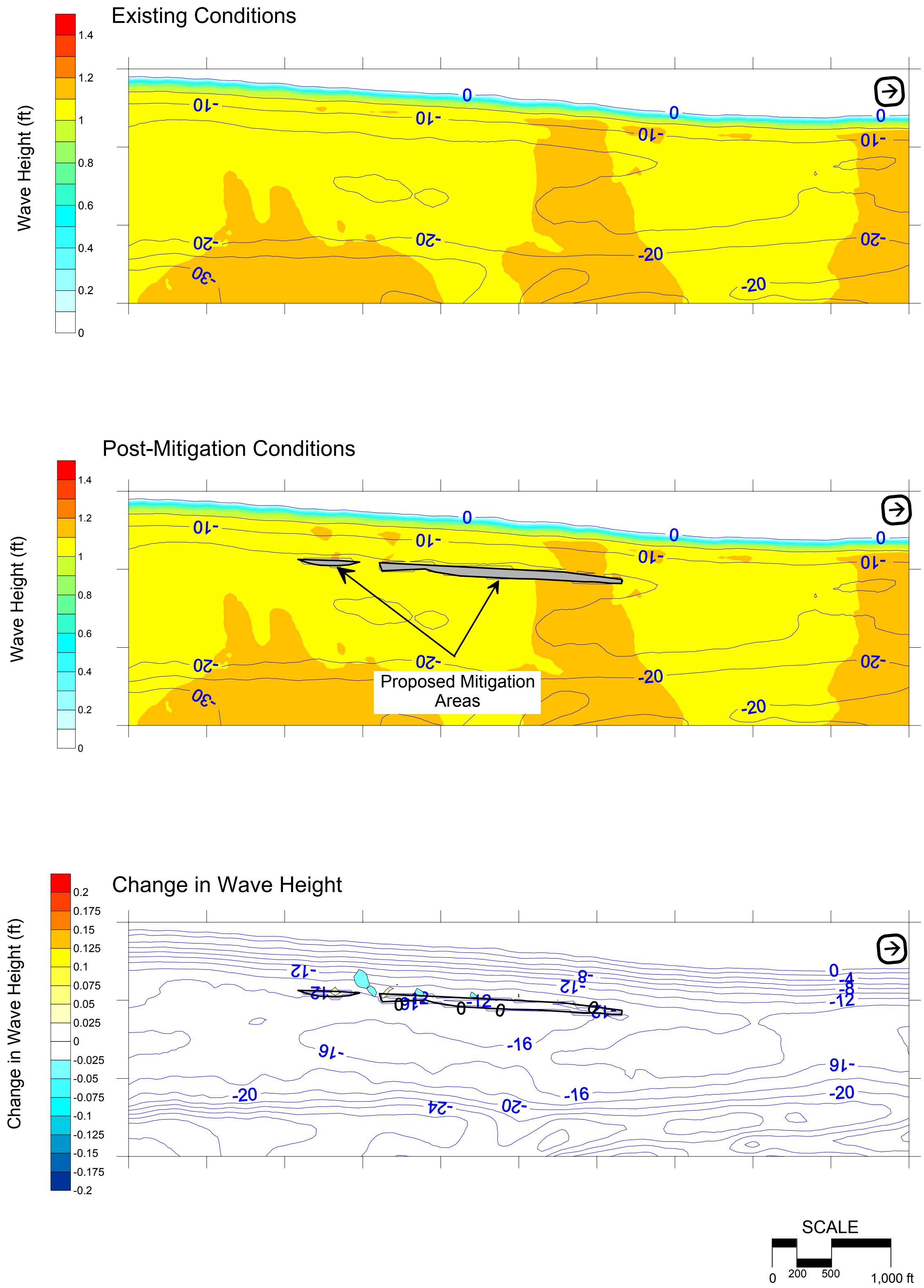


Figure 13 Changes in the average annual wave climate in the north Ft. Lauderdale areas (Areas #3 and #4 near FDEP R-62). The bottom frame indicates the change in wave climate over the proposed mitigation areas.

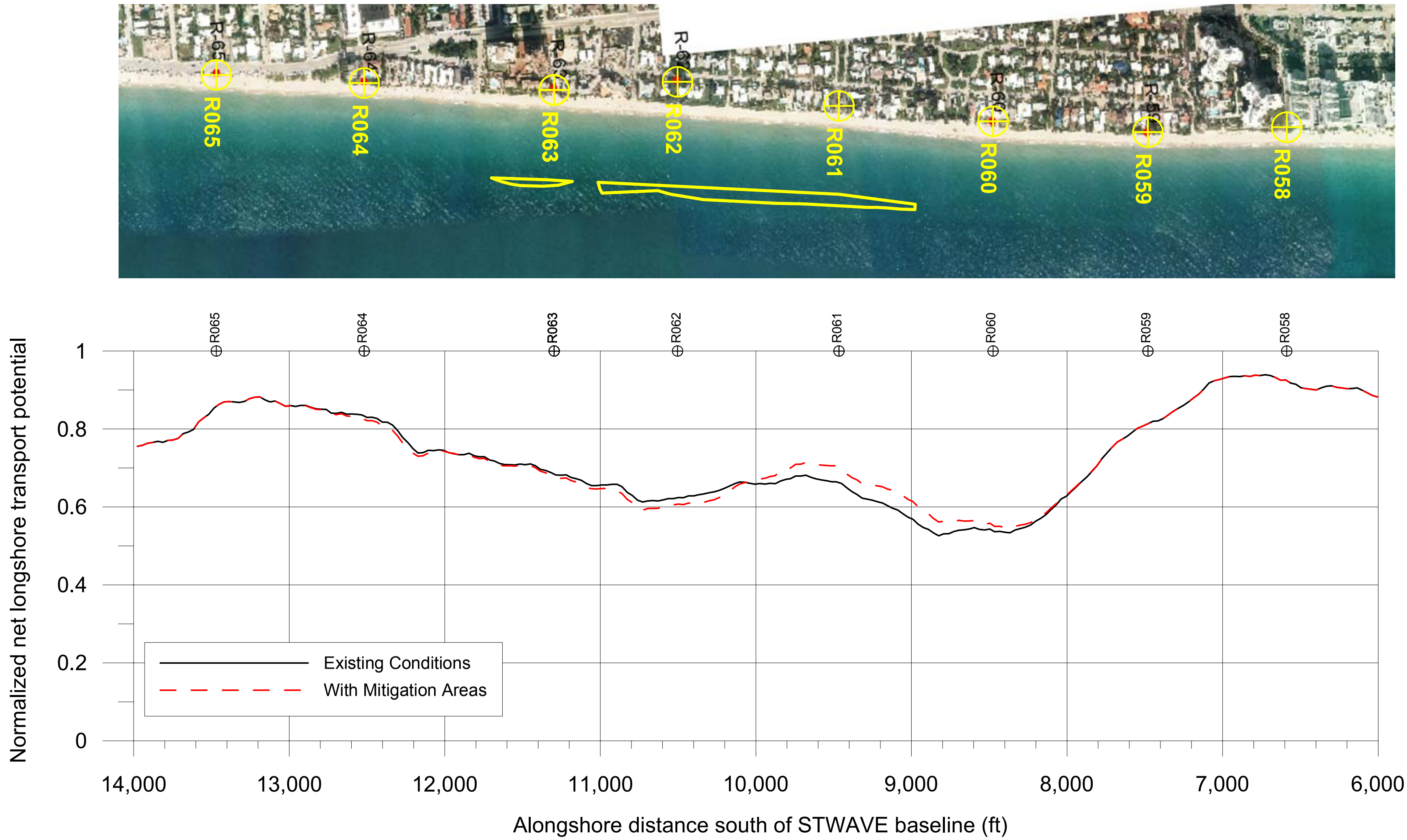


Figure 14 Normalized net longshore transport potential in the north Ft. Lauderdale area (Areas #3 and #4). Plot indicates the location of the proposed mitigation areas and the net longshore transport, southerly directed, with and without mitigation.

The transport potential curves in Figure 14 also indicate the same mode of behavior. Along the northern limits of the mitigation areas, the slight increase in wave height and the corresponding changes in wave direction produce an increase in the transport potential over a distance of approximately 1,600-ft near R-60 and R-61. A slight decrease in transport is predicted to extend southward to R-64. Comparing changes in gradients predicted in this area, a short segment north of R-60 may experience a slight increase in erosional stress over a 100 to 200 ft area, although it is unlikely that this average annual change would truly be discernable on the shoreline. The area between R-61 and R-62, in the southern lee of the mitigation area, is expected to be slightly more depositional than existing conditions. Overall, the initial changes in transport potential predicted for this area are on the order of 10% or less. Given the potential impacts of storms and the uncertainties associated with other coastal processes (sand availability, nearshore currents, etc.) these differences may not produce a measurable change on the beach.

Two additional areas are proposed for R-70 (0.48 acres) and R-76 (0.33 acres) in the Ft. Lauderdale area (Areas #5 and #6). Figures 15 and 16 present the predicted wave height changes and net transport potential changes in these areas. These mitigation areas are rather short in longshore extent, thus the impacts predicted are relatively minor. The southernmost area is predicted to create a localized increase in wave height of as much as 0.1 ft, on average. In terms of transport, similar patterns of increases and decreases are predicted, again the initial changes are anticipated to be less than 10%.

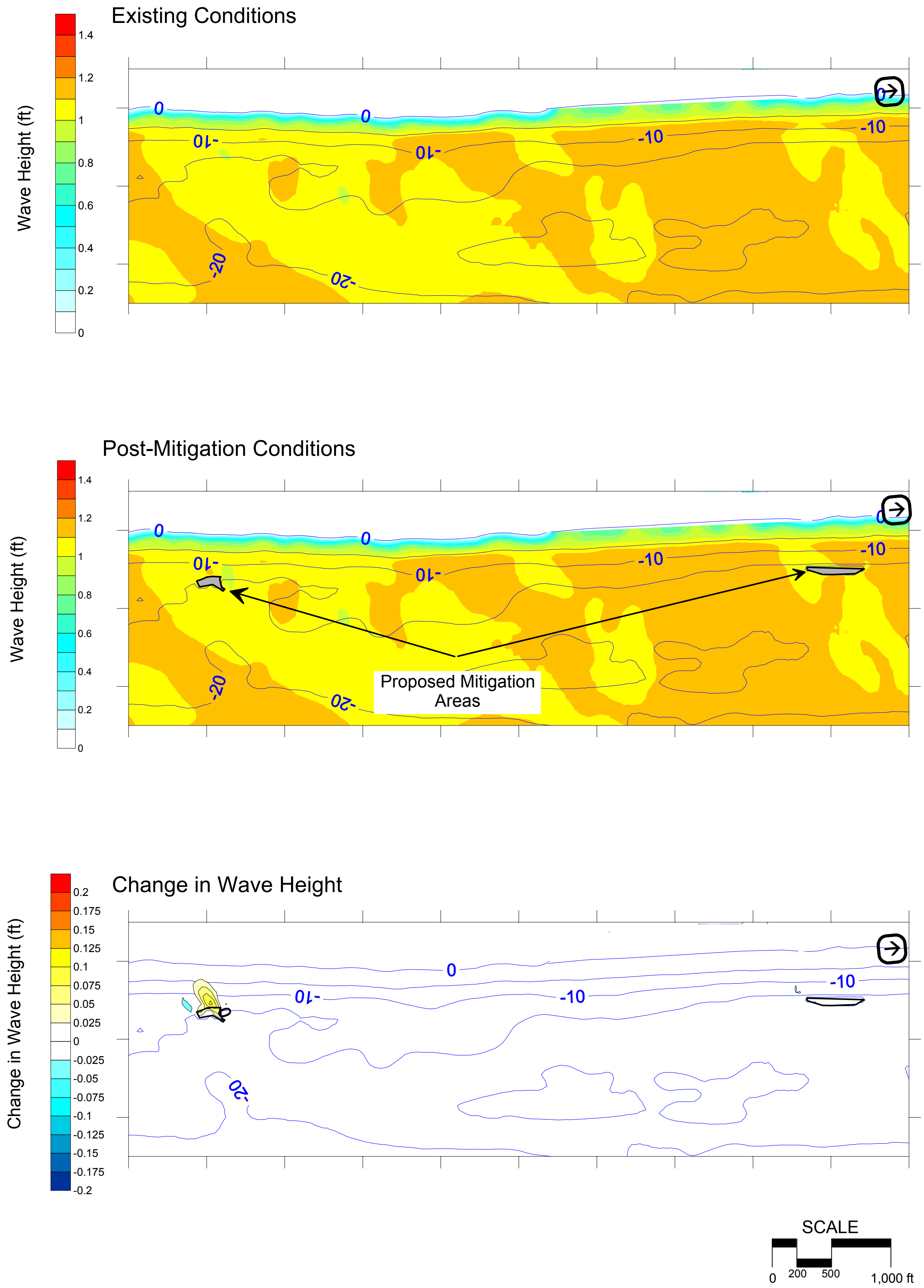


Figure 15 Changes in the average annual wave climate in the south Ft. Lauderdale area (Areas #5 and #6 near FDEP R-70 and R-76). The bottom frame indicates the change in wave climate over the proposed mitigation areas.

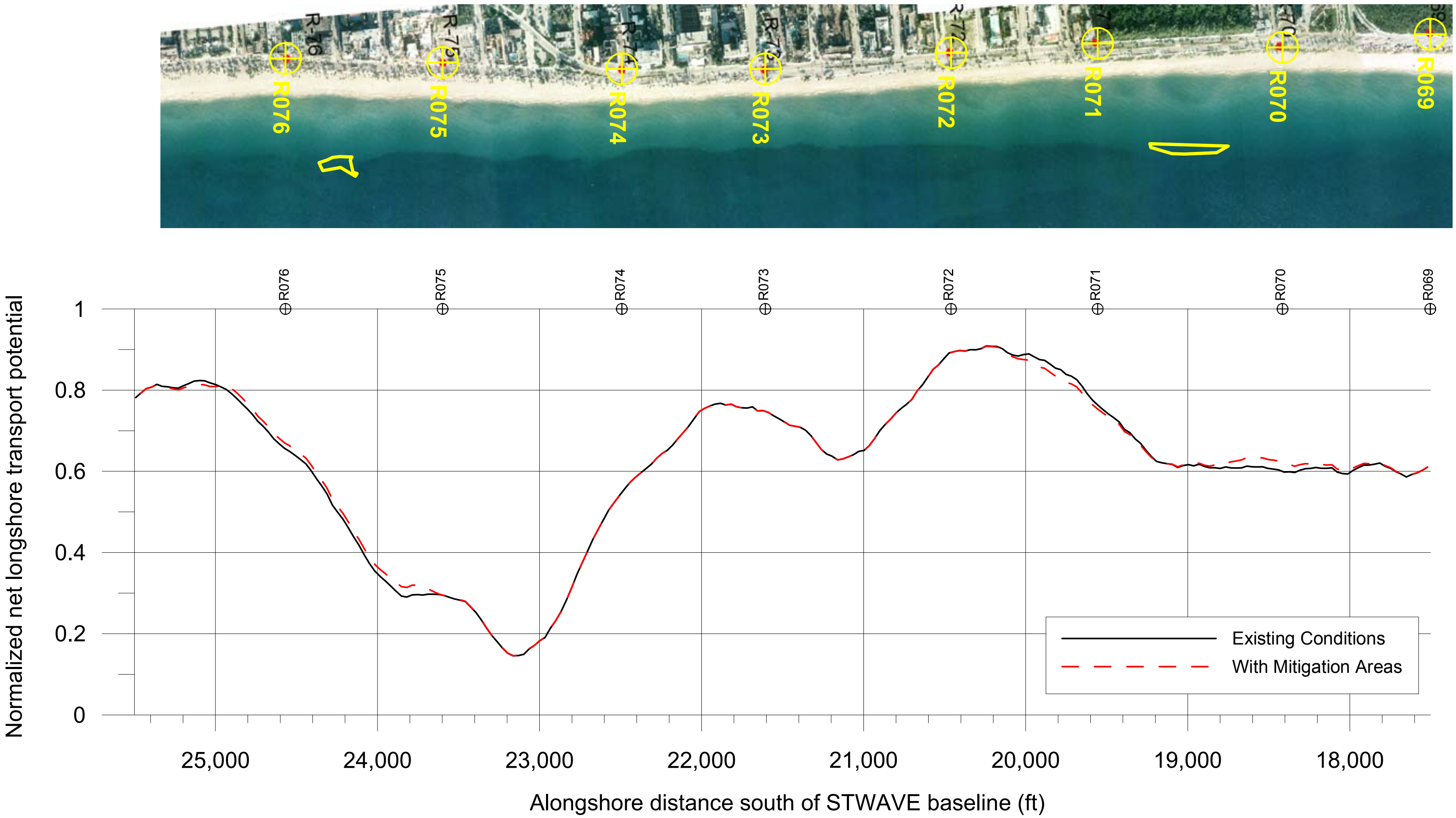


Figure 16 Normalized net longshore transport potential in the south Ft. Lauderdale area (Areas #5 and #6). Plot illustrates the location of the proposed mitigation areas and the changes in net transport predicted for the with and without mitigation cases.

4.3 Dania Mitigation Areas (Areas #7 through #9)

Figure 17 depicts the changes in the net average annual wave climate in the vicinity of R-102 in Dania. Three mitigation areas (#7 through #9) totaling 3.97 acres are proposed for an area just seaward of the 15-ft contour. The figure shows the alternating pattern of wave focusing and divergence through the gaps between the areas. Wave height changes over the mitigation areas increase by as much as 0.1 ft, with smaller magnitude decreases in the diverging areas.

Figure 18 illustrates the corresponding expected changes in the net average annual longshore transport climate created by the construction of the mitigation areas. Inspection of Figure 18 suggests that initial changes in transport would be less than 10%, and that in this area, changes in gradients of transport would be negligible.

4.4 Hollywood/Hallandale Mitigation Areas (Areas #10 and #11)

Figure 19 depicts the changes in the net average annual wave climate in the vicinity of Hollywood/Hallandale. Two mitigation areas (#10 and #11) totaling 7.57 acres are proposed in the vicinity of R-124 just seaward of the 15-ft contour. The design shape of these mitigation areas, which is dictated principally by the location of existing hardbottom features, is such that modifications to the wave field are predicted to be very minor, on the order of hundreds of a foot.

Correspondingly, Figure 20 illustrates the predicted minor initial changes in the net average annual longshore transport climate created by the construction of the mitigation areas. The proximity of the two mitigation areas, which cover almost 2,500 ft alongshore, creates an area of slightly increased transport over roughly 3,000 ft with a corresponding decrease in transport over the adjacent 1,200 ft to the south. Changes to gradients in transport are predicted to be negligible.

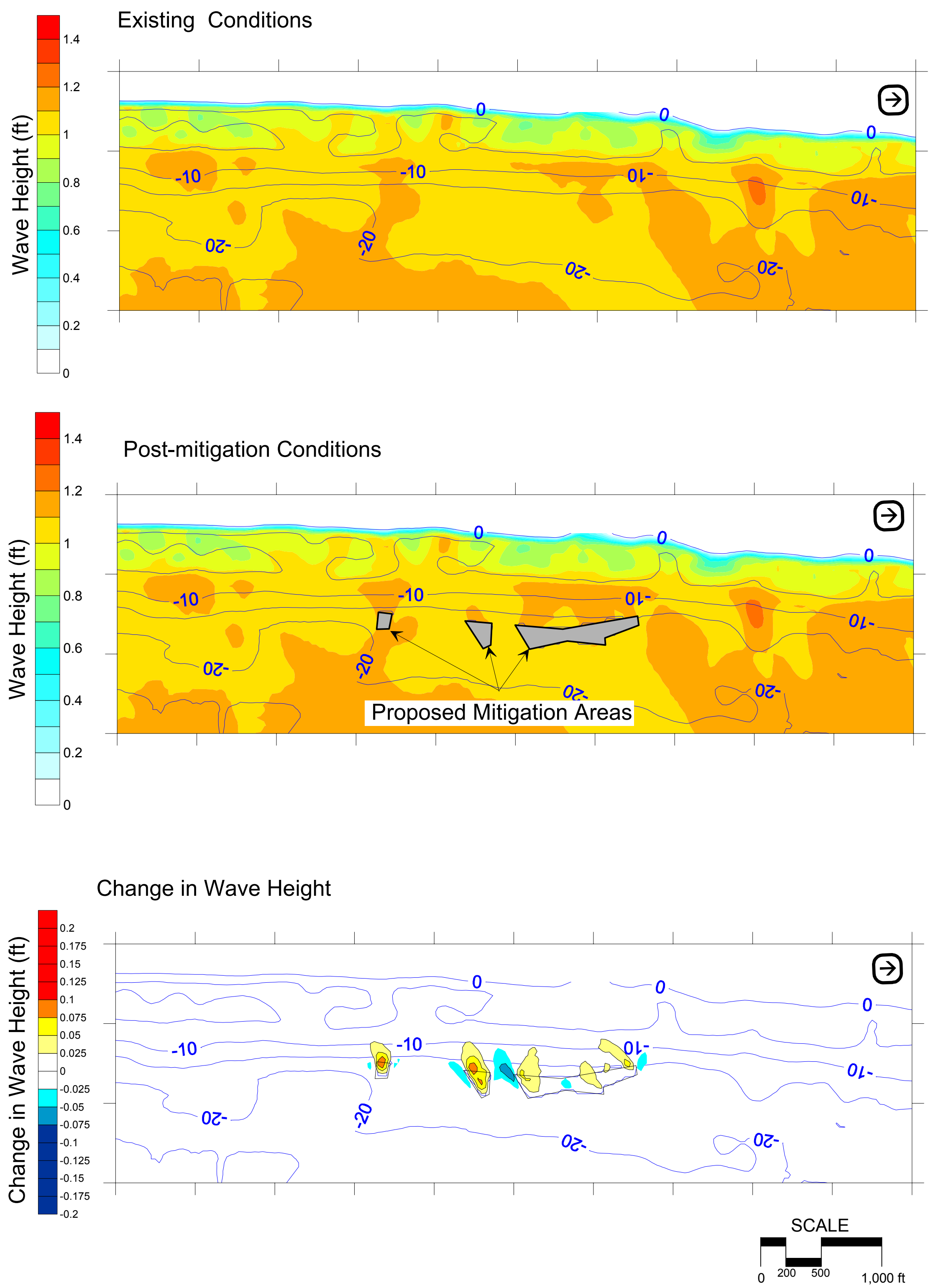


Figure 17 Changes in the average annual wave climate in the Dania area (Areas #7, #8, and #9 near FDEP R-102). The bottom frame indicates the change in wave climate over the proposed mitigation areas.

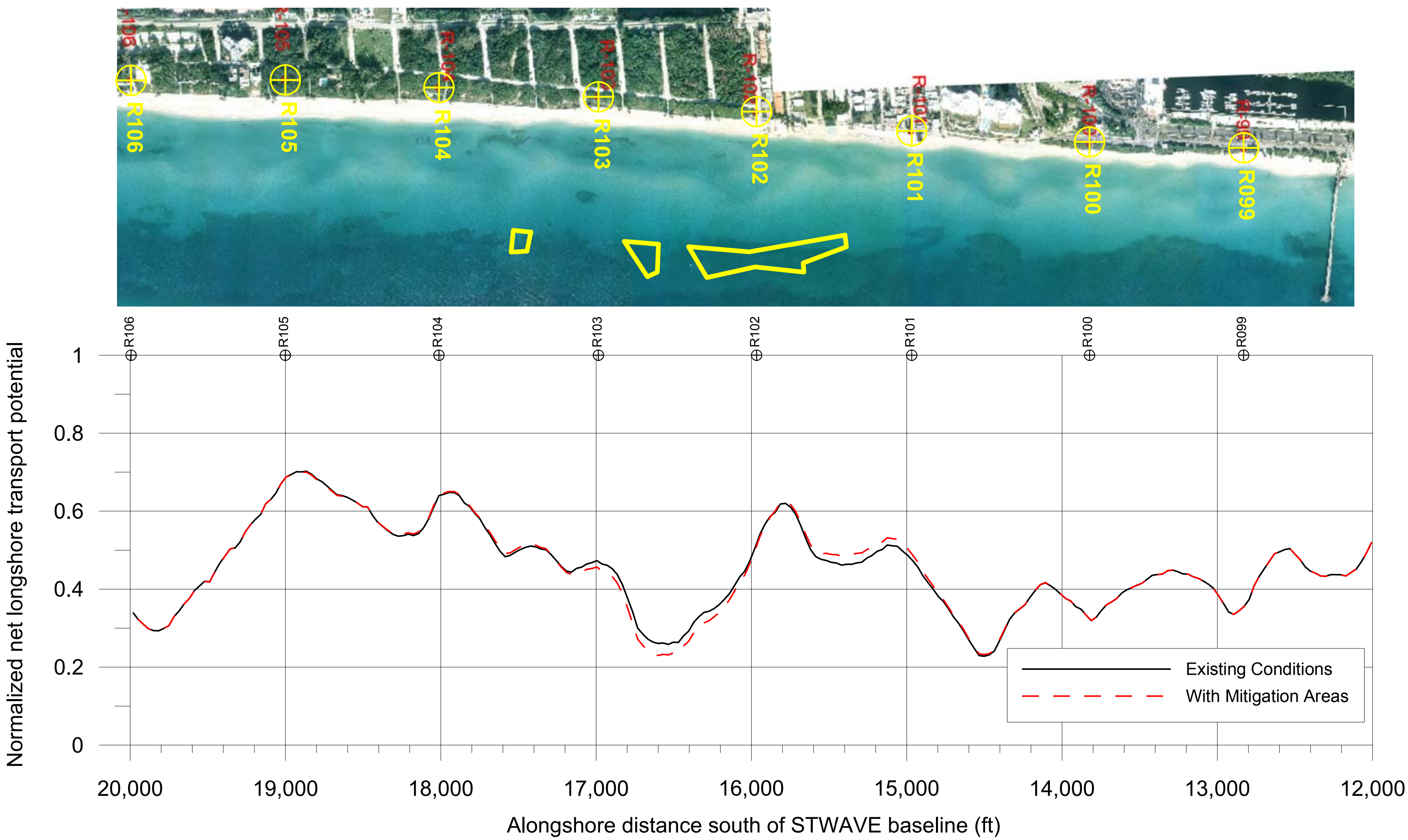


Figure 18 Normalized net longshore transport potential in the Dania area (Areas #7, #8 and #9). The figure illustrates the location of the proposed mitigation areas and the predicted variation in net longshore transport with and without the mitigation areas.

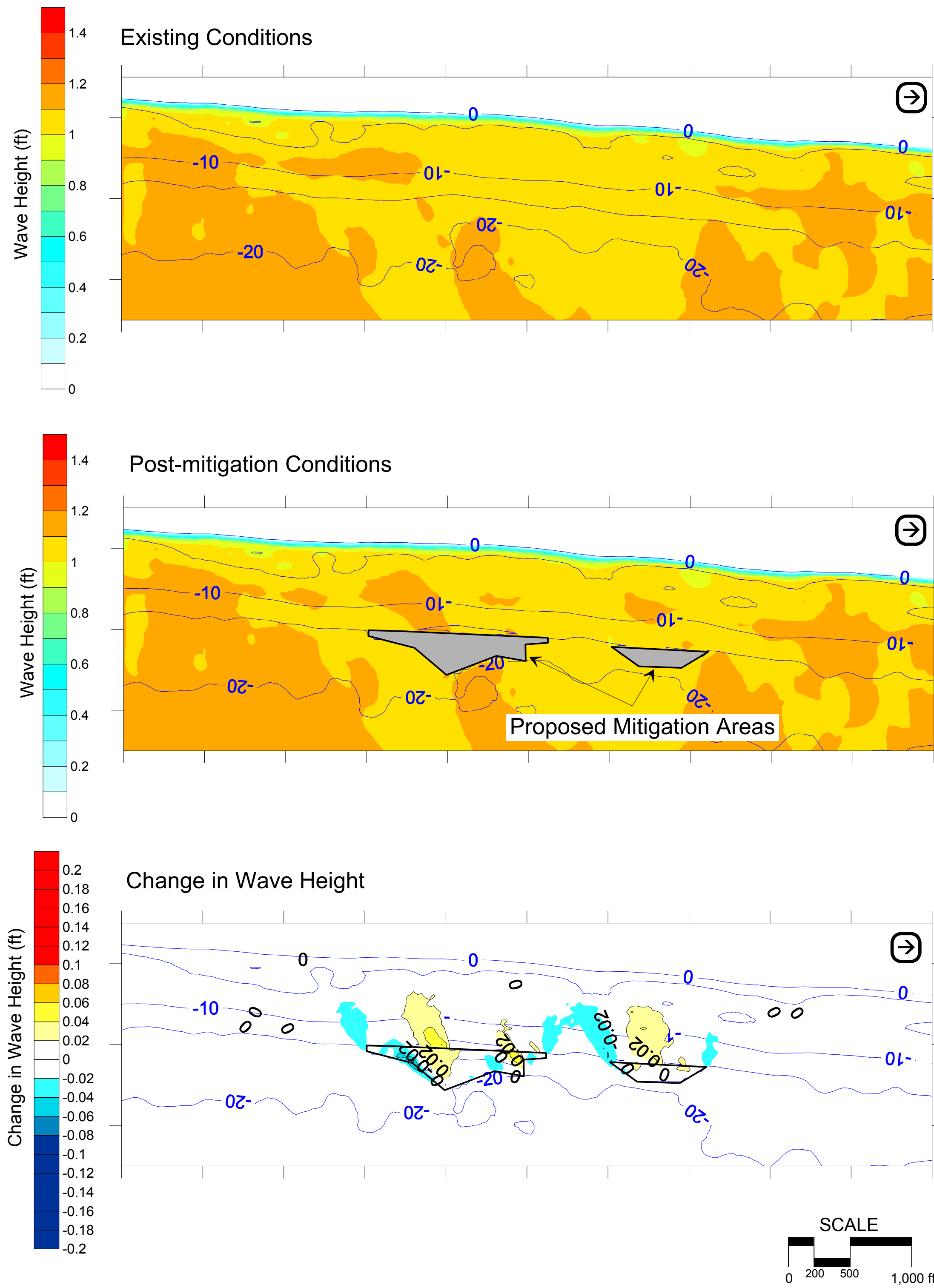


Figure 19 Changes in the average annual wave climate in the Hollywood / Hallandale area (Areas #10 and #11 near FDEP R-125). The bottom frame indicates the predicted change in wave climate over the proposed mitigation areas.

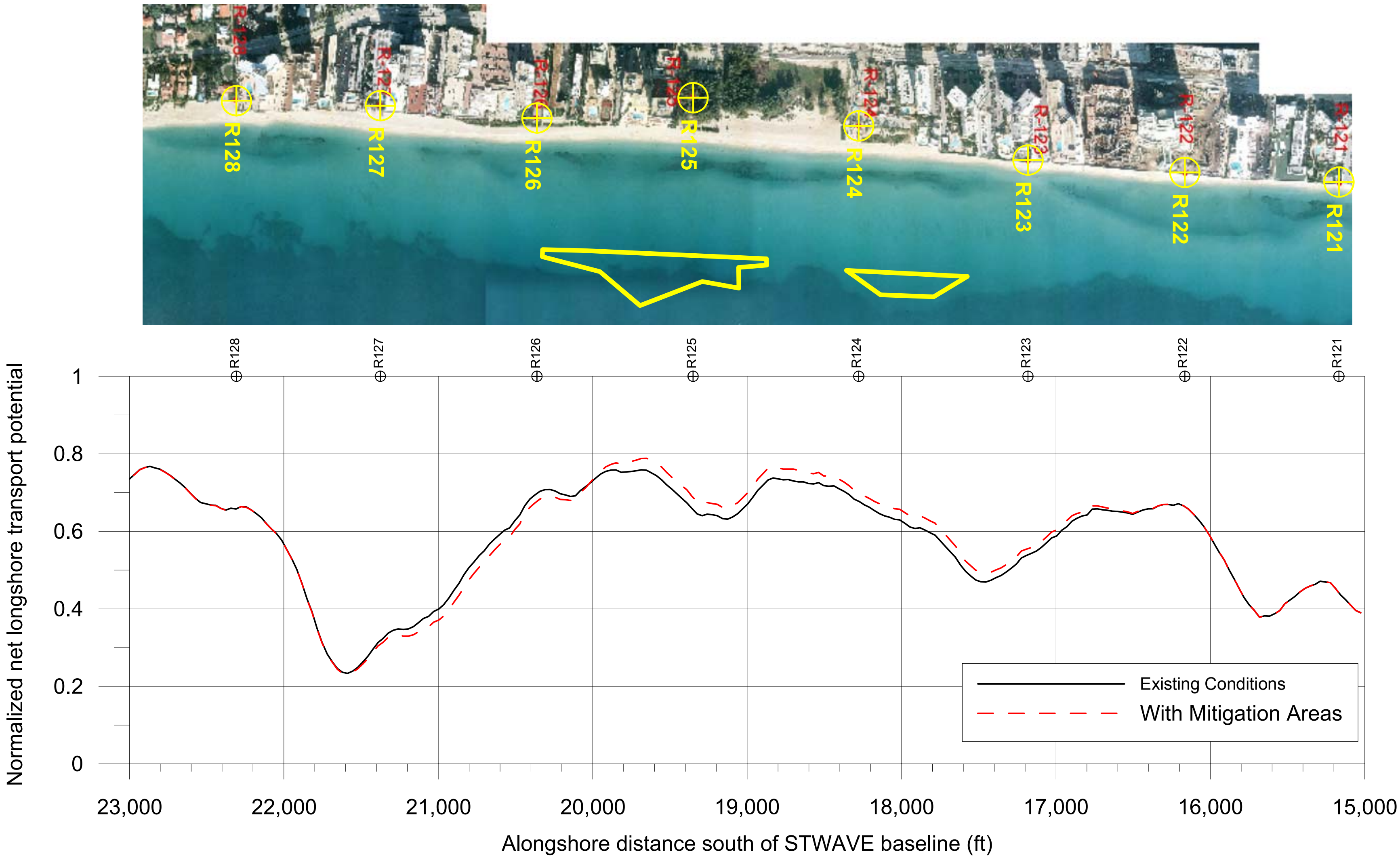


Figure 20 Normalized net longshore transport potential in the Hollywood/Hallandale area (Areas #10 and #11). The figure illustrates the location of the proposed mitigation areas and the net longshore transport potential predicted with and without the mitigation areas.

4.5 Changes Due to Larger Wave Events

Figure 21 plots the wave climate in the vicinity of R-45 in Lauderdale-by-the-Sea. This figure is presented to discuss potential changes caused by the mitigation areas under larger wave conditions. Results presented in Figure 21 are representative of the results from the other mitigation areas as well. The mitigation areas near R-45 Figure 21 presents the wave model results from Case 7, a 5.3-ft, 6.2s wave incident from the ENE. This condition represents a likely nor'easter condition. In this instance the pattern of wave height changes is quite similar to the previous figures, but the northeast corner of the mitigation area is expected to initially produce localized areas of wave height increases of up to 1.0 ft. The adjacent divergent areas are much broader spatially, but only experience decreases in height of approximately 0.2 ft.

It is important to note in Figure 21 that the damping effects of storm surge are not included. For the wave event described (Case 7), some degree of wave setup and wind-induced surge is likely (as well as possible coincident high- or low-tide conditions). An increase in the total water depth over the mitigation areas would act to minimize their potential alteration to a given wave condition. For example, for a 20-yr hurricane event, USACE (2001) suggests that the total storm surge is approximately 5 ft. Additionally, for larger waves incident to this area, increased wave breaking across the natural nearshore reef system is likely to occur.

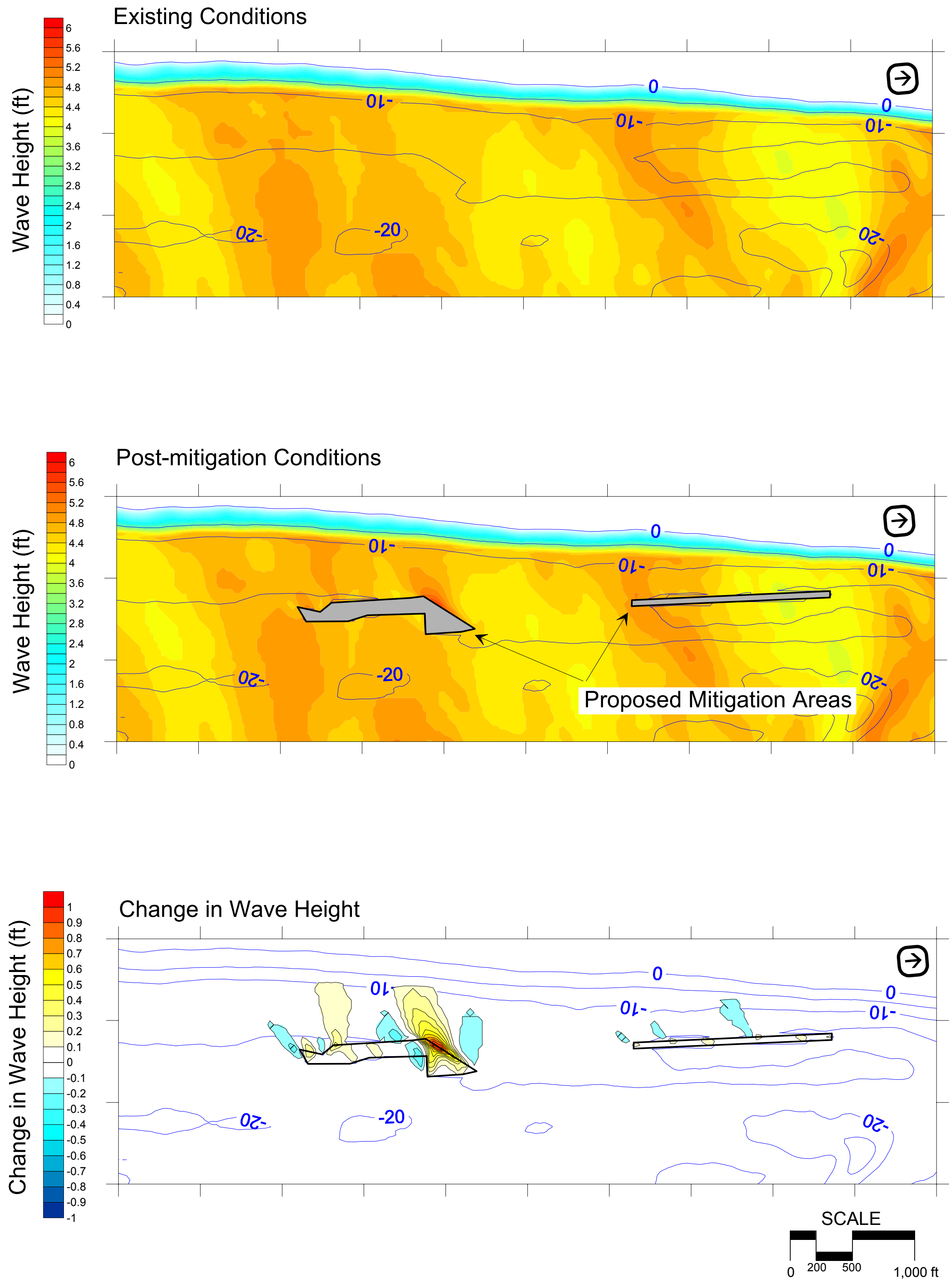


Figure 21 Changes in the local wave climate predicted for Case 7 in the Lauderdale-by-the-Sea area (FDEP R-45). The incident significant wave height is 5.3 ft, the peak period is 6.2 seconds, and the wave approaches from the ENE. The bottom frame depicts the predicted changes in wave height in the vicinity of the proposed mitigation areas.

5.0 CONCLUSIONS

Inspection of predicted potential wave height changes and wave-driven longshore transport changes suggests that the construction of the mitigation areas in the locales investigated herein would have only a negligible effect upon the leeward shorelines. For both wave heights and transport potential, the initially predicted average changes are on the order of 10% or less. Each mitigation area was found to generate an increase in transport along the shoreline at the northern end of the lee of the areas and a decrease along the adjacent southern segment. Changes in the *gradients* of longshore transport, which cause erosion and deposition, are of the same order of magnitude but occur only along very short segments of the shoreline (one hundred to two hundred feet in length). These potential alterations are expected to diminish as the stones in the mitigation areas settle to their final relief elevations.

Because the stones are expected to have a very minimal impact on the incident wave climate, they are also expected to have minimal impact on cross-shore sediment transport. The stones are to be placed seaward of the anticipated toe of the equilibrated beach nourishment project and will not interact with the beach profile in any significant way (e.g., the stones will not act to perch the beach, etc.).

6.0 REFERENCES

Bodge, K.R., and Kraus, N.C. (1991). "*Critical Examination of Longshore Transport Rate Magnitude*," Proceedings of 'Coastal Sediments 1991,' Seattle WA, American Society of Civil Engineers, New York, MY.

Dompe, P.E., and Hanes, D.M. (1992). "*Wave Data Summary: Hollywood Beach, Florida, January 1990 to May 1992,*" Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL, Report #UFL/COEL-92/016.

Hubertz, J.M., Brooks, R.M., Brandon, W.A., and Tracy, B.A. (1993). "*Hindcast Wave Information for the U.S. Atlantic Coast,*" Department of the Army, U.S. Army Corps of Engineers, WIS Report 30, Waterways Experiment Station, Vicksburg, MS.

Smith, J.M., Sherlock, A.R., and Resio, D.T., (2001). "*STWAVE: Steady-State Spectral Wave Model. User's Manual for STWAVE Version 3.0.*" USACE, Coastal Hydraulics Laboratory Instruction Report ERDC/CHL SR-01-1, February 2001, Vicksburg, MS.

Olsen Associates, Inc. (2002). "*Broward County Nearshore Hardbottom Mitigation Plan Hydrodynamic Stability Analyses,*" Report submitted to Broward County, FL.

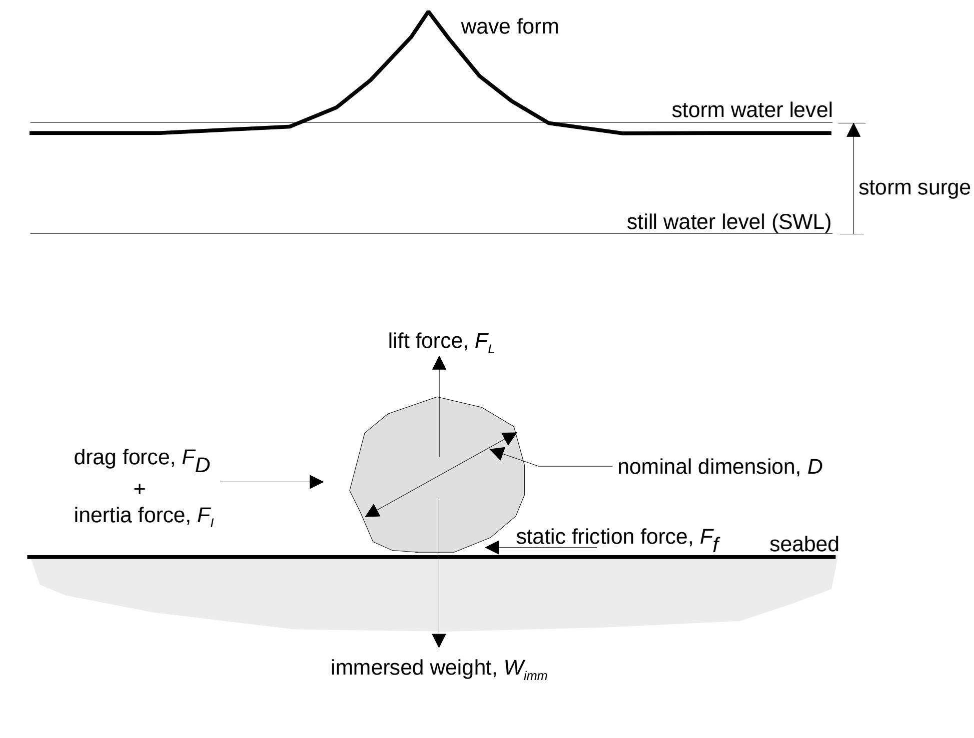
USACE, (1984). "*Shore Protection Manual*," U.S. Army Corps of Engineers, Department of the Army, Washington, D.C.

USACE, (2001). "*Broward County Shore Protection Project General Re-evaluation Report,*" U.S. Army Corps of Engineers, Jacksonville District.

BROWARD COUNTY, FLORIDA
SHORE PROTECTION PROJECT

NEARSHORE HARDBOTTOM MITIGATION

Stability Analysis



Prepared for: Broward County, Florida

BROWARD COUNTY
FLORIDA

Prepared by: Coastal Planning & Engineering, Inc./
Olsen Associates, Inc. (J/V)

January 2002

COASTAL PLANNING & ENGINEERING, INC.

olsen
associates, inc.
coastal engineering

Broward County Nearshore Hardbottom Mitigation Plan
Hydrodynamic Stability Analyses

January 2002

1.0 INTRODUCTION

The implementation of nearshore hardbottom mitigation entails the placement of limestone boulders in shallow water (15 to 20 ft water depths, typical) over broad, sandy areas. Existing hardbottom features in these water depths exhibit typical relief of less than 1 ft up to 2 ft relative to the ambient seabed[1]. It is assumed that any limestone boulder placed in these areas will experience one to two feet of ultimate settlement. Therefore, to ensure that relief similar to that which is common to the nearshore area is created, stone sizes on the order of four feet and greater in nominal dimension are required.

Hydrodynamic stability analyses presented herein focus on the resistance of a stone to sliding along the sand bottom and/or tipping/rolling under the influence of water waves. Stream Function Wave Theory (SFWT) (Dean, 1965) is applied to calculate the appropriate wave forces. Storm surge elevations were selected based on a 20-yr storm return period.

Results of these analyses indicate that the minimum nominal stone size sufficient to produce the desired relief following settlement, approximately 4-ft in nominal dimension, is predicted to remain stable until and after complete settlement is achieved. These boulders are expected to be sufficiently stable in the protected areas landward of the shallowest significant reef formation (First Reef, Figures 2.1 and 2.2), which exhibits typical crest elevations of 12 to 15 ft below the National Geodetic Vertical Datum of 1929 (NGVD29). Large storm waves (on the order of 11 to 12 ft and greater) experience a significant degree of breaking on the seaward face of First Reef, lowering the amount of wave energy that approaches the shoreline and proposed mitigation areas.

1

The areas designated for mitigation are generally typified by a sandy veneer of 1 to 2 ft in thickness overlain on rock substrate.

2.0 STORM SURGE & WAVE CONDITIONS

2.1 Storm Surge Elevations

Boulder stability analyses herein are based on a 20-yr storm event and depth-limited wave breaking conditions (for a given total water depth, the largest wave that is reasonably expected to occur is approximately 0.8 times the water depth at breaking). The use of depth-limited conditions limits the need for extensive analysis of the local wave climate and is considered to be conservative, since depth-limited wave conditions may not occur in many areas landward of First Reef. For a 20-yr hurricane event, the Federal Emergency Management Agency (FEMA) predicts a storm-surge elevation of 5 ft above NGVD29 (USACE 2001 (Figure B-3)). While that surge elevation is used throughout the present analysis, the application of the depth-limited wave breaking assumption (both locally and seaward of a given mitigation site at First Reef) over a range of total water depths allows for the investigation of a wide range of possible storm conditions and mitigation site depths, based principally on total water depth.

2.2 Wave Conditions

For purposes of design, depth-limited wave breaking conditions at the mitigation sites were initially selected for purposes of investigating the stability of limestone boulders (specific gravity = 2.1) of nominal dimensions of 4 ft and greater[2]. In reference to the potential mitigation areas landward of First Reef along the Broward County shoreline, typical placement depths range between 15 and 20 ft (still water depth relative to NGVD29). Adding a 5-ft surge and assuming the well-established rule of thumb breaking index of 0.8 (e.g. Dean and Dalrymple, 1990), the corresponding design wave height would range between 16.0 and 20.0 ft (assuming the breaking wave height equaled 0.8 times the local total water depth, including surge).

2

Note: Discussion of site-specific average annual wave conditions can be found in the companion to this report that discusses potential changes to the alongshore transport conditions following construction of the mitigation areas (Olsen Associates, 2002).

In the study area, however, the presence of the shallow crest of First Reef serves to limit the maximum wave height that could occur in the placement area for a given surge level. To investigate the effects of First Reef on the incident storm wave climate, the propagation of large storm waves was modeled over the existing bathymetry in the study area. These bathymetric data are high-resolution data collected by laser surveying techniques. The wave propagation was modeled using the STWAVE wave refraction/diffraction model (Smith et al., 2000). The bathymetric grids applied depth information at 32.8 ft (10-m) spacing, sufficient to resolve many of the gaps and other irregular features of the Broward County nearshore area (see Olsen Associates, 2002 for details on this modeling). Figure 2.1 plots a profile cross-section of the nearshore bathymetry in the vicinity of FDEP monument R-45 (Lauderdale-By-The-Sea). The water depth across the seabed and reef system is plotted in the lower frame of the figure and clearly demonstrates the presence of Third Reef, roughly 1.3 miles offshore in over 50 ft of water depth. Second and First Reefs are also clearly depicted in the figure with crests in typical water depths of 35 and 13 ft, respectively.

In Figure 2.1, a 20-ft, 12.0-second wave is represented by a narrow-banded wave spectrum and introduced on the offshore edge of the STWAVE grid in approximately 135-ft water depth (including surge). This wave condition was selected from the U.S. Army Corps of Engineers Wave Information Study data for Hurricane Andrew in August 1992 (WIS data, e.g. Hubertz et al., 1993). The variation in significant wave height over the irregular sea bottom is depicted in the upper frame of the plot. The model predicts that the storm waves will shoal from just over 20 ft to over 24 ft as they pass over Third and Second Reefs. As the waves approach a total water depth of approximately 39 to 40 ft, wave breaking begins to occur. Since the STWAVE model is a spectral wave model, the wave climate can be thought of as the superposition of numerous waves of varying periods and directions, focused about the peak period (12.0 seconds in this case). Thus, a portion of the wave spectrum begins to break in this water depth. As the waves continue to propagate over the seaward face of First Reef, significant breaking occurs, reducing the significant wave height from 24 ft to approximately 10 to 11 ft. Thus a 20-ft storm wave is reduced in height by nearly 50% by the presence of First Reef. This phenomenon is beneficial for the design of the present mitigation project. Figure 2.2 depicts the extent of the reef formation in this area.

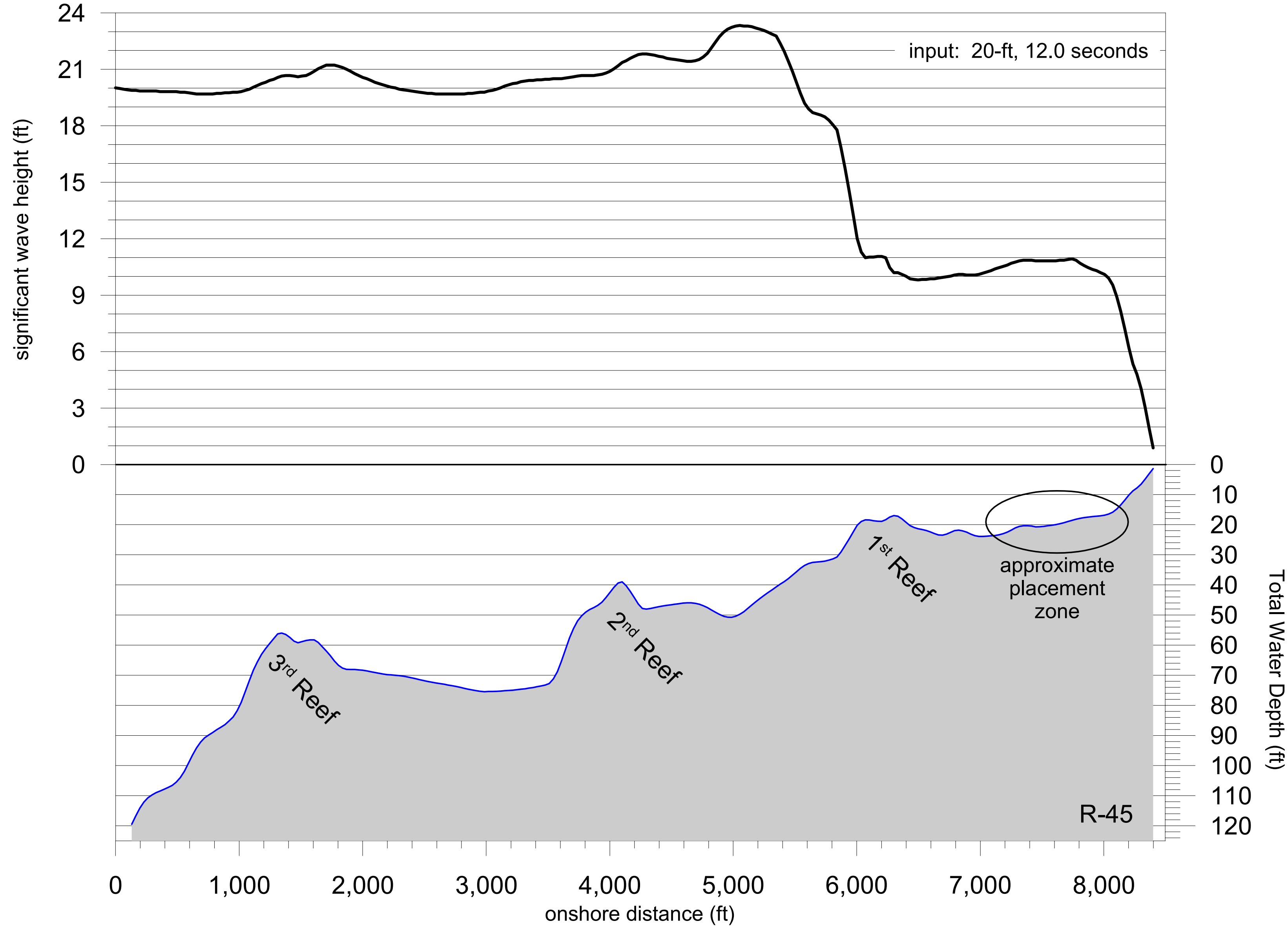


Figure 2.1 Example wave propagation of storm waves over the nearshore bathymetry in the vicinity of R-45 in Lauderdale-By-The-Sea. The figure illustrates the substantial sheltering provided by First Reef from wave attack.

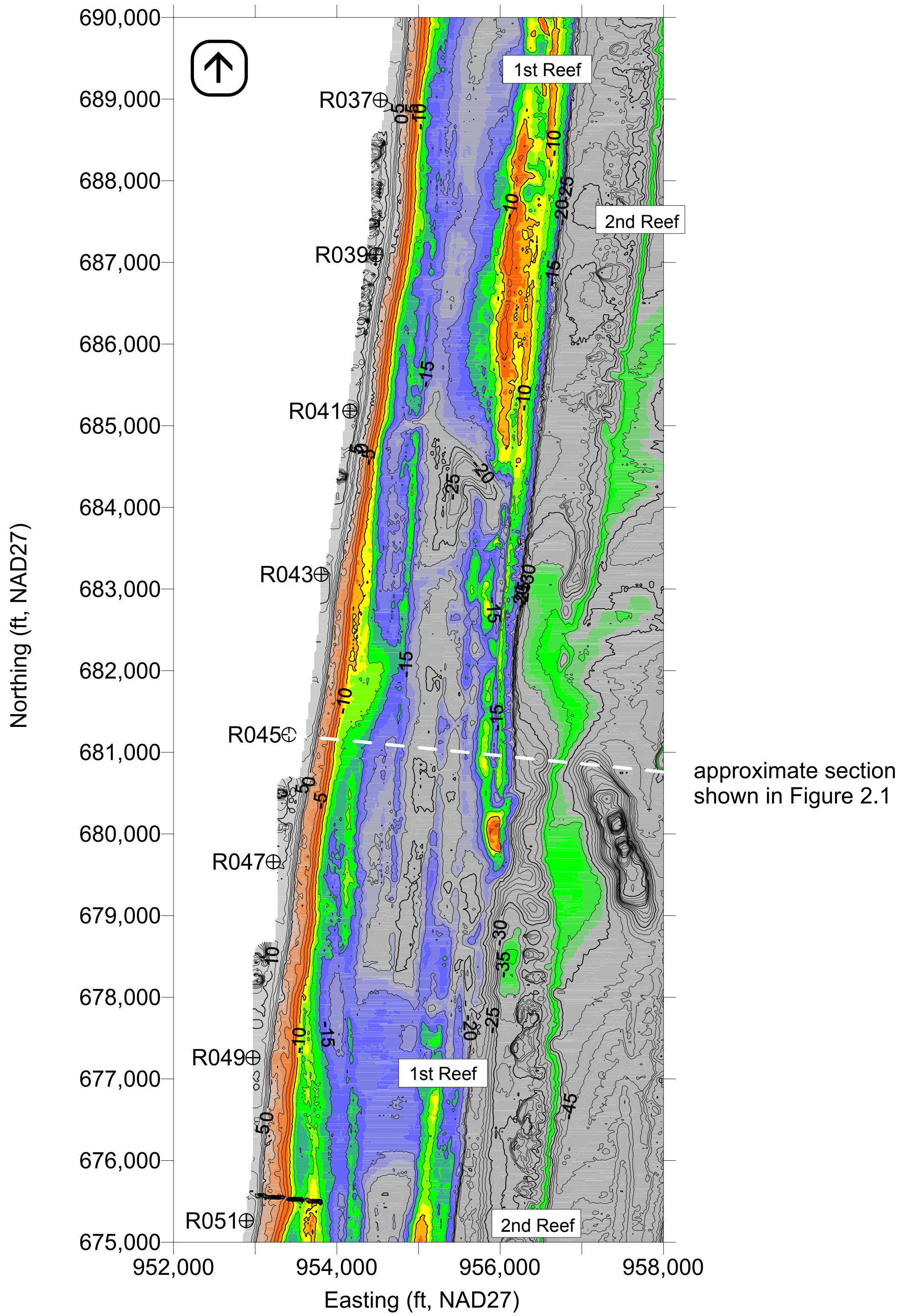


Figure 2.2 Nearshore bathymetric features in the vicinity of Lauderdale-by-the-Sea. The figure depicts the relief of First and Second Reefs. Contours represent seabed elevations relative to NGVD29.

Note, however, that care must be taken to inspect the crest elevation of First Reef in those areas where boulders are intended for placement. Numerous gaps exist along the crest of First Reef, some of which exhibit elevation differences of up to 10 ft or more (Figure 2.2). These gaps may allow for much larger waves to pass First Reef relatively undisturbed, creating the potential for much larger wave forces acting on the mitigation boulders. To account for the variability of the crest elevation of First Reef, wave force analyses were based on waves up to 0.8 times the local total water depth (*0.8h*) as well as waves reaching 0.60 times the local water depth (*0.6h*). While First Reef will frequently reduce the incident wave height to a height lower than *0.6h*, the factor of 0.6 was used to correspond to the tabulated Stream Function Wave Theory conditions (the Case 4-C and 5-C conditions, see below).

Stream Function Wave Theory (SFWT) Dean (1965) introduced a numerical wave theory to describe the kinematics and dynamics of water waves in the nearshore region. Dean (1974) presents tables of various wave properties for 40 different wave cases that cover a range of wave periods and wave conditions approaching breaking. These tables were applied in the present analyses to determine the wave-induced forces acting on boulders of various sizes in various water depths. The tabulations of drag force and inertia force in Dean (1974) were compiled based on the forces acting on a cylindrical pile above the seabed. Inspection of the general approach and applicable force coefficients suggests that applying this methodology to the present situation provides an appropriately conservative description of the wave forces acting on the boulders.

For the water depths of interest and the wave periods typically associated with storm waves in this area (9 to 12 seconds, typical), the relevant cases are 4-C, 4-D, 5-C, and 5-D. These cases will be applied over the range of total water depths to investigate boulder stability.

3.0 STABILITY ANALYSIS

Figure 3.1a illustrates the force and moment balances applied in the present investigation. Constructive or restoring forces acting on the boulders arise from the weight of the boulder itself, $\boldsymbol{W}$. The dry weight of the boulder is partially offset by the buoyant force, $\boldsymbol{F_B}$, created by the displacement of saltwater created by the immersed boulder. The combination of these two forces produces the immersed weight, $\boldsymbol{W_{imm}}$. Also acting in the vertical direction is the lift force, $\boldsymbol{F_L}$, caused by differences in pressure that arise as the horizontal flow passes over the object. In the horizontal direction, destabilizing forces arise from the force of drag, $\boldsymbol{F_D}$, caused by the horizontal component of the variation in pressure around the object in the flow. Additionally, the pressure gradient necessary to accelerate the fluid back and forth about the object creates an effective buoyant force in the horizontal direction on the object. The force needed to accelerate the fluid particles around the object also contributes to the horizontal forces (the added mass effect). These last two forces combine to create the inertia force, $\boldsymbol{F_I}$. Opposing the horizontal drag and inertia forces is the static friction force, $\boldsymbol{F_F}$.

The forces described above are defined as follows:

$$W_{imm} = (\gamma_{stone} - \gamma_{seawater}) * 0.6D^3 \qquad \textbf{(1)}$$

where the unit weight, γ, of the limestone boulders and seawater are taken to be 131 and 64 lbs/ft^3, respectively, and the volume of the limestone boulders is assumed to be slightly larger than the corresponding spherical volume based on the diameter[3], $\boldsymbol{D}$. The drag force is approximated by:

$$F_D = \frac{1}{2}\rho C_D A U^2 \qquad \textbf{(2)}$$

3

The Shore Protection Manual (USACE, 1984) provides data for the relationship between stone weight and nominal dimension. For a spherical object, the ratio of volume to diameter cubed is 0.52, or π/6. The SPM recommends a ratio of 0.65 for angular stone. It is assumed herein that the limestone boulders will be somewhat more spherical (hence the 0.6 ratio). The nominal dimension of an irregularly-shaped stone is computed from the average length of the stone in three orthogonal dimensions, based on the longest dimension of the stone (e.g., the average of a stone's length, width, and height).

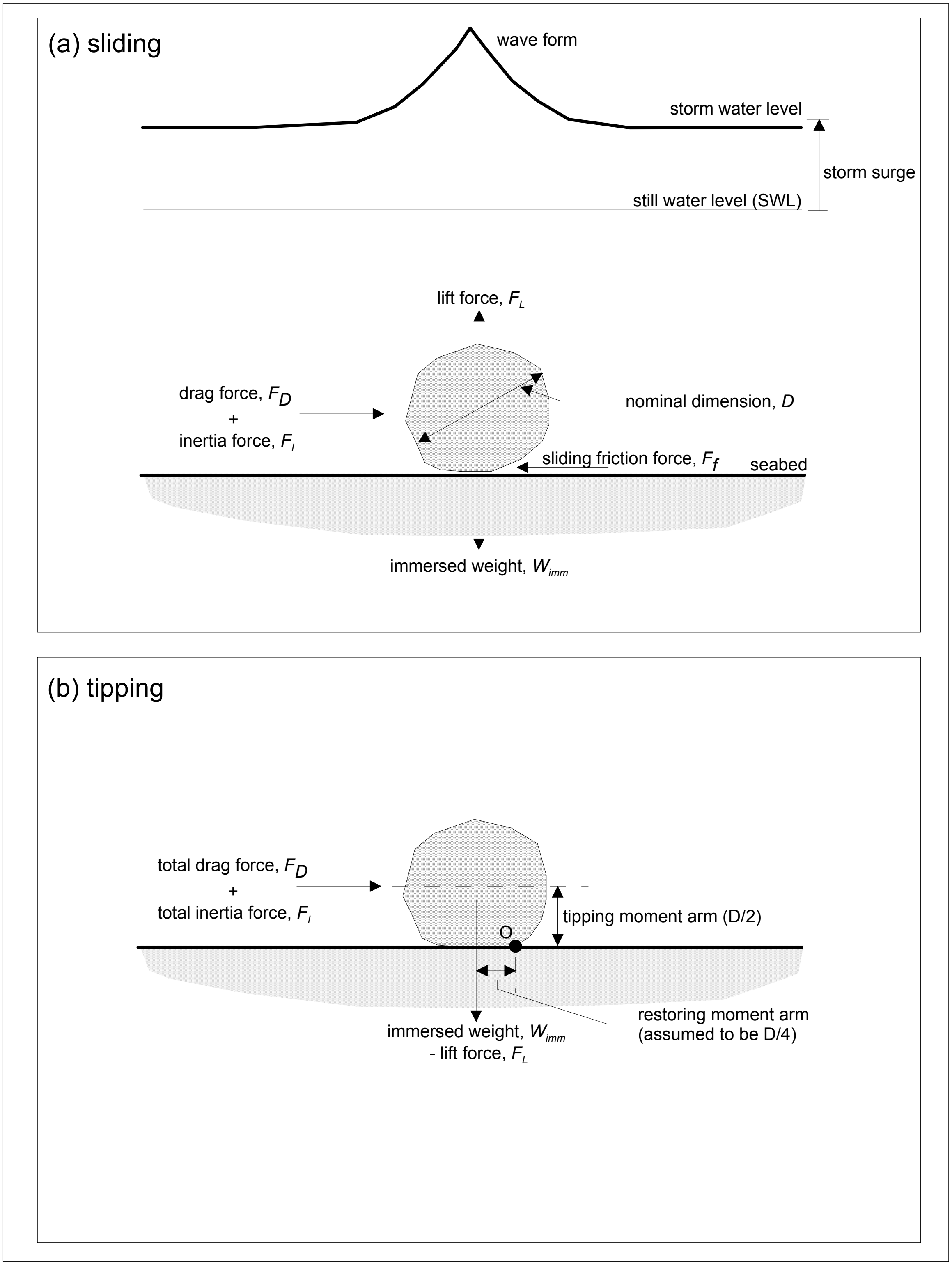


Figure 3.1 Schematic of force and moment balances applied in the present analyses.

where ρ is the density of seawater (1.99 slugs/ft^3), C_D is an empirical drag coefficient, A is the frontal area of the object normal to the direction of flow (the projected area a person would see when looking toward the object from a direction parallel to the upstream flow, again in this case), and U is the flow velocity in the horizontal direction past the object. The frontal area used in the SFWT tables is that of a cylinder of diameter D with a height above the seabed equal to the diameter. In the present analyses, C_D is assumed to be 0.4, consistent with a rough sphere in fully turbulent flow (e.g. Munson et al. 1998, also Torum, 1994). While the tabulated stream function tables provide data for the integrated force on a cylindrical pile up to a distance, s, above the seabed (equal to D in this application), the use of this value for the semi-spherical boulders is deemed conservative (due to the increased frontal area of a cylinder). The conservatism in this calculation is somewhat offset by the use of the reduced drag coefficient for a rough sphere.

The inertia force is approximated by

$$F_I = \rho C_m V \frac{dU}{dt} \qquad \textbf{(3)}$$

where C_m (= 1.5, e.g. Dean and Dalrymple, 1990, and Torum, 1994) is an empirical inertia coefficient that includes the added mass effect, V is the volume of the object in the flow field (the volume of a cylinder of height $s = D$), and dU/dt is the horizontal acceleration of the water particles in the wave field. The lift force is similarly calculated as

$$F_L = \frac{1}{2} \rho C_L A U^2 \qquad \textbf{(4)}$$

where C_L is an empirical lift force coefficient taken to be 0.4 in the present analyses (e.g. Munson et al. 1998). Opposing the drag and inertia forces in the horizontal direction is a resisting friction force that arises at the interface between the seabed and the stone. That friction force is defined as

$$F_f = \mu F_n \qquad \textbf{(5)}$$

where μ is the coefficient of sliding friction and F_n is the force normal to the seabed, defined as the vector sum of the immersed weight and the lift force ($F_n = W_{imm} - F_L$).

The approach taken herein is to calculate the value of μ required to prevent sliding under each wave condition, water depth, and stone size. Comparing that value of μ to published or assumed values of μ for sand, etc., provides guidance as to whether the stone may slide under a given set of conditions[4]. If the computed friction coefficient is high, the stone is assumed to be likely to slide under that condition, and vice-versa.

To estimate the likelihood that a stone would tip over (or roll) under a given wave condition, the restoring moment was computed assuming an origin point on the seabed located a distance of D/4 away from the horizontal centroid of the stone (Figure 3.1b). This assumes the stone is somewhat octagonal in cross-section, closely approximating a more-or-less round stone received from a quarry. The restoring moment is computed from the moments about 'O' by summing the moments generated by the immersed weight (the restoring force) and the destructive, tipping forces of lift, drag, and inertia. The criteria of a positive restoring moment (counter-clockwise moments are defined as positive in Figure 3.1b) provides guidance on the desired horizontal and vertical dimensions of the stone (D_h and D_v, respectively).

The ratio of D_v/D_h provides another stability criteria for the boulders. Values of the ratio greater than 1.0 indicate that the boulders can be placed such that the longest dimension of the stone may be in the vertical direction (perpendicular to the seabed) and not tip over (depending on the actual value of D_v/D_h), whereas values less than 1.0 indicate that the stones must be placed on the seabed in a "squat" orientation such that the longest dimension of the stone must be parallel to the seabed to prevent the stones from being tipped over. While the tipping of a lone boulder on the seabed may ultimately move that boulder to a more stable position, it is also possible that the stone may be tipped over onto another stone and into a less stable orientation. In the present analysis, the ratio of D_v/D_h was investigated for each computation of static friction, μ, to determine if a round stone $(D_v/D_h \approx 1.0)$ would be likely to be tipped/rolled over.

4

In other words, the combination of the sandy seabed and the limestone boulder must have a friction coefficient **of at least μ** (computed) in order for the stone to resist sliding under the given wave condition and stone size. In the cases where the computed μ is much lower than any reasonable value for a sand/limestone friction coefficient, it is assumed that the stone cannot slide.

4.0 RESULTS & DISCUSSION

The kinematics and dynamics of stream function waves were computed for a range of mean water depths between 10 and 20 ft. Boulder sizes between approximately 4.0 and 8.0 ft were considered. Table 4.1 lists the wave periods and wave heights that correspond to the various cases tabulated by Dean (1974) for the range of total water depths considered. In many locations, the wave heights corresponding to the near-breaking conditions would be unlikely to occur landward of First Reef (the 4-D and 5-D cases). Overall, however, the offshore conditions needed to generate the truly depth-limited wave breaking conditions in the listed water depths can occur.

Table 4.1 Tabulated wave conditions investigated in the present analysis.

Total Water Depth*	Wave Case (Dean, 1974)	Wave Height (ft)**	Wave Period (s)
15	4-C	9.0	12.1
15	4-D	12.0	12.1
15	5-C	9.0	9.0
15	5-D	12.0	9.0
17	4-C	10.2	12.9
17	4-D	13.6	12.9
17	5-C	10.2	8.2
17	5-D	13.6	8.2
21	4-B	8.4	14.3
21	4-C	12.6	14.3
21	4-D	16.8	14.3
21	5-B	8.4	9.1
21	5-C	12.6	9.1
21	5-D	16.8	9.1
25	4-B	10.0	15.6
25	4-C	15.0	15.6
25	4-D	20.0	15.6
25	5-B	10.0	9.9
25	5-C	15.0	9.9
25	5-D	20.0	9.9

* Still water level plus dynamic storm surge (tides, wind stress, wave setup, etc.)

** Wave heights for the 4-D and 5-D cases assume that $H = 0.8h$, the 4-C and 5-C cases assume that $H = 0.75(0.8h) = 0.6h$, the 4-B and 5-B cases assume that $H = 0.5(0.8h) = 0.4h$.

Figure 4.1 plots a portion of the results of the analyses for stability against sliding. The safety factors plotted in Figure 4.1 are derived from an assumed coefficient of static friction for sand of $\mu = 0.5$ (e.g. Randall and Panarese, 1976). This conservative value for is compared to the coefficient of friction of sand on sand, computed from the internal friction angle of sand to be approximately $\mu = 0.65$[5]. Given the uncertainty in determining the true coefficient of static friction for limestone on sand, it is desirable to maintain a reasonable factor of safety in addition to the conservatism built into the force and moment balance calculations. In that regard, if the minimum size of boulder desired for the mitigation relief requirements, 4-ft, can achieve a reasonable factor of safety based on $\mu = 0.5$ (on the order of 1.5 or higher), then that stone size or larger is deemed acceptable.

In all cases, the wave forces produced at each phase of the wave passage were investigated to determine the least stable condition for each wave. In general, this worse-case condition occurs approximately 20 to 30 degrees away from the crest of the wave due to the increasing effect of the inertia force. This behavior increases for the deeper water and longer period cases. Care must be taken in interpreting the results of Figure 4.1 because the wave conditions (height and period) vary as a function of water depth due to the discrete wave conditions available in Dean (1974). In general, however, it can be determined that stone sizes less than 3 ft are not expected to be stable, and stone sizes between 3 and 4 ft are anticipated to be marginally stable (with low factors of safety). Overall, placing the same size stone in deeper water behind First Reef provides increasing factors of safety against sliding. For the present analyses, those conditions that provide any factor of safety against sliding (values greater than 1 in Figure 4.1) generally produce shape ratios of $D_v/D_h \geq 1.0$, indicating that stones that are slightly taller than wider would not be expected to tip over.

Figure 4.2 plots the increase in the factor of safety against sliding for a constant wave condition over varying water depths. This situation would more closely approximate the behavior seen in Figure 2.1, where First Reef provides substantial sheltering against storm waves. In Figure 4.2, an 11-ft, 11-s wave is applied to 4-, 5-, and 6-ft stones over the range

---

5

The internal friction angle of cohesionless sand is approximately 33 degrees. The coefficient of static friction is computed from $\mu = tan(\phi)$ (e.g. Das, 1994).

of depths of interest. The figure demonstrates that the safety factor increases as the depth increases. In shallower water, the safety factor decreases to roughly 1.3 for a 4-ft stone. While that safety factor is still greater than one, the risk of instability caused by a rogue large wave that for some reason might pass First Reef is considered to be unacceptable.

For the still water depths presently planned for the mitigation areas, 15 to 20 ft, factors of safety for 4- to 6- ft stones approach 2.0, providing an increased level of confidence against movement. These depths correspond to 20-yr-storm-event total depths of 20- to 25-ft. Figure 4.2 also indicates that the stones can be placed in an 'upright' condition with reasonable assurance that they will not tip over or roll. This is particularly beneficial in the sense that the stones will not have to be placed in a specific orientation.

Several factors not considered in the present analysis provide an increased level of conservatism and confidence in the stability of the placed boulders. The boulders are expected to settle somewhat in the sandy lense of the mitigation areas. Settlement of up to two feet is entirely possible. The settlement will lower the profile of the object in the flow, thus reducing the force applied to the boulders by the waves. Also, the settlement in the sand will provide increased resistance to sliding or rolling. The potential settlement, however, also precludes the use of smaller stones, thus the desire for stones larger than 4-ft in nominal dimension. Additionally, the stones will likely be placed in close proximity to one another, providing an additional stabilizing factor. Further, the present analysis assumes a specific gravity for limestone of 2.1. This value is reasonable for Freeport, Bahamas, rock, but limestone obtained from Florida quarries may be more dense (SG $\approx$ 2.3 to 2.4).

An anecdotal example of successful stone placement exists off John U. Lloyd State Park south of Port Everglades. At that location (near FDEP survey monument R-94) several boulders were placed in shallow water at the toe of the beach. While the exact dimensions and water depths of the stones was unavailable, the stones are believed to be approximately 2-3 ft in nominal dimension and appear to lie in mean water depths of 10 to 12 ft. County staff have noted that these piles of stones have remained stable through many storms, including Hurricane Andrew and Tropical Storm Gordon. This stability is attributed to the sheltering effect of First Reef, which is quite shallow in this area.

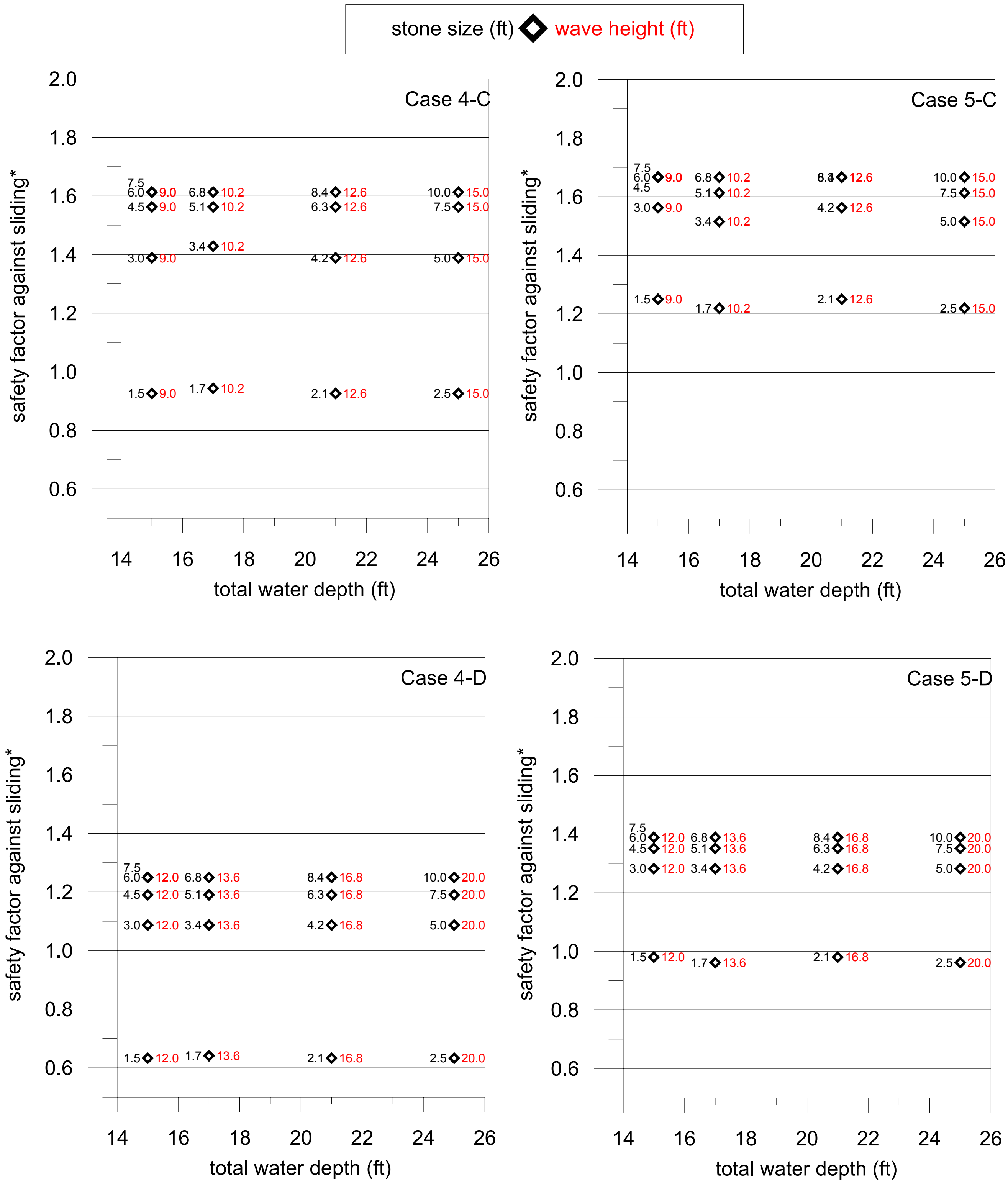


Figure 4.1 Factors of safety against sliding computed directly from the tabulated wave cases in Dean (1974). Note that wave heights and wave periods vary in each graph (see Table 4.1). *Factors of safety derived from an assumed coefficient of static friction of $\mu = 0.5$.

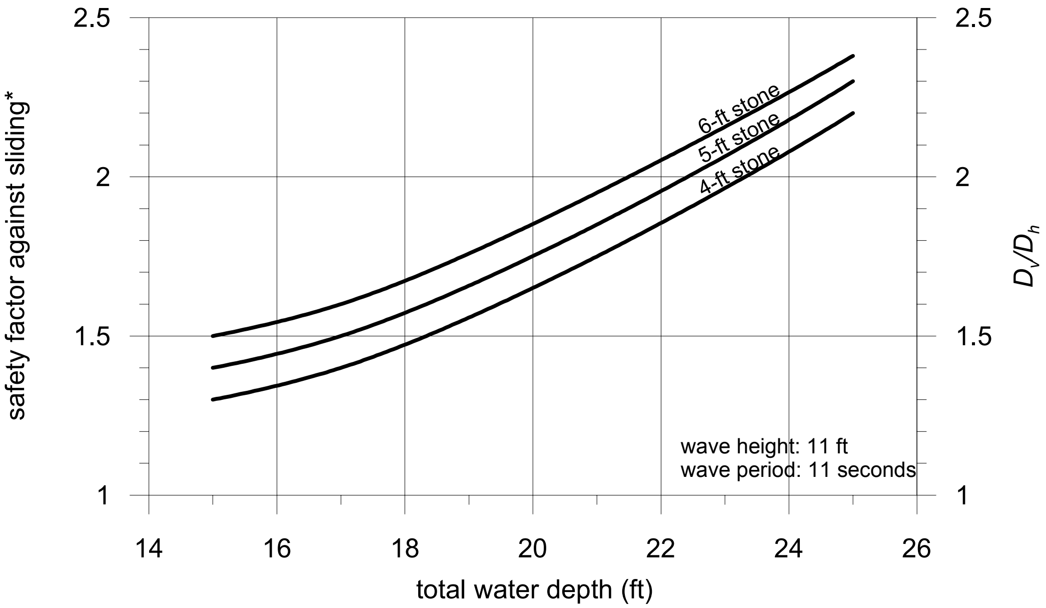


Figure 4.2 Variation in safety factor and dimension ratio D_v/D_h for a constant wave condition over a range of total water depths (mean water depth *plus* total storm surge). Based on the assumed static friction coefficient of $\mu = 0.5$* and the geometry associated with the tipping/rolling criteria, the two values are approximately equal for a given condition.

5.0 CONCLUSIONS & RECOMMENDATIONS

The stability of limestone boulders proposed for placement in the nearshore waters of Broward County, FL, was investigated for the potential for the stones to slide or tip/roll. Stream Function Wave Theory (Dean, 1965) was applied to determine the forces and moments applied by the passage of waves over the boulders. The analyses herein focused on limestone boulders larger than 4-ft in nominal dimension placed in still-water depths of between 15 and 20 ft landward of the first occurrence of the extensive offshore reef system in the area (First Reef).

Based on the analysis presented herein, similar stone placement in the area, and experience with limestone boulder placement in other applications, it is predicted that stones of a nominal dimension of 4 ft or greater will remain stable in terms of sliding and tipping/rolling in mean water depths of 15- to 20-ft during a 20-yr storm event. Further, it is recommended that

A) stone placement be limited to depths equal to or deeper than 15ft (MSL),
B) the minimum stone size be approximately 4.0-ft in nominal dimension,
C) mitigation should be sited in areas sheltered as much as possible by First Reef, such that significant wave breaking occurs on the seaward side of First Reef.

While it may seem logical to specify the largest stones possible in order to produce the greatest degree of relief, care must be taken to assess the potential impacts of the large stones on the longshore transport regime. Large stones (greater than 6-ft) that do not settle as expected may provide too great a degree of wave sheltering, causing potentially undesirable impacts to the shoreline leeward of the mitigation areas (refer to the companion report, Olsen Associates, 2002). Furthermore, from a stone production and placement standpoint, it may be impracticable to specify stones larger than 6-ft in diameter. The higher relief of larger stones may also represent a hazard to navigation, particularly prior to settlement.

6.0 REFERENCES

Das, B.M. (1994). "*Principles of Geotechnical Engineering, 3rd Ed.,*" PWS Publishing Company, Boston, MA.

Dean, R.G. (1965). "*Stream Function Representation of Nonlinear Ocean Waves*," Journal of Geophysical Research, Vol. 70, No. 18, pp 4561-4572.

Dean, R.G. (1974). "*Evaluation and Development of Water Wave Theories for Engineering Application, Volumes 1 and 2,*" Special Report Number 1, SR-1, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, VA (now Coastal Hydraulics Laboratory, Vicksburg, MS.).

USACE, (2001). "*Broward County Shore Protection Project General Re-evaluation Report,*" U.S. Army Corps of Engineers, Jacksonville District.

Hubertz, J.M., Brooks, R.M., Brandon, W.A., and Tracy, B.A. (1993). "*Hindcast Wave Information for the U.S. Atlantic Coast,*" Department of the Army, U.S. Army Corps of Engineers, WIS Report 30, Waterways Experiment Station, Vicksburg, MS.

Munson, B.R., Young, D.F. Okiishi, T.H. (1998). "*Fundamentals of Fluid Mechanics, 3rd Ed.,*" John Wiley and Sons, New York, NY.

Olsen Associates, Inc. (2002). "*Potential Shoreline Impacts from the Construction of Nearshore Hardbottom Mitigation Areas in Broward County, FL,*" Report in preparation for Broward County, FL.

Randall, F.A., and Panarese, W.C. (1976). "*Concrete Masonry Handbook for Architects, Engineers, Builders,*" Portland Cement Association, Skokie, IL.

Smith, J.M., Sherlock, A.R., and Resio, D.T. (2001)., "*STWAVE: Steady-State Spectral Wave Model. User's Manual for STWAVE Version 3.0.*" USACE, Coastal Hydraulics Laboratory Instruction Report ERDC/CHL SR-01-1, February 2001, Vicksburg, MS.

Torum, A. (1994). *"Wave-Induced Forces on Armor Unit on Berm Breakwaters," Journal of Waterway, Port, Coastal, and Ocean Engineering,*"Vol. 120, No. 3, pp. 251-268. American Society of Civil Engineers, Reston, VA.