UFL/COEL–92/002

EROSION, NAVIGATION AND SEDIMENTATION IMPERATIVES AT JUPITER INLET, FLORIDA: RECOMMENDATIONS FOR COASTAL ENGINEERING MANAGEMENT

Tidal Inlet Management at Jupiter Inlet: Final Report

by

Ashish J. Mehta
Clay L. Montague
and
Robert J. Thieke

Additional Contributors:

Michael DelCharco, Richard Faas, Scott Fears, Philip Harris, Earl Hayter, Ray Krone, Li–Hwa Lin and Trimbak Parchure

July, 1992

Sponsor:

Jupiter Inlet District
400 North Delaware Boulevard
Jupiter, FL 33458

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16. Abstract

In this final report on the investigation of the potentialities of improved coastal engineering management of Jupiter Inlet, Florida, three management-guiding issues were considered: better control of the erosion of the south beach, better navigation access and safety, and better control (reduction) of sediment influx into the inlet channel and upstream points in the Loxahatchee River estuary. The first two issues have been particularly outstanding, due to persistent concern for the inherent deficiencies in the protocol for sand pumping and placement on the beach that tends to erode away rapidly, and the concern for conditions for navigation of vessels in the proximity of the inlet in open waters. With regard to the third issue, despite the reasonably successful ongoing program to pump sand out of the borrow areas within the inlet channel, other areas such as some of the marinas in the inlet area, as well as the region of the Loxahatchee River west of the Florida East Coast Railroad bridge, have been experiencing slow but persistent sedimentation.

Contingent upon a series of coastal and environmental engineering investigations, a range of engineering actions that could mitigate erosion, navigation and sedimentation problems were considered. Based on the physical and ecological impacts that would be caused by these actions, two sets of action options that have net beneficial impacts due to action implementation have been proposed. The first is a set of interdependent action options that must be instituted inherently in a time-wise phased manner. The second is a set of independent action options which can be instituted as and when

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desired. For determining the overall feasibility of any action option, it will be necessary to weigh the technical benefits against costs, which are provided. It should be emphasized however that, considering the overwhelmingly observational nature of coastal science, the estimates of potential benefits are essentially and inherently subjective, and the costs very approximate, especially in cases where the desired technology is in the "bench" stage.

SYNOPSIS

In this final report on the investigation of the potentialities of improved coastal engineering management of Jupiter Inlet, Florida, three management-guiding issues were considered: better control of the erosion of the south beach, better navigation access and safety, and better control (reduction) of sediment influx into the inlet channel and upstream points in the Loxahatchee River estuary. The first two issues have been particularly outstanding, due to persistent concern for the inherent deficiencies in the protocol for sand pumping and placement on the beach that tends to erode away rapidly, and the concern for conditions for navigation of vessels in the proximity of the inlet in open waters. With regard to the third issue, despite the reasonably successful ongoing program to pump sand out of the borrow areas within the inlet channel, other areas such as some of the marinas in the inlet area, as well as the region of the Loxahatchee River west of the Florida East Coast Railroad bridge, have been experiencing slow but persistent sedimentation.

Contingent upon a series of coastal and environmental engineering investigations, a range of engineering actions that could mitigate erosion, navigation and sedimentation problems were considered. Based on the physical and ecological impacts that would be caused by these actions, two sets of action options that have net beneficial impacts due to action implementation have been proposed. The first is a set of interdependent action options that must be instituted inherently in a time-wise phased manner. The second is a set of independent action options which can be instituted as and when desired. For determining the overall feasibility of any action option, it will be necessary to weigh the technical benefits against costs, which are provided. It should be emphasized however that, considering the overwhelmingly observational nature of coastal science, the estimates of potential benefits are essentially and inherently subjective, and the costs very approximate, especially in cases where the desired technology is in the "bench" stage.

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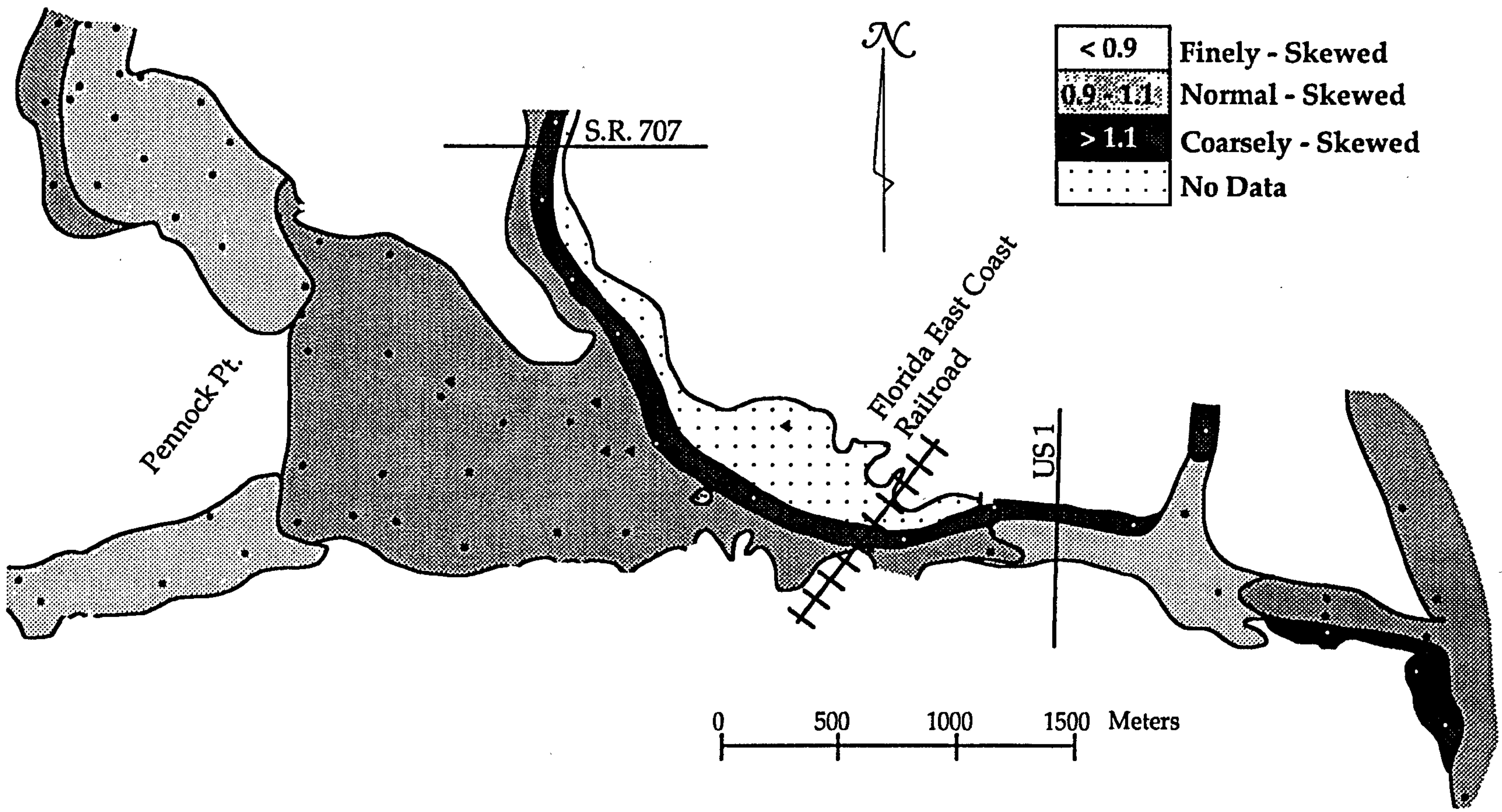
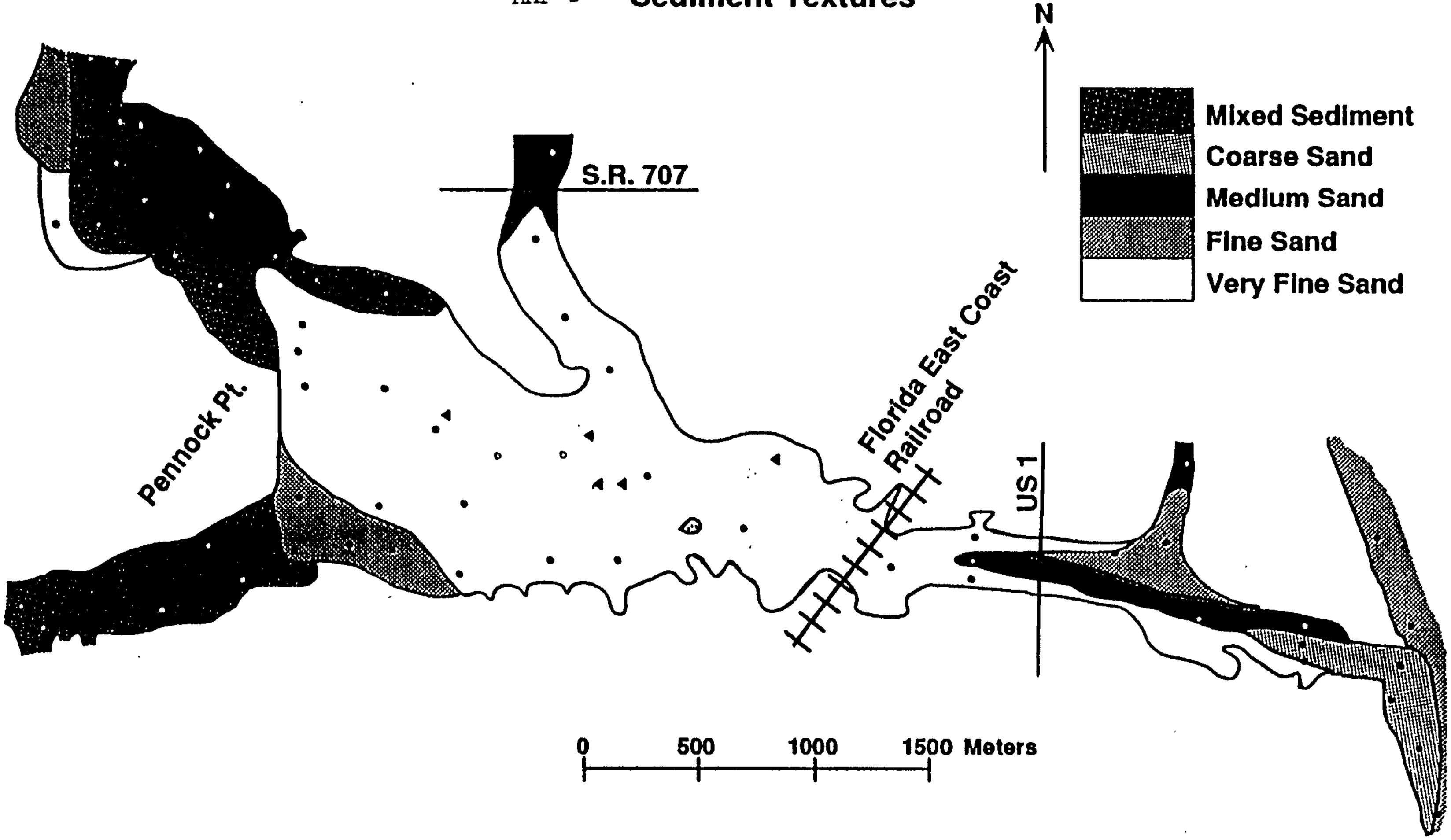


MAP 5 - Sedlment Textures



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1. INTRODUCTION

1.1 Preamble

The University of Florida (UF) undertook a coastal engineering management study for the Jupiter Inlet District (JID), for improving the engineering management protocols with respect to three main issues: beach erosion control, navigational safety, and control of sedimentation in the interior waters. The study was initiated on January 5, 1990. Five technical progress reports (Mehta et al., 1990a, 1990b, 1991a, 1991b and 1991c), based on a two year investigation and cited in the bibliography section, form the basis of the recommended coastal engineering management plan. The purpose of this final report is to recap the main findings discussed in more detail in the technical reports, and to highlight the management plan recommendations. We begin by providing a brief background of the study area.

1.2 Location and Description

Jupiter Inlet is located at latitude 26°56'35" N and longitude 80°04'18" W on the east coast of Florida in the northern part of Palm Beach County (Fig. 1.1). It is about 26 km south of St. Lucie inlet and about 23 km north of Lake Worth inlet. It is a natural inlet connecting Loxahatchee River to the Atlantic Ocean. The backwaters of Jupiter Inlet are shown in Fig. 1.2.

Long and narrow barrier islands is a characteristic feature of the coast in the vicinity of Jupiter Inlet. The barrier island north of Jupiter Inlet is called the Jupiter Island. The central portion of Jupiter Island, opposite the town of Hobe Sound, has been well-developed as a winter residence area over the past several decades. Many large and expensive homes are located near the beach in this area. The southern portion of Hobe Sound was less developed until the 1940's and the houses in this area were placed near the shore of Hobe Sound. Most of the individual properties extended coast to coast on the island, the width of which varied from 15 m to 50 m at low water.

According to the U.S. census of 1940, Hobe Sound had a permanent population of 874. The excess floating population was estimated to be around 100 in summer and 1,000 in winter. The permanent population of Palm Beach County and Martin County has increased substantially over the past few years as may be seen from data given in Table 1.1. Martin County is the adjoining county just north of the Palm Beach County.

The figures given for the years 1930 through 1990 are obtained from the Federal Census. The figures given for the year 2000 are estimates obtained from the Palm Beach County Planning Division and the Martin County Department for Community Development.

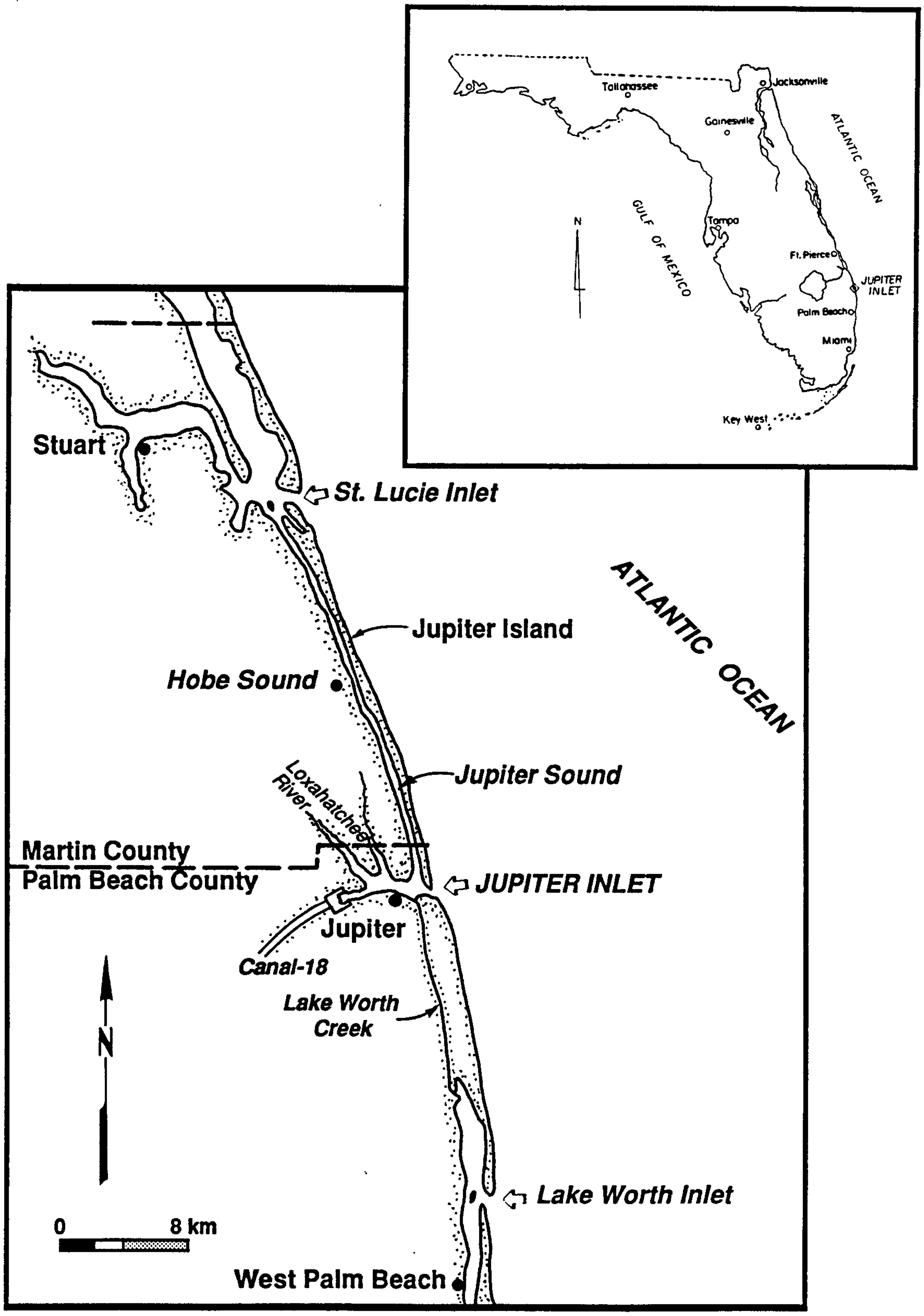


Figure 1.1. Area map of Jupiter Inlet.

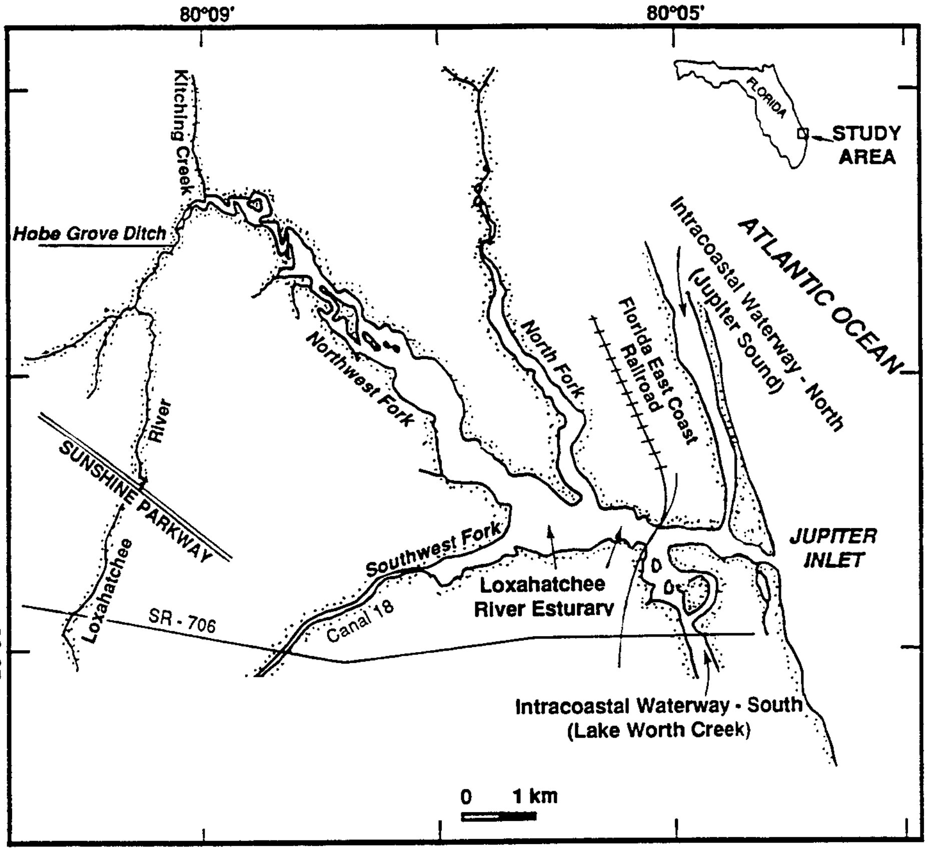


Figure 1.2. Backwaters of Jupiter Inlet.

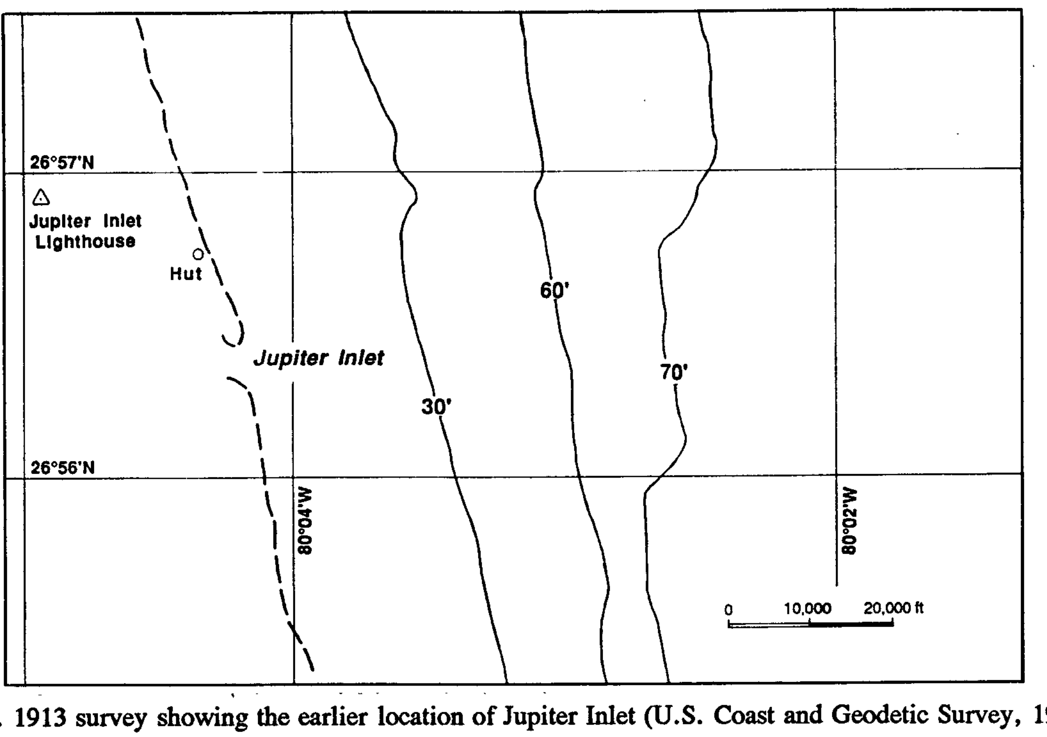


Figure 1.3. 1913 survey showing the earlier location of Jupiter Inlet (U.S. Coast and Geodetic Survey, 1913).

Table 1.1: Population of Palm Beach and Martin Counties.

Year	Palm Beach County	Martin County
1930	51,800	5,100
1940	80,000	6,300
1950	114,700	7,800
1960	228,100	16,900
1970	349,000	28,000
1980	567,800	64,000
1990	863,500	115,200
2000	1,113,200[a]	149,800[b]

[a]Estimate; Palm Beach County Planning Division.
[b]Estimate; Martin County Department of Community Development.

1.3 Historical Information

According to historical accounts, Jupiter Inlet has been in existence for at least over 300 years (U.S. Army Corps of Engineers, 1966). It is first shown on the explorers' maps in 1671 and other contemporary navigation charts. Originally, this was the only outlet for Loxahatchee River, Lake Worth Creek and Jupiter Sound. Part of the discharge from St. Lucie River and the southern part of Indian River was also diverted to the ocean through Jupiter Inlet. The total flow was sufficient to maintain adequate depth through the inlet except during severe storms when the inlet closed temporarily for short periods. This inlet has been known by several names (Dubois, 1981). First it was known as Hobe, or Jobe for a tribe of the aboriginal Jeaga Indians who lived near the inlet. On the Spanish maps, the river appeared as Jobe River, named for these Indians. The English interpretation of Jobe was Jove, which in turn became Jupiter. On the DeBrahm map of 1770, it is given as Grenville Inlet, formerly Jupiter. Hobe or Hoe-Bay continues as the nearby Hobe Sound. All are apparently related terms. In early days, the inlet was at times several hundred km south of the present location. The map of the Fort Jupiter Reservation, dated 1855, shows the inlet in this position.

St. Lucie Inlet, the next inlet due north, was a man-made creation in the year 1892. The Intracoastal Waterway connected Jupiter Sound to Lake Worth Creek in 1896 and Lake Worth Inlet was created in 1918. These constructions diverted much of the flow away from Jupiter Inlet, which in turn resulted in more frequent closure of the inlet. Between 1896 and 1909, under a special emergency authority, the Federal Government reopened Jupiter Inlet three times. Local interests also reopened the inlet several times between 1896 and 1922. The JID, created in 1921 by a special act of the Florida Legislature, spent in excess of $400,000 improving and maintaining the inlet between 1922 and 1960.

Until the year 1922, Jupiter Inlet was a natural inlet without any man-made training structures at the inlet mouth. Under the combined effect of tidal flow through the inlet and the predominant littoral drift in the southward direction, the inlet joined the Atlantic Ocean with an orientation in the south-eastern direction (Fig. 1.3). Mr. J.

C. Wagen, Chief Engineer of Lake Worth, Florida approved construction drawings in the year 1922, which included the following works at Jupiter Inlet (Fig. 1.4).

1. Cutting a channel in the easterly direction across the sand barrier. The channel was to be 30 m wide at bottom with 2.1 m depth below the mean low water level. This involved removal of about 2,800 m^3 of material.
2. Provision of a barrier across the natural south-easterly channel, the crest elevation of the barrier being 1.5 m above mean low water level, in order to divert the tidal flow through the new opening.
3. Construction of two jetties, each 120 m in length, 100 m apart, one on the north side and the other on the south side of the inlet. Typical cross-section of the jetty and the dredged channel are shown in Fig. 1.5.

The permit for the above construction works was issued on 20th April 1922 by Mr. Lansing H. Beach, Major General and Chief Engineer, U.S. Army. In 1922 JID built two parallel jetties about 107 m apart at the inlet. Subsequently, the jetties were extended and strengthened. In 1929, the north and south jetties were extended 60 m and 25 m, respectively. In 1941 a 2 m deep and 18 m wide channel was dredged close to the south jetty. In 1940 JID built an angular groin at the seaward end of the south jetty. The intended purpose was to increase current velocities and induce scouring between the jetties where closure of the inlet had recurred. However, the inlet again closed in 1942 and remained as such until 1947. Closure occurred due to a sand barrier about 90 m wide having a top elevation of 2.1 m above mean low water. Since JID reopened the inlet in 1947, typically biannual maintenance dredging has kept the inlet open for small-craft navigation. In 1956, a 90 m long concrete capped sheet pile jetty was constructed 30 m north of the existing north jetty. In 1966 JID, working with a consulting engineering firm, initiated a 15-year improvement program intended to ultimately provide: (1) Landward extension of the existing bulkheads; (2) jetties at the seaward ends of the existing bulkheads; (3) continued periodic maintenance dredging of the inlet channel; and (4) a trestle-mounted sand-transfer plant sited north of the north jetty (U.S. Army Corps of Engineers, 1966). Local interests estimated the cost of the 15-year program, including interim channel dredging maintenance, at about $800,000. Funds for the program were raised by taxes on property within the inlet taxing district. Palm Beach County contributed funds to JID periodically for fill placed on the south beach. A sand trap was dredged 300 m west of the inlet mouth in 1966. In the late 1960's, the jetties were modified. A "wing" on the seaward end of the south jetty was removed in 1967 in an effort to reduce shoaling within the inlet (Fig. 1.6). Both jetties were extended landward to prevent flanking. The present, about 60 m wide, channel requires regular maintenance dredging.

1.4 Chronology of Important Early Events

Year *Event*

1892 St. Lucie inlet was constructed by making an artificial cut through the barrier strip, about 10 km north of Jupiter.

1896 A canal was excavated connecting Jupiter Sound and the headwaters of Lake Worth Creek with Lake Worth.

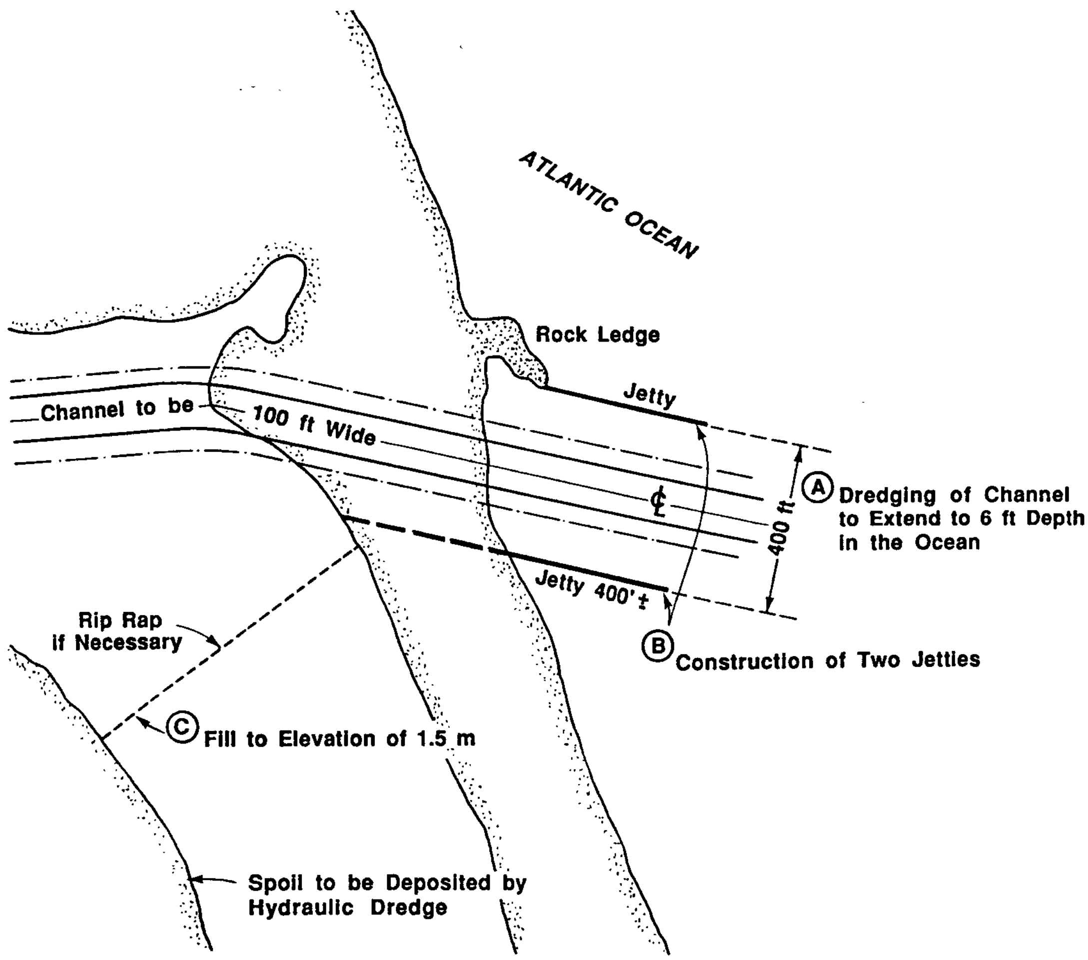


Figure 1.4. Details of the original construction works at Jupiter Inlet in the year 1922.

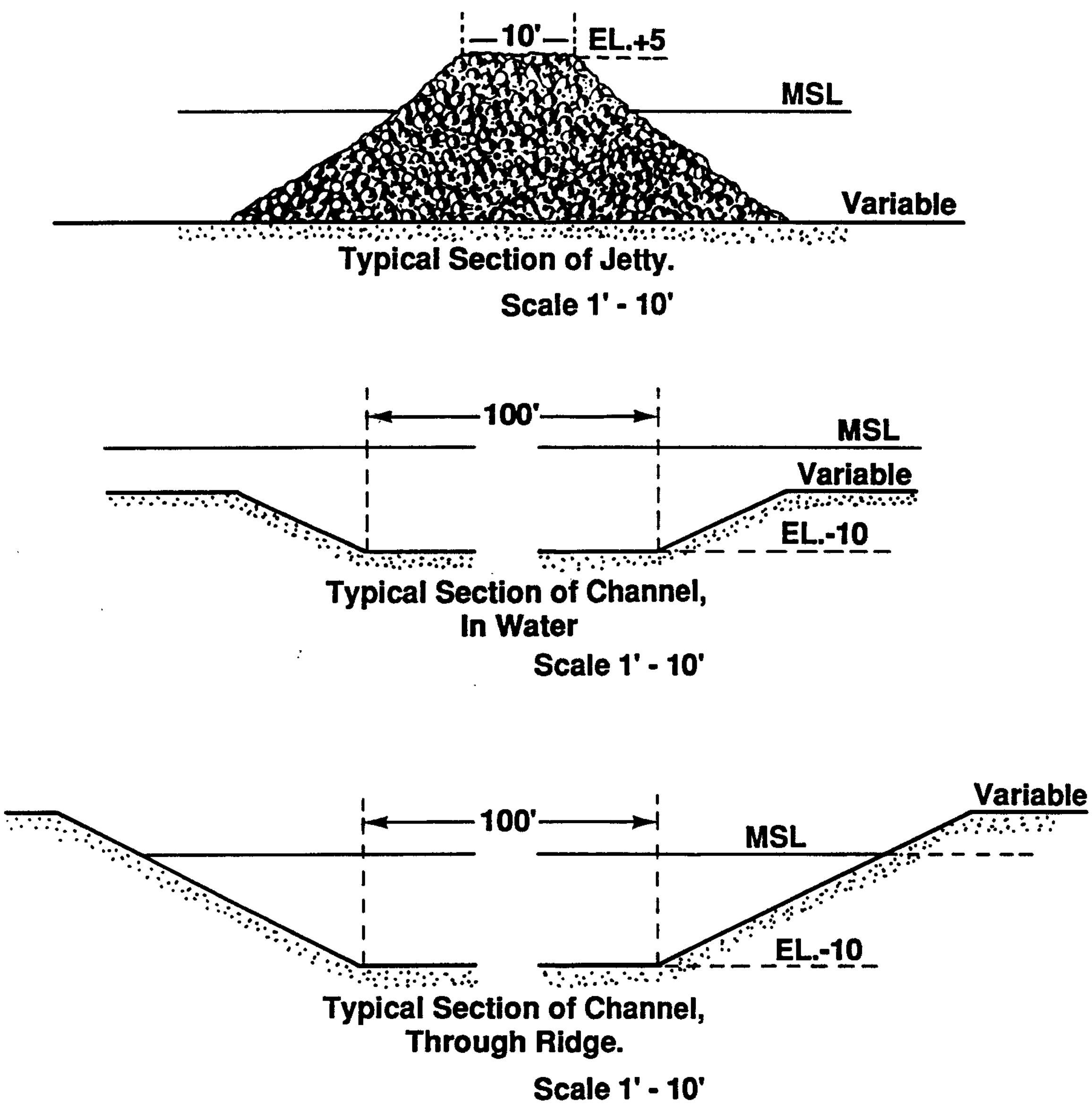


Figure 1.5. Cross-section of the jetties and approach channel constructed at Jupiter Inlet in 1922.

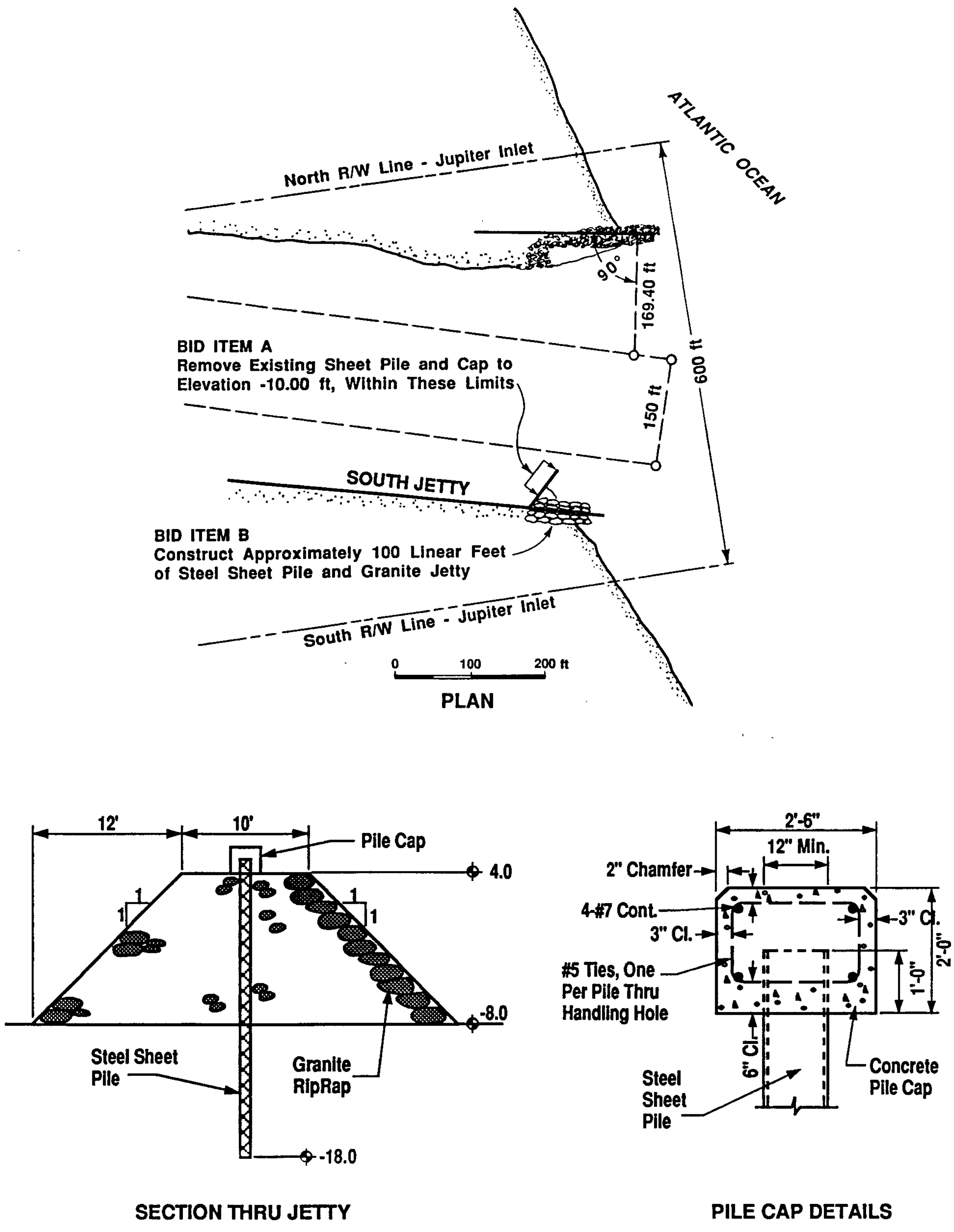


Figure 1.6. Modifications made to the south jetty at Jupiter Inlet in 1967.

1913-
1922 Inlet moved approximately 1250 ft north to its present position.

1922 Permit was issued to Jupiter Inlet District by the Chief of Engineers, U.S. Army to dredge a channel and construct two entrance jetties 122 m apart in order to provide a stable inlet with eastward flow direction.

1922 400 ft long jetties were constructed, 400 ft apart and a channel was dredged to meet 6 ft depth in the ocean.

1926 North jetty was constructed at St. Lucie Inlet. Seawall constructed on Jupiter Island.

1929 North jetty extended by 200 ft and south jetty extended by 75 ft.

1936 100 ft wide, 8 ft deep channel was dredged.

1940 Inlet District constructed an angular groin at the seaward end of the south jetty.

1942 Inlet closed and remained closed until 1947.

1947 House Document No. 765 was submitted to the 80th Congress, 2nd session of the U.S. House of Representatives.

1947 Inlet was reopened by dredging.

1957 Coastal Engineering Investigation at Jupiter Island were conducted by the University of Florida in order to recommend the best methods of protecting Jupiter Island beaches.

1960 Coastal Engineering Investigation conducted by the University of Florida for recommending the alignment of bulkhead along Jupiter Island beach.

1966 Sand trap was dredged 1000 ft west of the inlet throat.

1967 Angular groin at the seaward end of south jetty was removed and the jetty was extended by 30 m.

1.5 Recreation and Fishing

The Survey Report of 1966 (U.S. Army Corps of Engineers, 1966) mentions that the absence of a dependable, safe channel to the ocean through Jupiter Inlet restricted recreational crafts from full realization of potential boating benefits. Local boats had to await favorable conditions of tides and seas or travel via the Intracoastal Waterway to St. Lucie or Lake Worth (Palm Beach) Inlets in order to cruise or fish in the ocean. Information on the recreation boats in use in the Jupiter area in the year 1966 is given as an example in Table 1.2 (U.S. Army Corp of Engineers, 1966).

Frequently, small craft entering the ocean through Jupiter Inlet in the morning were compelled to return via Lake Worth or St. Lucie Inlets due to adverse weather or seas encountered on the return trips. Some local boatmen considered the hazard and inconvenience of using the Jupiter Inlet so great that they either kept their boats at West Palm Beach or no longer cruised or fish in the ocean. During optimum navigating conditions, normal controlling depths over the ocean bar limited recreational use to boats drawing less than 1 m. Even with favorable conditions of sea and swell, navigation was restricted to the hours of highest tide.

With the abundance of natural and improved inland waterways and the nearness of the Atlantic Ocean, recreational boating and sport fishing are two of the major local outdoor activities. Tourists and vacationers from

Table 1.2: Recreational boat use in the Jupiter area in 1966 (U.S. Army Corps of Engineers, 1966).

	Length (ft)	Average draft (ft)	Percent of fleet using: Jupiter Inlet	Percent of fleet using: Other inlets[a]
Inboards:				
	Up to 26	1.0 to 3.0	48	78
	26 to 40	2.0 to 4.0	27	94
	40 and longer	3.5 to 6.0	0	100
Outboards:				
	10 and 22	1.0 to 2.0	39	53

[a]Part or full time.

other parts of Florida and from many other states visit the area to enjoy fishing, boating, and other recreational activities. The following extract taken from the Survey Report of Jupiter Island (U.S. Army Corps of Engineers, 1966) describes the status of fishing:

> "In the 1962-1963 season a fleet of 21 king mackerel launches, comprised of 8 local and 13 transient boats, operated through Jupiter Inlet when tide and seas permitted safe passage. This is about the same number as was based at Jupiter in 1933-1934, when the inlet was open and usable by such craft. Of the permanently based local fleet, 7 boats are used only for king mackerel fishing in local waters, and 1 boat fishes year-round for other species. Operators of the 7 local boats fish for king mackerel as a secondary or supplemental occupation. The remaining 13 transient vessels follow the migrating schools. The fleet experienced varying degrees of restriction during the 1962-1963 season when large schools of king mackerel were concentrated offshore in the northern part of Palm Beach County. Evaluated benefit to the Jupiter fishing fleet is based upon the alternative of operating the fleet from West Palm Beach bases. Information from the field study indicates that the additional daily operating cost would be $5 per boat (10 gallons of gasoline at $0.34, 1 quart of oil at $0.60, and $1.00 added for daily engine wear and maintenance cost). Local boats fish about 45 days a year for king mackerel. Estimated annual savings in operating costs would be $225 per boat or $4,700 for the fleet. It is believed that the fleet size will remain relatively unchanged regardless of inlet improvement.
>
> The offshore waters of Palm Beach County support an important marine fishery. In recent years, annual food-fish landings have averaged over 4 million pounds. King and spanish mackerel have constituted about 85 percent of the total catch. Most of the fish landings, which are principally ocean species, have been carried through Lake Work Inlet. However, in the 1962-63

season, significant catches of king mackerel were brought in through Jupiter Inlet when weather and seas permitted.

There are no public terminals or docks in the Jupiter area. However, three private marinas provide berths for about 75 recreational and commercial craft. Covered dry storage for an additional 50 small recreational craft is also available. Commercial fish catches are unloaded at a marginal wharf and passed directly into waiting trucks. Available facilities, while privately owned, are generally open to all on equal terms. The closest marine railways are at West Palm Beach. Outboard craft may be serviced and repaired at local marinas. Existing facilities have highway connections and are adequate for present recreational and commercial small craft. Land has been acquired and plans have been prepared for two additional marinas in the vicinity of the inlet. Plans for one of these, announced in April 1964, would provide space for 350 boats at a coast in excess of $500,000. Adequate space is available for future expansion of terminals.

Commercial fishing is an important industry of Palm Beach County. King mackerel is the principal food fish landed, representing about 50 percent of the tonnage and dollar value of all food fish landed in the county in recent years. In the period 1958 through 1962, king mackerel fishing extends from December through March. During that period large schools migrate through the offshore waters. During the 1962-1963 season a fleet of over 50 inboard launches 5.2 to 7.6 m long, with maximum loaded drafts of 1.2 m, fished for king mackerel from Palm Beach County bases. The boats are operated by one- and two-man crews. All fish landed were processed through fishhouses in the West Palm Beach area. Fish landed through Jupiter Inlet were trucked to West Palm Beach for processing."

The Survey Report of 1966 also included projections of recreational boat traffic at Jupiter. These, even though dated, are given in Table 1.3 for illustration. Comparison of boat ownerships and population in Florida coastal counties shows that the per-capita ownership of recreational boats is greatly reduced as coastal counties increased in population. Therefore, per-capita ownership of recreational boats in Palm Beach County and the Jupiter Inlet area was expected to decrease from the rate of about 35 boats per 1,000 population in 1966 to about 15 boats per 1,000 population by 2017. The projected local fleet at Jupiter Inlet, as shown in Table 1.3, is based on 15 boats per 1,000 population in 2017 (1,469 boats). It would be interesting to compare the facts for the past years from 1967 to 1992 with the projections made in the year 1966. These data were not however readily available while compiling this report.

1.6 Navigation

A navigation channel 60 m wide and 3 m deep has been considered from the Jupiter Inlet entrance to the 3 m contour in the ocean. The length of this channel would be about 380 m (Fig. 1.7; note units in ft). Inside of

Table 1.3: Jupiter Inlet recreational boating benefits (U.S. Army Corps of Engineers, 1966).

Item	Type of Boat						Total
	Outboards		Inboards				
	Runabouts	Cruisers	Charter	To 26 ft.	26-40 ft.	40 + ft.	
Depreciated value-----	$600	$1,300	$8,000	$3,000	$7,000	$20,000	
Percent return--------	10	12	12	8	7	6	
Unit return------------	$60	$156	$960	$240	$490	$1,200	
Percent restriction----	11	11	15	12	14	22	
Unit benefit-----------	$7	$17	$144	$29	$69	$264	
Without improvement:							
Local fleet 1964:							
Number--------	131	58	0	45	9	11	254
Benefit---------	$920	$990	0	$1,300	$620	$2,900	$6,730
Added fleet by 1967:							
Number--------	52	24	0	17	3	2	98
Benefit---------	$364	$408	0	$493	$207	$528	$2,000
Added fleet by 2017:							
Number--------	630	280	0	200	40	30	1,180
Benefit---------	$4,410	$4,760	0	$5,800	$2,760	$7,920	$25,650
With improvement:							
Added fleet in 1967:							
Number--------	0	0	4	1	0	0	5
Benefit[a] -------	0	0	$3,840	$240	0	0	$4,080
Added fleet by 2017:							
Number--------	0	0	20	10	3	2	35
Benefit[a] -------	0	0	$19,200	$2,400	$1,470	$2,400	$25,470
Total number of boats							
(Year 2017)----------	761	338	20	255	52	43	1,469
(Year 1967)----------	$1,284	$1,398	$3,840	$2,033	$827	$3,428	$12,810
Total benefits (Year 2017)	$5,330	$5,750	$19,200	$9,500	$4,850	$13,220	$57,850

[a]Full unit return

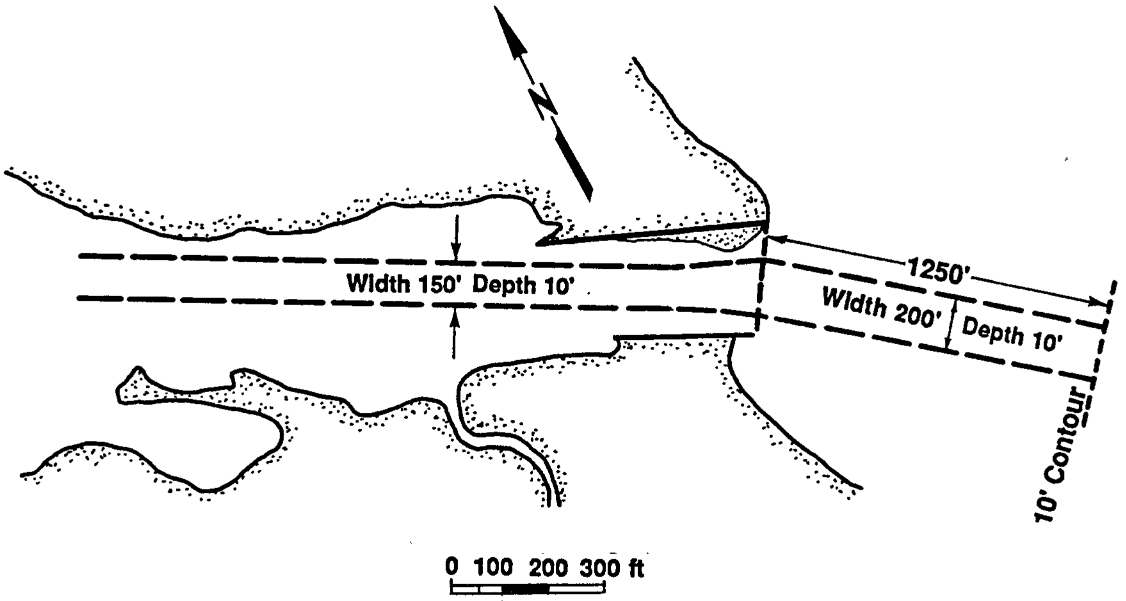


Figure 1.7. Layout of the navigation channel at Jupiter Inlet.

the inlet, the navigation channel would be 45 m wide and 3 m deep. The 3 m depth of channel was based on the following clearances:

Mean low water	0.3 m
Wave trough	0.9 m
Underkeel clearance	0.6 m
Draft of vessel	1.2 m

The 60 m width of the channel would provide enough room for a two-way traffic of boats 12 m long and 4 m wide.

Principal difficulties result from inadequate depth across the ocean bar at the entrance to the inlet. During periods of low tide or high seas or swells, passage over the ocean bar is extremely hazardous if not impossible. Local interests reported that at least five lives were lost in the 5-year period from January 1958 to March 1963, from capsizing of outboard boats in and near the inlet. Reported loss and damage to small crafts at Jupiter are given in Table 1.4 for illustrative purposes. The principal damage was to outboards grounding on the ocean bar or capsizing in the inlet. Outboards capsized in the inlet sustained damage ranging from minor superficial damages to complete loss. Representative costs for outboard grounding damage were: propeller replacement $12; water pump repair $25; lower unit replacement $130; and windshield replacement, $65. With allowance for boat damage that would occur regardless of inlet improvement, and allowance for undisclosed damage, annual benefit from reduction of damage to boats was estimated at $1,300 in 1964, $1,500 in 1967, and $7,000 in 2017. Prevention of loss of life was not evaluated.

1.7 Concluding Comment

Since its inception in 1921, JID has been consistently involved in managing navigation through Jupiter Inlet and, therefore, has had to contend with the auxiliary but inter-related issues arising from managing for beach erosion and sedimentation. In recent years ecological stresses on the inlet and the Loxahatchee River estuary have increased substantially, hence any examination of the impact of improvements with regard to management for beach erosion, navigation and sedimentation must simultaneously consider physical processes together with environmental factors. The subsequent chapters are therefore focussed along these lines.

In a review of literature and data of this engineering nature, mixed use of fps unit system and the SI system poses the usual problem of unit conversion. Following the contemporary convention, the SI system is used in the text, either by itself or together with the fps system, with some exceptions. On the other hand, fps unites have been retained in many figures and tables including, but not limited to, those derived from other sources. Necessary conversions are as follows:

Table 1.4: Reported loss and damage to small craft at Jupiter Inlet (U.S. Army Corps of Engineers, 1966).

Name of boat or type	Cause of damage and type	Reported cost
	1957	
Inboard cruiser	Capsized	$150
Outboard	Grounded	-
Outboard	Broached (1 insured)	-
	1958	
Outboard	Swamped	-
Inboard cruiser	Capsized (1 life lost)	-
	1959	
Inboard cruiser	Bent propeller	-
	1960	
Inboard cruiser	Grounded - cracked hull	75
Inboard cruiser	Grounded - sand in engine	-
Outboard	Broached (passenger thrown from boat)	-
Outboard	Grounded	-
	1961	
Inboard cruiser	Grounded	-
Outboard	Grounded - broken windshield	-
Outboard	Grounded - cracked lower unit	-
Outboard	-	325
Outboards	Grounded (5 incidents)	-
Outboards	Broken propellers (6 incidents)	
	1962	
Alumincraft outboard	Capsized	-
Richardson cruiser	Grounded, broken up	8,000
Inboard cruiser	-	150
Outboard	Propeller damage	-
	1963	
Ruby 5 (commercial fishing)	Grounded	600
Inboard-outboard	Grounded	50
Outboard skiff	Capsized (2 lives lost)	-
Outboard	Capsized (1 life lost)	-

To Convert	Into	Multiply By
centimeters	inches	0.3937
cubic meters	cubic yards	1.308
cubic meters per sec	cubic feet per sec	35.31
kilometers	miles (statute)	0.6214
meters	feet	3.281

For convenience of description the grain size is defined in terms of diameter, d, and ϕ the unit where deemed necessary. The relationship between these two is: $\phi = -\log_2 d$.

The essential elements of the management issues specific to Jupiter Inlet, as well as the present state of the inlet from a coastal engineering perspective and described next in Chapter 2.

2. MANAGEMENT ELEMENTS AND THE STATE OF THE INLET

2.1 Management Imperatives

As shown in Fig. 2.1, the water areas in the inlet region relevant to the study can be conveniently divided into three sub-areas: Region 1 (beaches and offshore area influencing the inlet and vice versa), Region 2 (inlet channel between the ocean ends of the jetties and the Florida East Coast Railroad, or FECRR, bridge), and Region 3 (including the area bounded between the FECRR bridge S.R. 707 and Pennock Point). The Intracoastal Waterway runs through Region 2, which serves as the connection between Jupiter Sound and Lake Worth Creek. Three forks of the Loxahatchee River enter Region 3. From the standpoint of JID's requirements for this study, Regions 1 and 2 are particularly important, whereas the importance of Region 3 only lies in terms of processes and recommended actions that are particularly relevant to Region 2.

As a characteristic feature of the beaches adjacent to sandy tidal inlets subject to a net littoral drift, the shoreline in the vicinity of Jupiter Inlet has readjusted itself relative to what would occur in the absence of the inlet, to create a northern accretion fillet of sand, and a southern deficit of sand as shown in Fig. 2.2. To maintain a navigable channel through the inlet and control the beach sand deficit problem, since the late Forties a coastal engineering management protocol has in fact been in place at this inlet. Over the years, partly based on two previous studies carried out by UF in 1969 and 1984 (Coastal Engineering Laboratory, 1969; Buckingham, 1984), this plan has evolved to its present state. A key element of the plan includes maintaining the channel through periodic dredging of the designated sand trap (Fig. 2.3), and managing the beach south of the south jetty by placement of sand derived from the trap. This protocol is aided by a similar dredging and pumping operation by the Army Corps of Engineers to remove excessive sand from the Intracoastal Waterway (Fig. 2.4). An important function of the two jetties is to maintain a trained navigable channel. The periodic dredging of the sand trap also serves to minimize the influx of sand in the interior areas including the marinas located in Region 2 and the aquatic preserve in Region 3.

The above mentioned management protocol has been functional to the extent that it has prevented catastrophic problems such as a barrier breakthrough with respect to the erosion of the south beach, has maintained a navigable channel, and has prevented excessive sedimentation of the interior as would, for example, clog the inlet completely. Such a clogging by sand did in fact occur in the mid-Forties, before the inlet was managed along the present lines. Due to increasing demands on the inlet and adjacent beaches arising from recreational and other needs, JID decided to seek possible solutions to three outstanding engineering needs as follows:

1. The need to increase the retention time of the sand placed on the south beach and reduce the threat of a land barrier breakthrough ("flanking") immediately south of the south jetty.

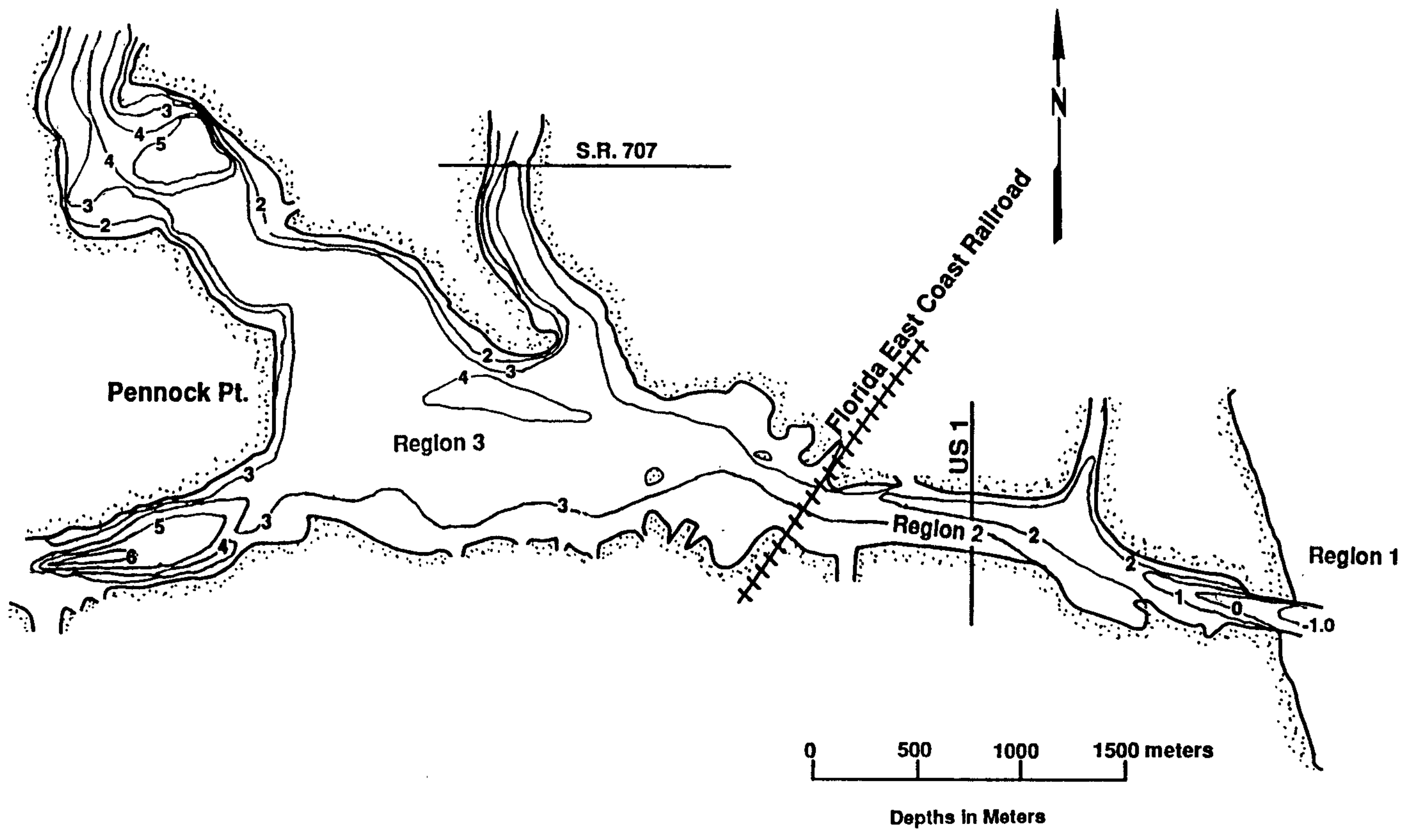


Fig. 2.1 Three water regions of Jupiter Inlet/Loxahatchee River relevant to the study.

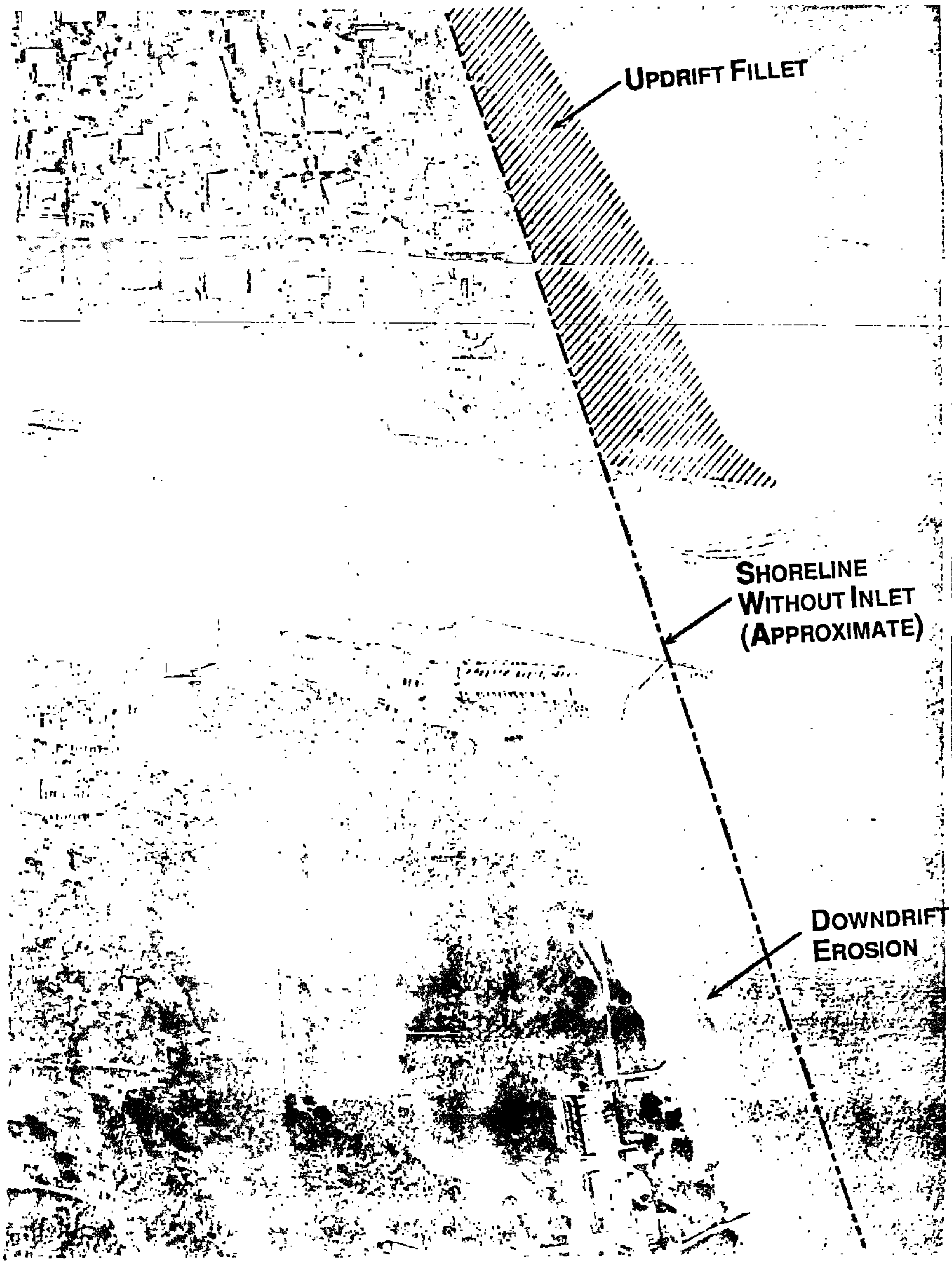


Fig. 2.2. Sand fillet and deficit at beaches contiguous to Jupiter Inlet.

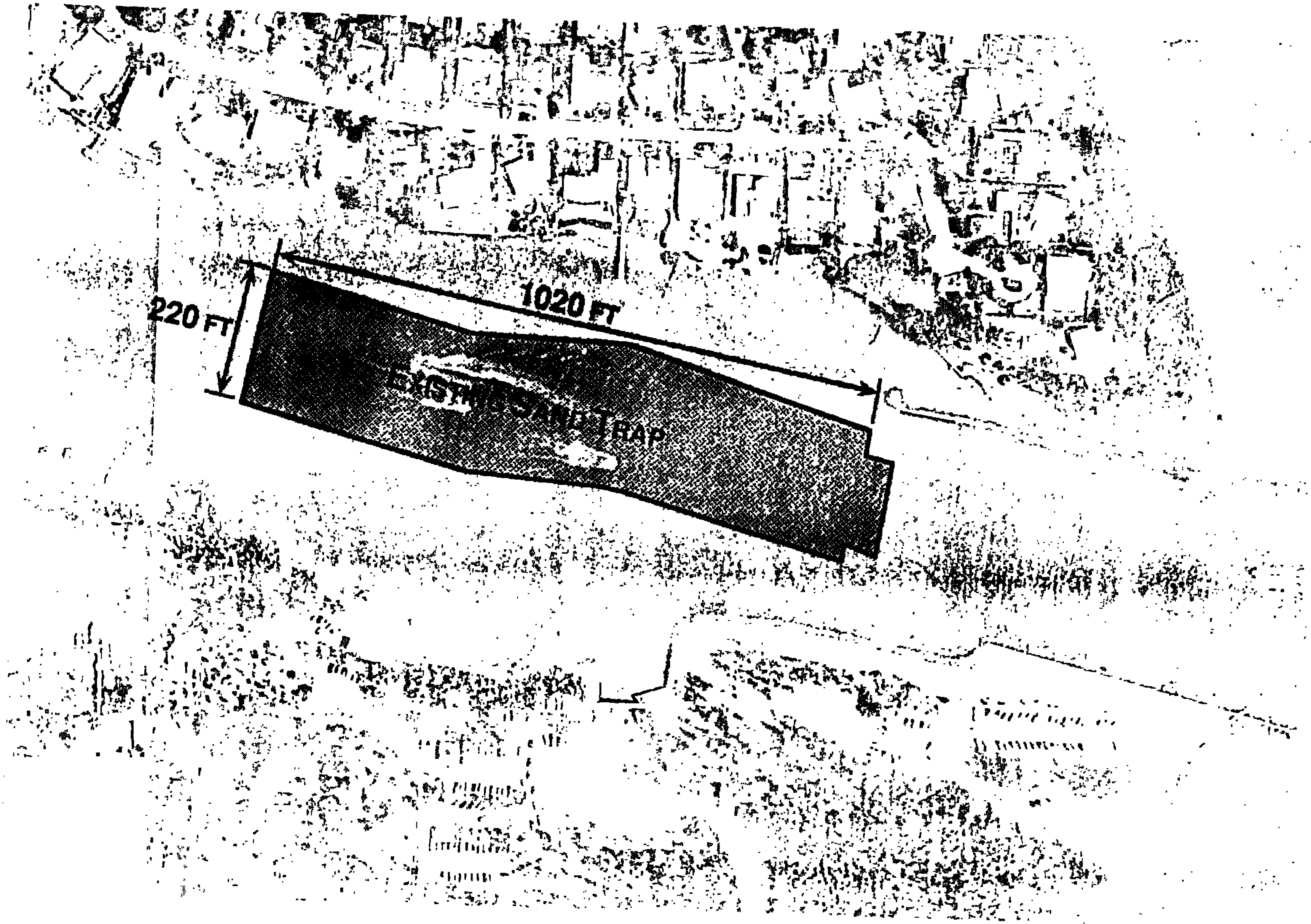


Fig. 2.3. JID sand trap.

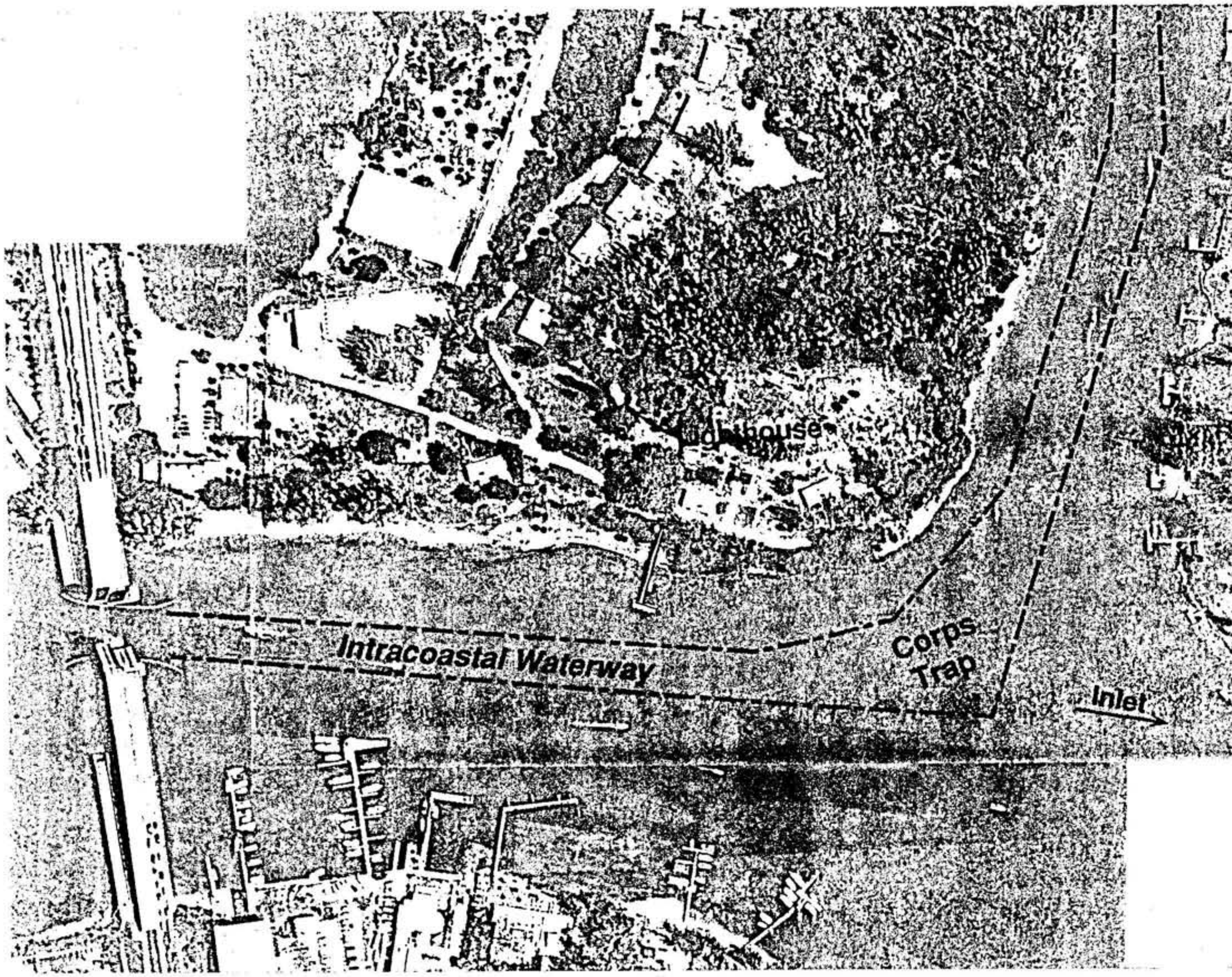


Fig. 2.4. Army Corps of Engineers sand borrow area in the Intracoastal Waterway, and the lighthouse.

2. The need to improve navigational safety, particularly as related to vessel passage in the area immediately offshore of the inlet, where accidents occasionally occur.

3. The need to reduce sedimentation in the interior areas, such as at the sites where the marinas are located (east of FECRR Bridge, along the south bank of the channel; Fig. 2.5).

2.2 Investigations

Seeking engineering solutions in regard to these needs must necessarily involve an examination of the potentialities for physical and associated ecological impacts. Thus, in addition to physical processes including waves tides, currents, salinity/fresh water, bottom sediment characterization and sediment transport (erosion, horizontal motion and deposition), as well as the present dredging protocol and navigational aids, assessments of the submerged vegetation (seagrass), mangroves (in Region 2), and rocky outcrops (in Regions 1 and 2) were carried out. Furthermore, sea turtle nesting, an ecological sensitive issue, was taken into consideration. These ecological "baseline" data were then used to make assessments of ecological consequences of all the principal physical impacts of the solutions considered. Fig. 2.6 shown the components and inter-relationships among the technical components of the study.

Based upon engineering investigations briefly noted next and described in the progress reports and related correspondence with JID, a suite of solution options based on what is practicable at Jupiter Inlet was considered, and in determining the choices, of the three primary issues -- beach erosion, navigational safety and sedimentation in the interior, where applicable the first two were weighed equally, while sedimentation, considered by JID to be a less problematic (i.e. more easily manageable) issue than the first two, was given a lesser weight. In every choice made the advantage or adversity of ecological impacts was considered. Summary descriptions of considered actions and their physical and ecological impacts follows a reference to the engineering investigations and finds in regard to the present state of Jupiter Inlet and the management protocol.

A cornerstone of this study was the series of coastal and environmental engineering investigations that were carried out to develop the technical bases for the selection of the engineering options. The basis for selecting the investigative methodology is rooted in the essential elements of inlet management elements as described in Appendix A (Mehta and Montague, 1991). The investigations themselves encompassed a number of field and laboratory measurements, and data analyses and interpretations, based upon these measurements as well as prior experience, technical knowledge and data (e.g. Chiu, 1975; Buckingham, 1984) available from other sources documented in the progress reports. In brief, the field studies included offshore wave measurement (over a 15 month period), tide and current measurements in Regions 1 and 2, bottom sediment sampling in all three regions, sand tracing studies in Regions 1 and 2, and seagrass and mangrove mapping in Region 2. A physical scale model of the inlet area (Region 1) was constructed and tested at UF. In addition, a suite of numerical models was used as an aid in analyzing the data collected in this as well as several previous studies to develop an understanding of the physical processes, a sediment budget for the inlet region, and physical and ecological impacts of the solution options (actions) considered.

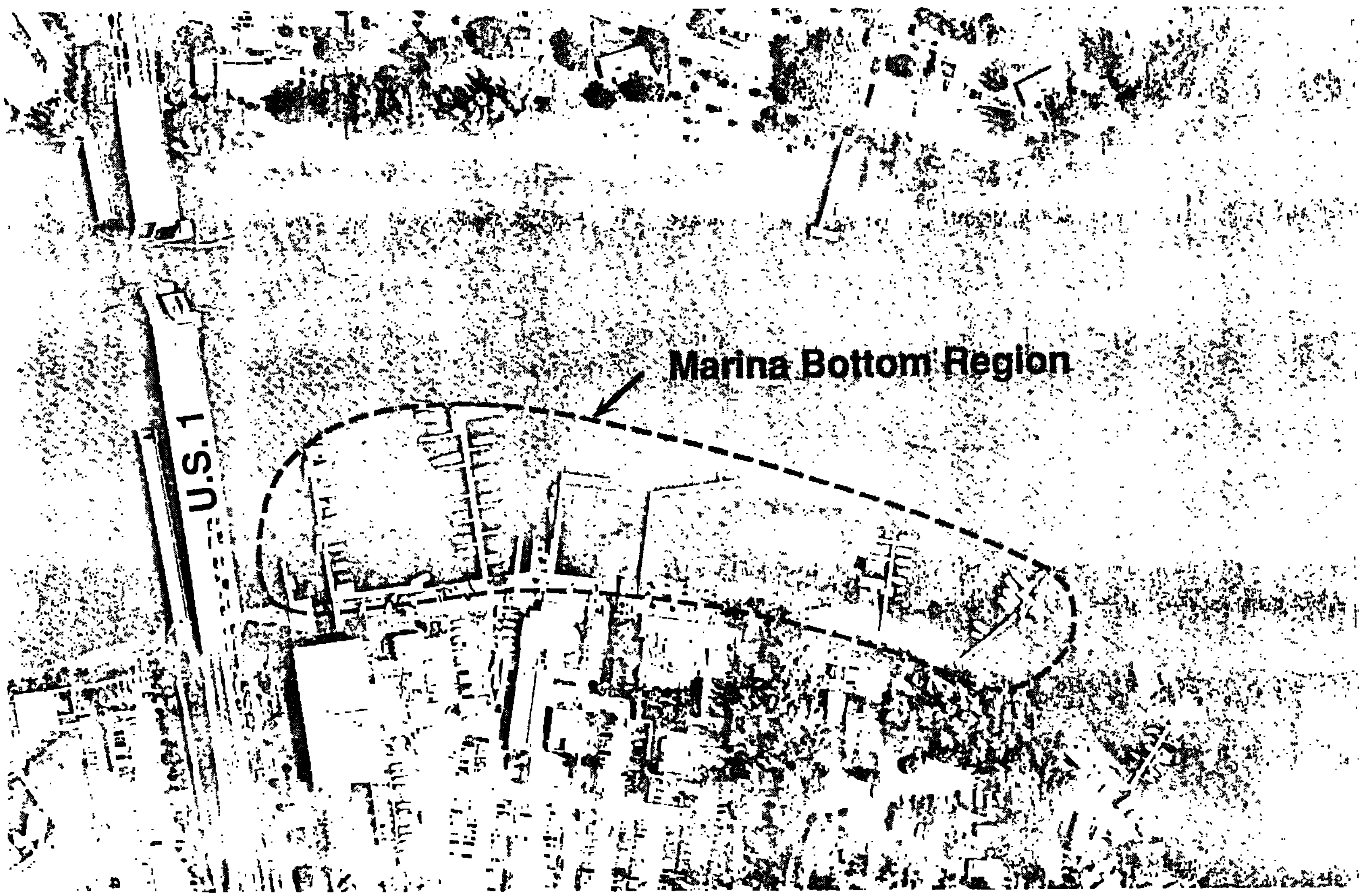


Fig. 2.5. Marinas of interest to the study.

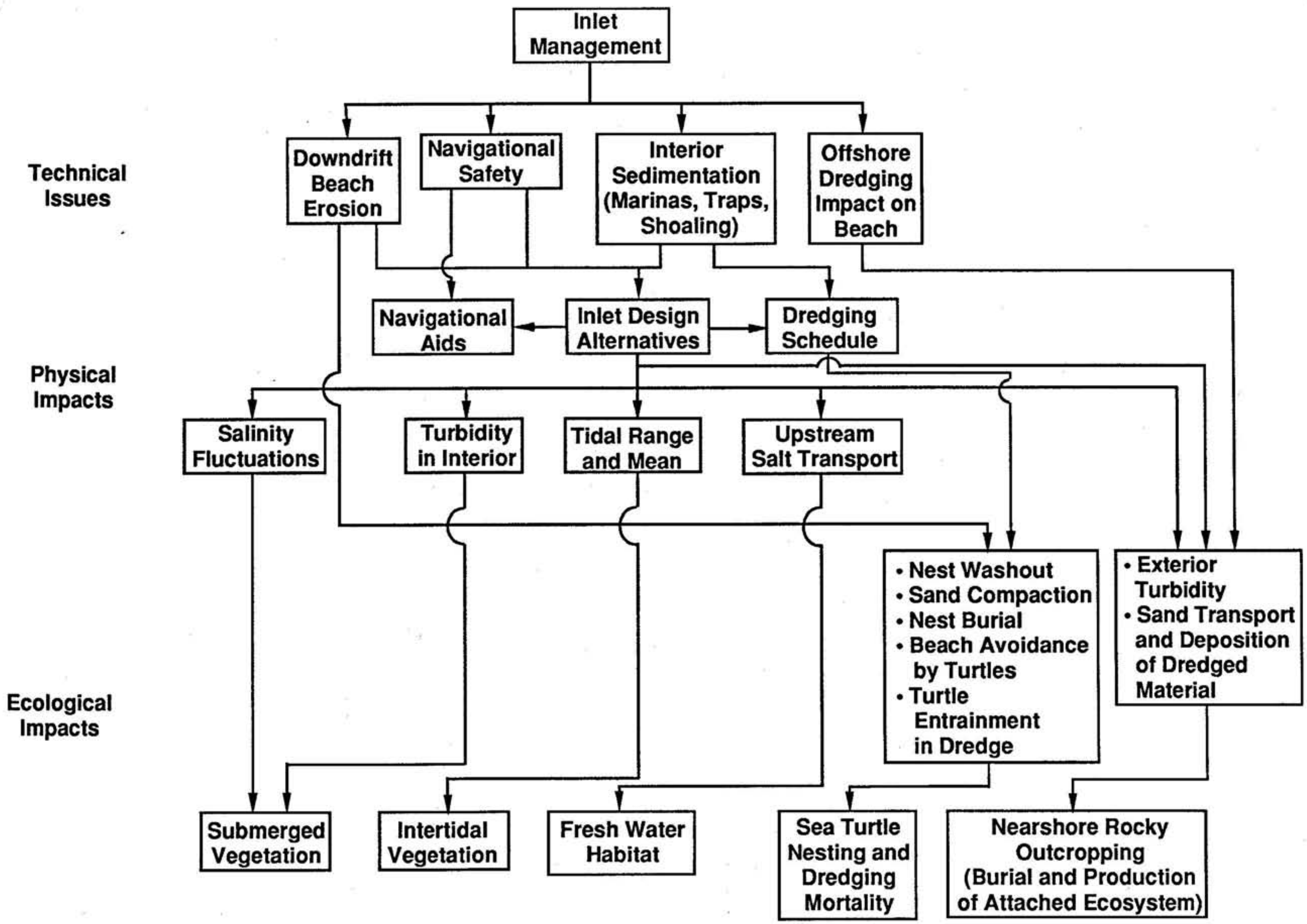


Fig. 2.6. Technical issues, physical impact studies and ecological impact studies for the inlet management plan.

It must be noted at this point that coastal and environmental engineering sciences are strongly observational in nature and, therefore, process-dependent technical conclusions must in turn rely on experience elsewhere with similar *and* dissimilar physical environments, and imposed engineering protocols. Mathematical and physical models, given their strengths and limitations in duplicating the physical phenomena, are essentially used as aids in arriving at rational engineering decisions, but they cannot, and should never be used as a sole basis for such decisions. No where in this study have we directly or directly implied that models have been either the sole or even the predominant basis of our engineering decisions. Neither should the reader anticipate or demand such an assertion.

2.3 State of the Inlet

The main findings with respect to the existing physical setting and the management protocol are briefly as follows:

1. In comparison with several other inlets, e.g. St. Lucie Inlet, Jupiter Inlet is reasonably well behaved, and well managed by JID, hence improvements to the existing management protocol are highly desirable but not absolutely critical.

2. A conservative (on the higher side) estimate is that as a result of the presence of the inlet, about 14,000 yd^3 (10,700 m^3) of sand out a total of 230,000 yd^3 (176,000 m^3) (long term annual mean) of net southward transport of sand are "lost" from the littoral transport zone to the offshore and the interior waters. This quantity, i.e. 14,000 yd^3 (10,700 m^3), amounts to an annual sand equity loss in regard to the beaches south of the inlet.

3. The shape and the volume of sand in the ebb shoal of the inlet change continually in response to the wave climate. The volume of sand tends to vary from season to season and year to year; estimates of the range of volume suggest that there are times when the volume is less than 500,000 yd^3 (382,000 m^3) when the wave activity is strong, to somewhat more than 1000,000 yd^3 (765,000 m^3) under milder wave conditions. Most of the sand is believed to be exchanged with the beach that the ebb shoal protects from heavy wave action; thus during more inclement times the ebb shoal supplies sand to the beach, while during calmer times the reverse process occurs.

4. The beach immediately south of the inlet is inherently prone to erosion, by virtue of the refraction and diffraction of waves that naturally occur in the vicinity of inlets, particularly those with jetties. The present sand dredging and pumping protocol to nourish the beach periodically is limited by: 1) the fact that some of the sand placed there returns to the channel by transport around the south jetty, 2) other sand moves southward, and 3) the retention time of the placed is low; the sand moves into the channel and also southward too rapidly in relation to the typical biennial placement schedule that has been usually (although not always, such as recently, when the inlet has been dredged annually) followed. Furthermore, the approximately 800 ft (240 m) stretch of the beach south of the south

jetty over which sand is typically placed appears to be somewhat short in length. Finally, no particular pumping season "windows" have been adhered to, although pumping is carried out during spring or summer for ease of dredging and transport of sand.

5. In addition to sand pumping from the interior borrow area or trap managed by JID (Fig. 2.3), the Army Corps of Engineers also pumps sand to the south beach from the Intracoastal Waterway (Fig. 2.4). Excluding those years when no sand was pumped to the beach, the total volume of sand pumped from the JID trap and the Corps trap has varied from as low as 30,000 yd^3 (22,900 m^3) in 1952, to as much as 209,000 yd^3 (160,000 m^3) in 1966. To date no specific frequency of pumping or minimum amount required to maintain the beach have been selected. A difficulty in such specifications is the annual variability in the condition of the beach, and the infilling rate of the traps. Furthermore, the Corps of Engineer's sand transfer protocol is merely fortuitous, since the Corps's principal need is to maintain the Intracoastal Waterway, as opposed to beach maintenance.

6. The present sand placement protocol is unrelated, placement- or timing-wise, to any considerations for sea turtle nesting habits. When the sand is placed such that steep, prograded beach profiles are established in the region immediately south of the south jetty, some turtle nests are lost due to relatively rapid erosion that typically occurs at these steep profiles. Relatively flat, tillable beaches that are supplied with sand on a regular basis for their stability are well suited to the Loggerhead sea turtles, which are endangered world wide.

7. Nesting sea turtles are an important ecological feature of the beaches north and south of Jupiter Inlet. Each year between the months of April or May and October, as many as 200 sea turtle nests are laid per km from Juno Beach to Jupiter Island. Management of sea turtle nesting beaches must address four main needs of nesting sea turtles: 1) access to nesting sites; 2) excavation of a nest to a depth of over 1 m (3.3 ft); 3) incubation of each nest for 60 d; and 4) successful emergence of hatchlings (which must dig out of nests). Access to nesting sites should be enhanced by a uniform moderate beach slope (1:10), without steep scarps, rising to a soft sand berm. Nest excavation and hatchling emergence should be enhanced by the presence of excavatable sand (loose sand of compaction less than 35 kg/cm^2 and not prone to crustal formations). Beach material should be coarse enough to prevent compaction, but it should not contain large rubble. Excavatable sand should be deep enough over any hard substrate to allow complete nest excavation (> 1.5 m, or about 5 ft, deep). Moreover, for sea turtle nesting to be successful, it is imperative that incubating nests not wash out before hatchlings emerge. Thus, whatever can be done to enhance beach profile stability, within the confines of the other criteria, should benefit sea turtles. In this regard, sand could be placed on the beach more than 30 days prior to the beginning of the nesting season to allow beach profile stabilization; the beach could be nourished more frequently (perhaps twice per year); and nourishment material could be placed away from hard structures that reflect wave energy, such as the south jetty (to avoid nest wash-out in the immediate vicinity of the jetty).

8. Submerged rocky outcroppings from the Anastasia formation form an important habitat for fishes and invertebrates in the nearshore zone all along the southeastern Florida coast. Rocky outcroppings may be especially important to spawning fishes. Few rocky outcroppings occur in the immediate vicinity of Jupiter Inlet, however, because of the accumulation of sand in the ebb shoal. This sand forms a shifting veneer over the rocks. Periodic storms bury and re-expose rocky outcroppings in the vicinity of Jupiter Inlet. At present, submerged rocky outcroppings appear approximately 1 km (0.6 mile) north of the inlet and northward. Other nearshore rocky outcroppings appear 1.2 km (0.75 mile) south of the inlet at Carlin Park. A small area of possible rocky outcroppings occurs about 1.3 km (0.8 mile) northeast of the inlet and a popular fishing site known as "Grouper Hole" is found 2 km (1.2 miles) due east of the inlet. A few exposed rocks occur directly inside the inlet mouth. Management considerations for rocky outcroppings include avoiding modifications that would bury rocks that have been exposed long enough to have developed diverse ecological communities. Long jetties may divert sand far downdrift and could conceivably contribute to the burial of some rocky communities. Jetties, however, are themselves artificial rocky habitat. They develop diverse ecological communities within a few years.

9. The inlet jetties have performed well in maintaining a stable navigation channel, thereby also protecting the adjacent land properties. However, the bulkheads separating land from water in many places along the interior banks are poorly designed and/or are in a poor condition. Also, too much concrete has been poured over parts of the Dubois Park beach, thus causing the hardened bank to reflect waves and hence erosion by sand transport away from the bank (Buckingham, 1984). In some places where bank protection is desirable, none exists. These conditions, coupled with significant boat wakes, have led to bank erosion in many places. Speeding boats are a major cause of the bank erosion problem. This erosion adds to the sediment at the bottom, thereby contributing to the reduction in navigable depths.

10. As to the causes of boat accidents that occur off the entrance, two types seem common; those in which the boat runs aground or is caught in wave action over the ebb shoal platform, and those in which the boat is attacked by waves abeam, typically from the northeast. Opinions on the need for improving navigational safety in this respect seem to vary; experienced navigators consider lack of navigation experience and hence judgment on the part of individuals as one of the principal causes of accidents. Coast Guard records show that alcohol related accidents also occur in this area.

11. A natural navigation channel maintained by the inlet currents typically exists off the inlet generally in the southeast direction, with depths on the order of 10 ft (3 m), but in places
where the littoral sand pathway intersects the channel, depths are less and navigation more difficult. The channel shifts in response to seasonal changes in the wave climate, and the Coast Guard considers Jupiter Inlet to be hazardous to navigation. The maximum drafts of vessels presently plying the waters cannot easily justify a deep,

i.e. deeper than 10 ft (3 m) navigation channel offshore such as at Fort Pierce and Palm Beach Inlets, unless future traffic growth patterns suggest otherwise.

12. The JID trap has performed reasonably well over the years, although a potential for somewhat improving its efficiency exists. The trap catches sand that enters from the littoral drift around both the jetties, and also over the jetties during storms when wind and wave-induced storm surge raises the water level and inundates the seaward ends of the jetties. Sand transport around and over the north jetty is four to six times greater than that from the south. The amount of sand caught by the trap annually varies widely because of the corresponding wide variations in the littoral drift. Estimates indicate for example that in 1956 the net southward drift was 433,600 yd^3 (332,000 m^3), while in 1968 it was only 63,400 yd^3 (48,500 m^3). The gross southward and northward drifts for the same two years were, respectively, 473,300 yd^3 (362,000 m^3), 39,600 yd^3 (30,000 m^3) and 989,900 yd^3 (757,000 m^3), 35,500 yd^3 (27,100 m^3).

13. As the sand enters the channel, the larger grains (around 0.4 to 0.6 mm size) fall out into the JID trap, somewhat smaller grains fall into the Corps trap, and some of the finer material (0.15 to 0.25 mm) is transported westward past the FECRR bridge. In recent years, with continual sedimentation and consequent decrease in depths in Region 3, the sand influx past the bridge has slowed to around 1,000 yd^3 (760 m^3) to 2,400 yd^3 (1,800 m^3) per year. Region 3 is the zone of the Loxahatchee River estuary where sea and fresh waters mix and there is a naturally high potential for sedimentation. Sediments of a variety of compositions enter this zone from the different connecting water bodies, one of which is the inlet channel. It is believed that a not wholly insignificant source of sand here is material derived from the banks of the Loxahatchee River due to boat wake induced erosion.

14. Some of the sand that is not caught by the JID trap deposits in the area where the marinas are located (Fig. 2.5). A representative rate of sedimentation in this area is about 0.5 ft (15 cm) per year. This area happens to occur along the side of a slight meander in the Loxahatchee River, and is naturally prone to sedimentation. Two other marinas located eastward appear to be much less prone to sedimentation, as they are semi-enclosed basins with well-defined entrances.

15. Seagrasses in the Loxahatchee River estuary inside Jupiter Inlet are an important habitat for juvenile fishes and invertebrates. Seagrasses are also important in sediment stabilization, wave energy reduction, and storm surge attenuation. East of the FECRR bridge are about 5.5 ha of seagrass beds. About 24% of the shoreline east of the FECRR bridge is adjacent to a seagrass beds. About half of the seagrasses in the estuary east of the FECRR bridge and south of the S.R. 707 bridge (in the north arm of the Intracoastal Waterway) are in one bed along the south shore just south of the north arm of the Intracoastal Waterway. Generally seagrass density in the beds declines toward the west. Seagrass beds exist between depth extremes from exposure to air at low water to a critical depth for adequate light penetration. Gentle bathymetric slopes between these extremes can result in large expanses of

seagrass beds. Seagrasses are also killed by high temperatures (above 35°C), such as may occur in shallow tidepools. Moreover, they are perhaps sensitive to high frequency, high amplitude fluctuations in salinity, such as may occur west of the FECRR bridge. Management considerations for seagrasses include effects of inlet modifications on water level, tidal amplitude, salinity regime, sediment loading, and light penetration.

16. The mangroves of the Loxahatchee River estuary are an important intertidal habitat for juvenile fish and invertebrates. Moreover, they help to stabilize sediments and protect shoreline property from the damaging effects of storms. About 4.9 ha of mangroves exist in the Loxahatchee River estuary east of the FECRR bridge. Approximately 55% are in the Dubois Park lagoon. Another 40% are in the south arm of the Intracoastal Waterway. About 38% of the shoreline is lined with mangroves. Changes in mean water level, tidal range, or sediment loading can change the extent of mangroves in the area. Management for mangroves includes consideration of the effects of inlet modifications on these variables.

2.4 Concluding Comments

Of the various sub-studies conducted and reported in the five progress reports, illustrative (but by no means all) sedimentological, modeling and ecological investigations are reproduced, partly or wholly, as appendices to this report as a mean of general information. Note that these studies formed a partial basis for the final development of the management recommendations, and should on no account be construed as the sole basis for the final development, in which other studies conducted within this project, as well as other projects plus experience elsewhere, were also considered.

Appendix B considers "bottom mapping" of the Jupiter Inlet/Loxahatchee River region of interest, while Appendix C discusses issues related to the littoral drift regime and sediment (sand) budget relevant to the study.

As an illustration of the basis for the development of quantitative decision matrices used as guides in evaluating the various technical issues, Appendix D is included to demonstrate the procedure by which physical model results related to various options for jetty modifications were initially examined using test data. The outcome, in the way of a decision matrix, was supplemented with other information, such as experiences elsewhere, as well as what would be practical at Jupiter Inlet, to develop the final management plan options.

In Appendix E, the manner in which one suite of mathematical models was used to examine the effects of jetty and other modifications on tides, currents and sedimentation is illustrated.

In Appendix F, an ecological assessment of the study region with reference to such factors as seagrass, mangroves, rocky outcrops and sea turtle nesting, are discussed. An attempt is made in Appendix G to propose some design criteria for sea turtle nesting beaches.

The engineering actions, per management plan, and their physical and ecological impacts are summarized in Chapter 3 next.

3. SUMMARY OF ENGINEERING ACTIONS AND THEIR PHYSICAL AND ECOLOGICAL IMPACTS

3.1 Preamble

The considered actions, including the so-called no new action option, and associated impact investigations, led to the development of a matrix which formed the rationale for making the choices for the recommended management plan. The matrix is presented in Table 3.1 (see also Fig. 2.6), and the 130 impact "boxes" in the matrix, identified by row and column numbers, are noted in what follows.

3.2 Actions and Impacts

I. No New Action

1. Present Protocol

1.1. Impact on Navigation Access

The present practice of trap dredging appears to be adequate to meet the requirements of maintaining a navigation channel in the interior (Region 2). The presence of the ebb shoal restricts traffic to some extent, and the Coast Guard cautions against navigation through this inlet. However, experienced navigators familiar with the inlet have been able to well negotiate through the natural passage (in Region 3) that typically occurs between the deeper offshore waters and the jetties. Navigation depths in the aquatic preserve (Region 3) are likely to continue to decrease, although at a very slow rate.

1.2. Impact on Navigation Safety

The frequency of accidents reported, primarily in the region offshore of the jetties, is unlikely to reduce. In 1988 for example, five accidents, including one alcohol related were reported. Total damage was around $25,000. Note however, that according to the Coast Guard, only about 10% of the accidents are typically reported.

1.3. Impact on Beach Erosion

The retention time of sand placed on the south beach is relatively short such that sand placed there moves elsewhere at a rate that is faster than desired, and the public shore facilities are periodically threatened. This concern, and the concern for a breakthrough of the barrier at the point of maximum shoreline erosion remain, since this stretch of the shoreline is unlikely to build up (accrete) without a different set of engineering actions.

1.4. Impact on Interior Sedimentation

Sedimentation problem in Region 2 is reasonably well managed, although the marinas are not well served by the present dredging practice. They are required to finance their own dredging, because the depths at many boat slips tend to reduce and make these slips commercially useless. The problem there

Table 3.1: Considered actions and impacts.

ACTIONS		IMPACTS				
CATEGORY	SUB-CATEGORY	NAVIGATION ACCESS	NAVIGATION SAFETY	BEACH EROSION	INTERIOR SEDIMENTATION	ECOLOGICAL CONSIDERATIONS
I. No New Action	1. Present Protocol	1.1	1.2	1.3	1.4	1.5
II. Trap Dredging	2. Volumetric Rate	2.1	2.2	2.3	2.4	2.5
	3. Frequency	3.1	3.2	3.3	3.4	3.5
	4. Trap Dimensions	4.1	4.2	4.3	4.4	4.5
III. South Beach Nourishment	5. Volumetric Rate	5.1	5.2	5.3	5.4	5.5
	6. Frequency	6.1	6.2	6.3	6.4	6.5
	7. Placement Timing	7.1	7.2	7.3	7.4	7.5
	8. Placement Location	8.1	8.2	8.3	8.4	8.5
IV. North Jetty	9. Height	9.1	9.2	9.3	9.4	9.5
	10. Length	10.1	10.2	10.3	10.4	10.5
V. South Jetty	11. Height	11.1	11.2	11.3	11.4	11.5
	12. Length	12.1	12.2	12.3	12.4	12.5
VI. Navigational Considerations	13. Lighthouse	13.1	13.2	13.3	13.4	13.5
	14. Channel Markers	14.1	14.2	14.3	14.4	14.5
	15. Boat Speed	15.1	15.2	15.3	15.4	15.5
VII. Outer Channel	16. Eastward Channel	16.1	16.2	16.3	16.4	16.5
	17. Southeastward Channel	17.1	17.2	17.3	17.4	17.5
VIII. Offshore Dredging	18. Volumetric Rate	18.1	18.2	18.3	18.4	18.5
	19. Frequency	19.1	19.2	19.3	19.4	19.5
	20. Location	20.1	20.2	20.3	20.4	20.5
	21. Placement	21.1	21.2	21.3	21.4	21.5
IX. Interior Trap Dredging	22. Location	22.1	22.2	22.3	22.4	22.5
	23. Dimensions	23.1	23.2	23.3	23.4	23.5
	24. Volumetric Rate	24.1	24.2	24.3	24.4	24.5
	25. Frequency	25.1	25.2	25.3	25.4	25.5
	26. Material Placement	26.1	26.2	26.3	26.4	26.5

appears to be dual; one is their naturally unfavorable site which is prone to sedimentation. The other is that finer fractions of incoming sand continue to be transported upriver beyond the JID trap. Sedimentation in Region 3 will continue, but the present rate of influx past the FECRR bridge, about 1,000 yd^3 (800 m^3), possibly as high as 2,400 yd^3 (1,800 m^3) is considerably lower than the rate of influx about two decades ago. In due course the depths in Region 3 may become unacceptably shallow for navigation.

1.5. Ecological Considerations

The present practices of sand disposal on the south beach require diligent transplanting of sea turtle nests following beach nourishment. This involved about 8 nests during 1990 nourishment activities. Risks to turtles that nest in new material placed immediately south of the south jetty include the possibility of nest washout from wave reflection off the south jetty during storms. Moreover, steep erosional scarps sometimes form just south of the jetty that may discourage some turtles from nesting.

Present practices of dredging and nourishment just south of the south beach may periodically bury rocks that become exposed from intermittent beach erosion immediately south of the south jetty. These rocks would not be exposed were it not for the considerable erosion and they do not remain exposed long enough to develop diverse biological communities. The exposed rocks of Carlin Park and elsewhere more than 1 km (0.6 mile) from the inlet are unlikely to be measurably affected by current practices.

The interior sedimentation now occurring may in due course increase the area suitable for seagrasses by increasing the total area between low water and the critical depth for light penetration. Likewise, the area suitable for mangroves may increase along interior shores that receive sediments. The process of stabilizing interior shoals may be enhanced by planting seagrasses and mangroves on some shoals. Unfortunately, salinity and other water quality conditions may fluctuate too drastically over shoals west of the railroad bridge to allow the full development of seagrass beds. This may not be as much of a problem for mangroves, however, which may become established despite fluctuations in water quality.

II. Trap Dredging

2. Volumetric Rate of Dredging

2.1. Impact on Navigation Access

A larger dredging rate (e.g. a minimum of 60,000 yd^3/yr vs. 45,000 yd^3/yr; or 45,900 m^3/yr vs. 34,400 m^3/yr) will generally require a longer operation period for the dredging equipment. Channel access may therefore be slightly restricted for somewhat longer time periods during dredge operation. A larger rate may also imply a larger trap size (see Section 4.1), in which case access may be improved slightly provided uneven shoaling does not occur.

2.2. Impact on Navigation Safety

Effects are similar to those on navigation access. Larger dredging rates may reduce safety slightly if dredging equipment is required to operate in channel for longer time periods. Associated larger trap sizes will tend to improve access.

2.3. Impact on Beach Erosion

Increases in the dredging rate itself are not expected to directly affect beach erosion. However they do imply larger nourishment rates, which would tend to decrease erosion effects (Section 5.3; also Harris, 1991). Reduction or absence of trap dredging would tend to reduce beach erosion since more sand would tend to bypass the system naturally, possibly at the expense, of course, of a navigable channel.

2.4. Impact on Interior Sedimentation

Increases in the dredging rate, particularly since they imply an increase in trap size (Section 4.4), are expected to reduce interior sedimentation, since more sand is trapped at the inlet mouth. This assumes that sand influx from the system boundaries is not changed by other actions.

2.5. Ecological Considerations

The impacts from dredging at Jupiter, Florida pertain primarily to volume of material dredged per dredging event, trap location, dredging frequency, and material disposal. The type of material removed from the trap *per se* is not presently an environmental issue since it consists of unstable sand of very low organic content and limited ecological production, diversity, or habitat value. Increasing the volume from, say, 43,000 yd^3/y (a mean value based on earlier years of dredging) to 60,000 yd^3/y (33,000 m^3/y to 46,000 m^3/y) is unlikely to create an issue involving the material being dredged as long as it continues to be unstable sand suitable for beach nourishment and is collected from within defined trap boundaries.

Death of biota from entrainment in the dredge is possible, including death of sea turtles. Increasing the volume dredged or frequency may increase the opportunity for entrainment of biota. However, since the material being dredged is itself neither biologically rich nor an attractive habitat for fragile organisms, significant entrainment may be limited to the happenstance entrainment of a few of the organisms passing through the inlet during dredging. Dredged material could be monitored to assess the significance of death through entrainment.

Increasing the volume of dredging will necessitate either more frequent dredging or greater volumes dredged per event. Larger dredges -- perhaps associated with higher volume events -- are likely to entrain more and larger biota. Furthermore, high volume-per-event dredging suspends more material in the vicinity of the dredge and creates a larger sediment plume, but does so less frequently than lower volume-per-event dredging.

Nevertheless, with high volume events, the plume of suspended sediment is more likely to reach sensitive habitat. Sediment suspended in the water reduces light penetration to submerged surfaces, such as submerged rocks and seagrass beds in the vicinity of the dredge. Light reduction may reduce primary productivity of attached algae and seagrasses for the period of dredging. Subsequent sedimentation of suspended materials may occur on the sedentary animals and plants living on submerged rock or seagrass beds that are reached by the sediment plume.

Sediment screens around the dredge should reduce any impact from sediment plumes. If sediment screens are used, impacts on seagrass beds and submerged rocks in the vicinity of the dredging are not likely to be a significant addition to the natural fluctuation of suspended sediments in the vicinity of the trap.

3. Frequency of Dredging

3.1. Impact on Navigation Access

Increases in the trap dredging frequency (e.g. from once/two years to once/year to twice/yr to semi-continuous) will, in general, tend to improve navigational access by constantly inhibiting the growth of shoaling regions to restrictive dimensions. However, high-frequency dredging operations (i.e. semi-continuous) will also impose certain access restrictions since the dredging equipment will be in place for the majority (or the entirety) of the operational year.

Provided a cost effective fluidization system can be installed in the trap, a continuous, or "as needed" sand transfer operation can be achieved. Presently such a system is not available, but ongoing experiments may lead to a commercially available system in five or six years.

3.2. Impact on Navigation Safety

Effects are similar to those in Section 3.1, although are expected to be only slight. Increased frequency may promote safety minimally by reducing shoaling, with the drawback of a potentially near-permanent obstruction during semi-continuous operations.

3.3. Impact on Beach Erosion

Increasing frequency tends to reduce south beach erosion only though the nourishment process (Section 5.3). Otherwise effects are expected to be minimal. Reduction in frequency may promote more natural bypassing (at the expense of increased shoaling and reduced navigational access).

3.4. Impact on Interior Sedimentation

Although the total annual rate is more significant in reducing interior sedimentation, increased dredging frequency will, in general, aid in this process by providing a buffer against longer term variability in shoaling rates.

3.5. Ecological Considerations

The frequency, intensity, and style of dredging are inter-related. Ecological impacts relate primarily to the volume of material dredged per event as outlined in Section 2.5. Infrequent dredging will necessarily involve more volume per event. This may require longer event durations and heavier equipment. At the other extreme, nearly continuous dredging requires a sand pump and fluidizer bed, but the disturbance and volumes moved at any one time are much lower. Continuous sand pumping will likely minimize local ecological impact. Unlike intermittent dredging, continuous pumping does not cause a sudden perturbation of the area that requires a period of recovery. Moreover, entrainment of passing biota is unlikely in a sand fluidizer system and sediment plumes at the dredging site may be all but eliminated if fluidized sand is pumped out from below.

4. Trap Dimensions

4.1. Impact on Navigation Access

Two trap sizes are proposed: 1) a length of approximately 1,020 ft (310 m) and width of roughly 220 ft (65 m); or 2) a larger trap with a length extension of 1,120 ft (340 m) and a width of 270 ft (80 m). Access will in general be improved with the larger trap since deeper conditions will prevail for a longer time period. Although the projected filling rates are estimated to be 20% higher than existing conditions for the larger trap, but only 5% higher than existing for the smaller trap, this difference is accounted for by the trap size.

4.2. Impact on Navigation Safety

Effects are similar to those on navigation access. A larger trap with deeper conditions will tend to reduce shoaling and improve safety, although this is not likely to be a major effect.

4.3. Impact on Beach Erosion

Increased trap size implies a larger nourishment rate (Section 5.3) which will tend to reduce erosion. Aside from this, the trap size will have little direct effect on beach erosion.

4.4. Impact on Interior Sedimentation

An increase in trap size will, in general trap more sand at the inlet mouth and thus reduce interior sedimentation. Sediment modelling simulations indicate that the larger trap configuration will reduce the net sediment flux past the FECRR bridge by around 23% over existing bathymetry. The smaller trap size will only reduce the net flux by around 4%.

4.5. Ecological Considerations

Increasing the trap dimensions is expected to have little impact by itself. This assumes that the type of material within the new dimensions is unstable sand, suitable for beach nourishment, that no rock must be removed by blasting to achieve these dimensions, and that the tidal prism does not change after dredging the larger trap.

The tidal prism controls such aspects as water level, tidal range, current, and salt transport. Changes in the tidal prism may cause changes in intertidal and submerged vegetation, and in salt transport up the northwest fork of the Loxahatchee River. Results of the hydrodynamic model constructed as part of this study indicate no measurable impact of the present or proposed trap dimensions on salinity intrusion or tidal flows to the limits of the model boundaries.

At present the bottom in the western part of the trap is underlain by hard rock, which will have to be removed by way of capital dredging, a one-time operation lasting perhaps a few days. This removal in itself should create no significant ecological impacts.

III. South Beach Nourishment

5. Volumetric Rate of Nourishment

5.1. Impact on Navigation Access

The rate of annual sand placement on the south beach is not expected to significantly affect navigational access if considerations involving timing and location are observed (Sections 7.1, 8.1). Placement of large amounts of sand close to the south jetty may result in substantial sediment flux into the inlet as observed in tracer and drogue studies. Placement of sand under or prior to storm conditions may cause large initial profile adjustment with potential shoaling of the outer channel.

5.2. Impact on Navigation Safety

In the same manner as the discussion on navigational access, the rate of annual sand placement on the south beach is not expected to significantly affect navigational safety if considerations involving timing and location are observed (Sections 7.2, 8.2).

5.3. Impact on Beach Erosion

Erosion of the south beach is crucially dependent on the rate of beach nourishment. In general, larger nourishment rates will reduce beach erosion (subject of course to the availability of sand to be dredged, which may be altered by other actions such a jetty modifications). For example, a nourishment rate of 45,000 yd^3/yr (34,400 m^3/yr) has be shown to not offset the persistent sediment deficit and to generally permit critical levels of erosion to occur. A minimum rate of 60,000 yd^3/yr (46,000 m^3/yr) has been shown to make up the deficit and simulations indicate this rate will also provide an effective buffer against natural variability in the transport rates. Coordination of nourishment from the Army Corps of Engineers trap with material dredged from the JID trap will expedite the attainment of this larger rate.

5.4. Impact on Interior Sedimentation

Effects of the nourishment rate on interior sedimentation are expected to be minimal provided considerations of timing and location are observed (Sections 7.4, 8.4) in order to prevent conditions which promote a large influx of material into the inlet channel.

5.5. Ecological Considerations

An increase in nourishment volume, say from 43,000 yd^3/y to 60,000 yd^3/y (33,000 m^3/y to 46,000 m^3/y), would enhance the slope and stability of the beach profile for sea turtle nesting and for ecological communities of nearby beaches and dunes. Assuming all of this material can be placed sufficiently north of the nearshore rocky outcroppings at Carlin Park, impact of this added sand to rocky outcroppings should be low, unless storms redistribute some of this sand over these rocks (see Section 7.5).

6. Frequency of Nourishment

6.1. Impact on Navigational Access

No significant effects are expected provided considerations of timing and location are observed (Sections 7.1 and 8.1), particularly for the case of near-continuous bypassing, if and when this protocol is undertaken.

6.2. Impact on Navigational Safety

No significant effects are expected provided considerations of timing and location are observed (Sections 7.2 and 8.2), particularly for the case of near-continuous bypassing, if and when this protocol is undertaken.

6.3. Impact on Beach Erosion

The effect of nourishment frequency on beach erosion is connected with the issue of nourishment timing and is particularly significant in the context of the natural variability in the longshore transport. Highly infrequent nourishment (i.e. once/two years) exposes the beach to greater risk of possible successive large transport years with subsequently greater erosion. Increasing the frequency of dredging reduces such risk. Semi-continuous dredging minimizes such risk, and also affords the flexibility of modifying bypassing rates to accommodate the natural variability in the transport conditions.

Although the Corps' dredging and sand pumping operations are independent of those of JID, coordination between the two dredging operations so as to actually effect a twice per year pumping needs to be considered. Given the May-October non-pumping window during peak sea turtle nesting season, pumping by JID in April (around the usual time chosen by JID in the past) and Corps in November (often the time chosen by the Corps in the past) has potential advantages for retention of the beach sand. Firstly, pumping sand by JID and the Corps at the same time, e.g. in April, may amount to rapid rate of erosion of excessively placed sand at one time. Secondly, Corps pumping in November would serve as a feeder beach, supplying sand to the areas further south without the high risk of re-transport of sand into the inlet, since the wave then are from the northeast.

6.4. Impact on Interior Sedimentation

Effects of the nourishment frequency on interior sedimentation are expected to be minimal provided considerations of timing and location are observed (Sections 7.4, 8.4) to prevent a large influx of material into the inlet channel, particularly for the case of near-continuous bypassing.

6.5. Ecological Considerations

As with dredging (Section 2.5), nourishment events of lower frequency will usually involve more volume per event, a greater perturbation of the beach, larger sediment plumes, and longer ecological recovery time. One or two events per year might have less impact than one event every two years, though many of the benefits of increasing nourishment frequency probably don't accrue until nearly-continuous or at least twice per year sand pumping is achieved. Nearly-continuous sand pumping involves much smaller disturbances and volumes moved at any one time. Such pumping will likely minimize local ecological impact.

It is unclear how nesting sea turtles will respond to continuous sand pumping, however. If the effects of piping sand to the beach are subtle (sound is within background frequencies and amplitudes, turbidity plumes are within background turbidities), impact on sea turtle behavior may be negligible. Careful monitoring of sea turtle reactions may be required, but the ecological benefits of sand pumping in providing stable, suitable beach profiles for nesting may offset any small effects of pumping activities during the nesting season. It may be necessary to turn off continuous pumping during the peak egg-laying season (May through August). Even so, continuous pumping may be advantageous for appropriate beach profiling prior to the nesting season.

7. Placement Timing

7.1. Impact on Navigation Access

Placement of large quantities of sand on the beach near the south jetty during or just prior to periods of large northerly transport may result in significant amounts of sediment flux into the entrance channel. Similarly, placement of large amounts of sand during or just prior to major storm events may result in large amounts of erosion or large scale profile adjustment with potential shifts in the offshore channel as well.

7.2. Impact on Navigation Safety

Effects are similar to those on navigational access. Safety may be impacted by entrance shoaling due to sediment influx following placement during intense northerly transport (particularly near south jetty), or by offshore channel shifting due to sediment placement during or before storm events.

7.3. Impact on Beach Erosion

Timing of nourishment significantly effects shoreline evolution, and is mitigated by the turtle nesting window (May through October) during which placement of dredged material on the south beach is not permitted. Placement after the window will subject the nourished material immediately to winter storms with subsequent large-scale profile adjustment, and has been shown to result in small summer beach volumes. Nourishment prior to the window is seen to result in large summer beach volumes; winter storms then act on a beach which has already achieved a large degree of profile equilibrium and less erosion would then tend to occur.

A possibility exists for selecting two rather than a single sand placement time. Two choices include pre-May (e.g. April) and post-October (e.g. November) periods. While sand placed during the latter period will in general have a lower retention time than the former, a more continuous, and therefore more desirable, sand pumping protocol would be established. In consonance with past practices, the JID trap would be utilized in April, and the Corps trap in November. In this way, there would be a lower pile up of sand on the beach; hence lesser amount would be transported into the inlet following the April placement. The November placement would serve as a feeder beach for the beaches further south of the inlet. Due to the direction of wave action, this sand would not typically move into the inlet.

7.4. Impact on Interior Sedimentation

Timing effects are significant to interior sedimentation if large amounts of material are placed near the south jetty during summer conditions with northerly transport. Field studies have shown that substantial amounts of sediment can enter the inlet under such conditions, and may aggravate interior shoaling. Similar effects may occur if sand is placed near the south jetty during intense wave conditions which suspend large amounts of sand. Two placements per year, e.g. in April and in November, could reduce the influx of sediment as noted in Section 7.3.

7.5. Ecological Considerations

The main ecological consideration in the timing of beach nourishment is the sea turtle nesting season. A stable and gentle beach profile is needed prior to and throughout the nesting season. Furthermore, disturbance from nourishment activities must be minimized during the season. Peak egg-laying activity is from May through August, but earlier and later activity by some individuals is common. Eggs require roughly 2 months to hatch. To account for these factors, the U.S. Fish and Wildlife Service includes the period from March 1 through November 30 as the sea turtle nesting season in the vicinity of Jupiter Inlet.

8. Placement Location

8.1. Impact on Navigation Access

Options for locations of placed material include 1) immediately south of the south jetty, 2) roughly 1/4 mile (0.4 m) south of the south jetty, and 3) at multiple points spanning the above distance and extending downcoast. Navigational access will tend to be impacted most severely by placement close to the south jetty, particularly if the timing is such that conditions are most conducive for "leakage" of sand into the channel. If a continuous system is employed, monitoring of wave climate and transport to identify such conditions is essential to avoid the wasted effort of pumping sand which will tend to immediately re-enter the inlet. Dispersed placement may also impact outer channel access to a lesser degree, since less profile disequilibrium will exist and smaller initial fluctuations would be expected.

8.2. Impact on Navigation Safety

Effects are similar to those for navigational access. Safety may be impacted by channel shoaling resulting from placement of sand close to the south jetty. Concentrated placements of sand will cause a high degree of profile disequilibrium and initial shifting, with potential impact on the outer channel.

8.3. Impact on Beach Erosion

Placement of sand close to the south jetty in conjunction with summer transport conditions (i.e. placement prior to the turtle nesting window) will tend to increase beach erosion, since the sand is typically lost into the inlet channel. Placement further downcoast, although apparently "sacrificing" the beach immediately south of the jetty, will, in the case of pre-window timing, tend to reduce beach erosion since the sand replenishes the exposed sections of beach upon adjustment. A 10% increase in the retention time of placed sand may be achieved by a proper redesign of the presently followed placement plan. This placement configuration should <u>not</u>, however be considered with post-window timing since the winter storm conditions would tend to most severely impact the unprotected beach immediately south of the jetty, resulting in critical erosion. Thus if the Corps is encouraged to place its material in November, that material should be placed within the first around 800 ft (240 m) of the south jetty, in accordance with the present practice.

In general, spatially and temporally more dispersed placement than at present will tend to reduce erosion effects over concentrated placement, since initial profile adjustment losses will be minimized.

8.4. Impact on Interior Sedimentation

Interior sedimentation will tend to be increased by scenarios which involve placement of sand close to the south jetty. This is particularly true for continuous bypassing systems, in which failure to monitor wave conditions to identify circumstances which encourage sediment influx (i.e. northward transport) will tend to increase interior shoaling. Nourishment further downdrift will tend to inhibit dredged sand re-entering the inlet. Dispersed placement will also reduce this influx by reducing initial profile shifts, although this effect will be minimal for placement at any substantial distance from the south jetty.

8.5. Ecological Considerations

Beach Profile: From the standpoint of sea turtle nesting, the nearshore and onshore beach profile should be maintained with a slope similar to that of nearby unimpacted areas where sea turtles nest. This is roughly 1 unit of rise for every 10 to 20 units of run in the zone from mean sea level to 100 ft (30 m) toward land. Placement of material within these limits prior to the nesting season will enhance the beach as a sea turtle nesting area if neither the profile changes (develops steep scarps) nor the beach erodes during the nesting period.

Placing the material close to the swash zone at several points along the beach (rather than high on the beach at only one point) uses more of the natural surf energy rather than heavy machinery to distribute the sand along the beach. This may improve the development of a natural beach profile composed of natural sand-grain sizes. By reducing the need for heavy sand-moving and tilling equipment on the beach, this approach should also minimize the disturbance to the ecological community of the intertidal beach, including sea turtle nests, should any have been laid prior to nourishment.

Longshore Placement: Naturally, from the standpoint of offsetting beach erosion, placing beach nourishment material just south of the south jetty is logical. After nourishment, however, wave refraction, diffraction and reflection off the south jetty may rapidly alter the post-nourishment beach profile and cause sudden sand erosion. Since beach nourishment can make the profile attractive to nesting sea turtles, the beach immediately south of the south jetty (approximately the first tenth of a mile or 160 m) may become an "attractive nuisance" for nesting sea turtles. Nests laid in this area may wash out before they hatch. Nests laid here should be relocated or the area should be effectively fenced to keep sea turtles from nesting in this short stretch of beach. The construction of a "dog-leg" or "hooked" extension of the south jetty may obviate some of this concern, however (see Section 12.5).

Nearshore rocky outcroppings appear at Carlin Park, 3/4 mile (1.2 km) to the south of Jupiter Inlet. To protect these rocks, beach nourishment material should be placed between the south jetty and sufficiently north of the rocks to avoid directly covering them with sediment from nourishment operations. If the amount of material placed is greatest nearer the south jetty, and tapers off toward the Carlin Park rocks, impact on these rocks should be minimized to near zero. However, it is always possible that a storm may shift sand over these rocks at some future date, a recurring natural process.

IV. North Jetty

9. Height of North Jetty

9.1. Impact on Navigation Access

The seaward end of the concrete-capped north jetty has a step-like structure; section I, the seaward-most, 275 ft (84 m) long section has an elevation of 6.9 ft (2.1 m) with respect to NGVD. The next landward segment, section II is 175 ft (53 m) long and is 2 ft (0.6 m) higher. Landward of section II is the remainder of the jetty, section III, which is 2 ft (0.6 m) higher than section II. This jetty has served well in maintaining navigational access to the inlet, but during times of storm surge water and sand are transported over the jetty, particularly sections I and II, which causes sedimentation in the inlet interior. Raising these two sections would mitigate this problem. For example, in accordance with test results from the physical model study, section I may be raised by 3 ft (0.9 m) and the effect monitored. Further, section II may be raised by 3 ft (0.9 m) as well. These modifications are however not likely to impact navigational access.

9.2. Impact on Navigation Safety

Raising sections of the north jetty will not measurably impact safety of navigation since navigation through this inlet is feasible only under non-extreme conditions.

9.3. Impact on Beach Erosion

Raising sections of the north jetty may have a beneficial effect with respect to beach erosion on the south side, as sand bypassing may increase during storm conditions.

9.4. Impact on Interior Sedimentation

The purpose of raising section of the north jetty is to reduce sand influx. The very roughly estimated 3% reduction by raising section I and an additional 5% by raising section II would amount to a reduction on the order of 5,000 yd^3 (3,800 m^3) per year. This number is believed to be conservative and the actual saving may be higher. Such a reduction would have two advantages: 1) it would mean a reduction in the cost of dredging of the JID trap (as well as the Corps of Engineers trap), and 2) it would reduce the problem of sedimentation in the marina area, which is presently estimated to be on the order of 0.5 ft (0.15 m) per year.

9.5. Ecological Considerations

Increasing the height of the north jetty by 3 ft (0.9 m) could have positive ecological benefits if by blocking sand entry to the inlet during periods of higher water, sand bypassing actually increases. Greater sand bypassing would reduce the volume of dredging necessary inside the inlet and would reduce the necessity to actively nourish the beach. If, however, the effect of blocking the sand during higher water levels is simply to build the ebb shoal, dredging will still be required to replace eroded sand along the south beach. If such is the case, the environmental impact on the south beach will be the same as without the increased jetty height, and some of the dredging impact may simply be shifted from the existing traps inside the inlet to the ebb shoal or elsewhere (perhaps to an area where impacts have not yet been evaluated).

10. Length of North Jetty

10.1. Impact on Navigation Access

Physical model study results indicate that the possibilities of extending the north jetty are along a curvature in the southeastern direction. The purpose of such an extension would be, firstly to improve navigation by increasing the sheltering effect of the jetty against wave action, and secondly to reduce sediment influx into the inlet by improving bypassing around the inlet. Model results suggest that for the sheltering effect to be effective in the channel, the jetty extension would have to be well in excess of 200 ft (61 m). A 400 ft (122 m) extension would materially improve navigational accessibility. The likely amount of reduction of sand influx, if at all in the long run, is uncertain.

10.2. Impact on Navigation Safety

Extending the north jetty along a southeastward curvature by 400 ft (122 m), would be expected to impact navigational safety in a positive manner by measurably reducing the wave heights in the channel to less than one-half the present.

10.3. Impact on Beach Erosion

Extending the north jetty is likely to increase downdrift beach erosion adjacent to the south jetty by creating a "sand shadow", in spite of the fact that: 1) model results indicate an extension would increase the sheltering of the area immediately south of the south jetty, and 2) calculations suggest that there may be a slight (but perhaps statistically insignificant) reduction in sand influx into the inlet. The reason for the possibility of increased erosion immediately south of the south jetty is that north jetty extension would cause the littoral sand pathway to be diverted seaward, the extent of diversion being dependent on the length of the curved, southeastward extension of the jetty.

A length of extension greater than 50 ft (15 m) may result in a measurable increase in erosion. For a 400 ft (122 m) extension for example, the deficit of sand on the south beach, presently estimated to be on the order of 0.24×10^6 yd^3 (0.18×10^6 m^3), could increase to as much as 0.9×10^6 yd^3 (0.69×10^6 m^3). Since however the fraction of the net littoral sand transported into the inlet per unit time may also decrease (certainly not increase), this added erosion may pose a sand management problem. At Boca Raton Inlet for example, ebb shoal dredging has been carried out to mitigate increased downdrift beach erosion caused by a 180 ft (55 m) extension of the north jetty.

Given this possibility, caution is warranted in any plan to lengthen the north jetty without additional measures including the installation of a sand bypassing system for transferring sand on as needed basis. Such a system could include a fixed bypassing plant such as at Palm Beach inlet (however one with an improved mechanical and aesthetic design and efficiency), or a fluidization system. A system of the latter type is currently being tested at Oceanside Harbor in California. The technical viability of this system, proven theoretically and in laboratory experiments, remains to be checked thoroughly in the field. Even if proven in the field, a commercially available system is unlikely to be available over the next one-half decade.

10.4. Impact on Interior Sedimentation

Calculations suggest that, a 400 ft (122 m) extension on the north jetty would initially reduce the influx of sand in the inlet by about 25%. It is unclear if this advantage would be retained however, after the shoreline north of the north jetty eventually achieves a new equilibrium configuration. Experience elsewhere suggests that in fact the eventual reduction in sand influx, in the absence of any active bypassing system, may not be significant.

10.5. Ecological Considerations

Although a safer navigation channel will result and some sand may be prevented from entering the inlet (obviating some dredging), increasing the length of the north jetty by any amount in excess of 50 ft (15 m) will measurably exacerbate the beach erosion south of the south jetty, even if natural sand bypassing is improved by this jetty modification. Longer jetties will send by-passed sand further to the south before it comes ashore to build beaches. Calculations suggest that the point where the sand pathway reattaches itself to the shore would move southward such that the distance between the south jetty and the reattachment point would increase by about 25% over the present for a 400 ft (122 m) extension. Hence, maintenance of the south beach near the south jetty will require more movement of sand by continuous pumping or heavy machinery. The impacts of beach nourishment have been covered in Sections 5.5, 6.5, 7.5, and 8.5.

As noted, longer extensions of the north jetty will push bypassed sand even further south and lengthen the eroding zone south of the south jetty. A 400 ft (122 m) extension of the north jetty could perhaps cause bypassed sand to cover the rocky outcroppings at Carlin Park 3/4 mile (1.2 km) to the south.

On the positive side, however, jetty extensions will provide some additional rocky substrate for the development of habitat similar to that provided by natural nearshore rocky outcroppings in the area. Presently many fishes and invertebrates use the rocks of the existing jetties as habitat. Additional habitat will likely result in additional use at Jupiter Inlet. The positive aspects of these additions, however, would accrue to the placement of many kinds of artificial reef structures offshore of Jupiter Inlet without the concomitant negative effects of beach erosion.

Another important consideration of jetty extension in general is the potential for impact on the tidal prism. The tidal prism controls such things as water level, tidal range, current, and salt transport. Changes in the tidal prism may cause changes in the location and productivity of intertidal and submerged vegetation, and changes in salt transport up the northwest fork of the Loxahatchee River. Results of the hydrodynamic model constructed as part of this study however indicate no measurable impact of considered jetty extensions on salinity intrusion or tidal flows to the limits of the model boundaries.

V. South Jetty

11. Height of South Jetty

11.1. Impact on Navigation Access

Raising the height of the south jetty, presently 5.5 ft (1.5 m) high with respect to NGVD, e.g. by 3 ft (0.9 m) as suggested by the physical model study, will not materially affect navigational access.

11.2. Impact on Navigation Safety

Raising the height of the south jetty, e.g. by 3 ft (0.9 m), will not measurably influence navigational safety.

11.3. Impact on Beach Erosion

Raising the height of the south jetty, e.g. by 3 ft (0.9 m), could somewhat reduce beach erosion immediately south of the jetty, as this would reduce the transport of sand over the jetty during significant storms. Field evidence however suggests that the transport of sand around the jetty which occurs over each flood tide is not insignificant, and that this transport around may be a greater contributor to beach erosion than transport over the jetty during storms. Via this mechanism the erosion is believed to be particularly significant when material dredged from the interior areas is placed on the south beach. Given these conditions, the efficacy of reducing beach erosion by sand transport into the interior by raising the jetty is likely to decrease rapidly with increasing height, and the added benefit of raising the jetty to a height greater than 3 ft (0.9 m) may be negligible. At this height, sand influx may reduce by about 2,000 yd^3 (1,500 m^3). This estimate is conservative and the actual reduction may be higher.

11.4. Impact on Interior Sedimentation

Comments made under Section 11.3 also hold in this case, namely that raising the south jetty by any height greater than e.g. 3 ft (0.9 m) may not measurably reduce the rate of interior sedimentation further.

11.5. Ecological Considerations

Increasing the height of the south jetty will have much the same ecological impact as increasing the height of the north jetty (see Section 9.5). By achieving its intended purpose of preventing overtopping of sand during periods of very high water, less trap dredging and beach nourishment may be required. Greater height, however, may increase wave reflection during periods of simultaneously very high water and high winds from the southeast. This may cause increased scour of the beach just south of the south jetty, thus exacerbating the present problem of unstable beach profiles just to the south of the south jetty during the sea turtle nesting season (see Section 7.5). Perhaps by using a gentle angle for the south sidewall of the jetty e.g. by riprap placement, this problem could be somewhat reduced.

12. Length of South Jetty

12.1. Impact on Navigation Access

Lengthening the south jetty, optimally by a 175 ft (53 m) "hooked" extension, and coupled with a 3 ft (0.9 m) rise is not expected to measurably alter navigational access, as long as this extension is either linear along the direction of the existing jetty, or in the southeastern "hooked" direction.

12.2. Impact on Navigation Safety

Lengthening the south jetty as noted in Section 12.1 is not likely to alter the present level of navigational safety.

12.3. Impact on Beach Erosion

Model results and related considerations suggest that, for example, up to 175 ft (53 m) extension of the south jetty as a southeastward dog-leg or hook would reduce erosion immediately south of the south jetty by enhancing the region sheltered against wave action, and by reducing the (sand-laden) water movement around the modified jetty, and promote retention of beach sand. Extensions greater than this length on the other may interrupt the littoral sand pathway which would diminish the overall beneficial effect of extension as noted, although experience at Baker's Haulover Inlet, where however the drift is much smaller, suggests that at appropriate locations considerably longer south jetty extensions can be very effective in retaining sand. In Fig. 2.2 the approximate position of the shoreline that would exist in the absence of the inlet is shown. Note that the north jetty protrudes much more into the ocean than the south jetty relative to the no-inlet shoreline. Thus as long as the south jetty remains "shorter" than the north jetty, the latter will predominantly determine the erosion deficit and shoreline orientation of the south beach by way of its "shadow" effect when the beach-eroding waves occur from the northeast.

12.4. Impact on Interior Sedimentation

By virtue of the type of beneficial extensions of the south jetty noted in Section 12.3, the same extensions would reduce sand influx into the inlet. The required annual dredging of the sand trap with a raised and extended south jetty could reduce by up to 10,000 yd^3 (7,700 m^3).

12.5. Ecological Considerations

Unlike lengthening the north jetty (see Section 10.5), lengthening the south jetty by 175 ft (53 m) should have overall positive ecological effects if these modifications achieve their intended purposes of reducing beach erosion and reducing sand flow into the inlet from the south. These benefits accrue from the more stable beach profile that should result just south of the south jetty, the reduced necessity for dredging traps inside the inlet, and the reduced need for beach nourishment. The impacts from dredging are covered in Sections 2.5, 3.5, and 4.5. The impacts of beach nourishment have been covered in Sections 5.5, 6.5, 7.5, and 8.5. The value to nesting turtles of stable beach profiles immediately south of the south jetty have been covered in Section 8.5. In addition, as with the north jetty extension, extension of the south jetty will provide more substrate for ecological development of rocky habitat.

Impact from the suggested south jetty modifications on existing rocky outcroppings or ecological productivity and diversity in the Loxahatchee River is unlikely. Results of the hydrodynamic model constructed as part of this study indicate no measurable impact (less than 0.5 ppt change in either direction) of proposed jetty extensions on salinity intrusion or tidal flows to the limits of the model boundaries.

VI. Navigational Considerations

13. Lighthouse and Jetty Beacons

13.1. Impact on Navigation Access

The lighthouse (Fig. 2.4), although not managed by JID, occurs within the study area and serves to identify Jupiter from offshore. While it alone can not be used for navigation in the inlet area, its role to identify Jupiter Inlet as a navigational access is evident.

Addition of two beacons,on eat each tip of the jetties, in accordance with Coast Guard specifications, would improve navigation access (siting). See also Section 14.1.

13.2. Impact on Navigation Safety

The lighthouse is not a means to ensure navigational safety, which must be considered by other means. Beacons at jetty tips may not measurably improve navigation safety however, since a fair number of accidents appear to be occurring offshore of the jetties. See also Section 14.2.

13.3. Impact on Beach Erosion

The lighthouse has no tangible bearing on the problem of beach erosion. Same for beacons.

13.4. Impact on Interior Sedimentation

The lighthouse has no tangible impact on sedimentation in the interior region of the inlet. Same for beacons.

13.5. Ecological Considerations

Operation of the lighthouse has no known local ecological impact; however, somewhat wild speculation may include a possible effect on navigation by migrating animals into and out of the inlet. It is unknown how most migratory animals in the sea navigate. Sea turtles, for example, probably recognize beaches by their features, and they and other organisms may detect dissolved materials emanating from inlets. It is known that sea turtles can be discouraged by lights turning on and off directly on the beach as they come ashore to lay eggs. On the other hand, it is possible that sea turtles and other organisms (perhaps manatees) have come to recognize the coast of Florida from far offshore just as vessels do -- by noticing the pattern of lights at night along the coast. Failure to operate the Jupiter light may require a period of adjustment by sea turtles and other migratory animals that can detect the light.

Beacons on the jetties could conceivably disorient a small number of both adult and hatchling sea turtles that appear very near to the jetties. If lights are installed with appropriate consideration of the Florida Department of Natural Resources Sea Turtle Protection Plan guidelines for permanent lighting, this effect should be negligibly small and permissible.

14. Channel Markers

14.1. Impact on Navigation Access

At present all channel markers occur well within the inlet; there are no markers either at the seaward end of the inlet or in the offshore area. Note that this inlet has been designated by the Coast Guard to be hazardous to navigation. Therefore, any changes in the existing arrangement will to some extent be the management responsibility of JID. As noted in Section 13.1, If changes must be made, then it appears that marking the tips of the two jetties by beacons (one at each jetty) will be useful to navigators as identifiers of Jupiter Inlet. The beacons, per Coast Guard specifications, should be operated on a regular basis; they should not be programmed to operate as indicators of entrance accessibility, e.g. as related to weather and sea conditions.

14.2. Impact on Navigation Safety

Addition of beacons as entrance markers will not materially alter the present degree of navigational safety in the inlet area.

14.3. Impact on Beach Erosion

There is no tangible correlation between the installation of channel markers and beach erosion.

14.4. Impact on Interior Sedimentation

There is no tangible correlation between channel markers and the rate of sedimentation in the interior areas.

14.5. Ecological Considerations

The placement of simple markers to identify the channel should have minimal ecological impact. If the markers include anti-fouling treatments, a small associated impact can be expected on sensitive organisms, however this would be a minuscule addition to the total surface area covered by anti-fouling paints in the vicinity of Jupiter Inlet. Markers without anti-fouling treatments will add to the substrate for rocky-shore ecological communities, but again this would be a tiny additional effect.

15. Boat Speed

15.1. Impact on Navigation Access

The issue of boat speed regulation is not directly associated with access to navigation.

15.2. Impact on Navigation Safety

Regulation of boat speeds is obviously linked to navigational safety. Regulation of boat speed especially in the seaward area of the inlet is unquestionably important to improvement of safety.

15.3. Impact on Beach Erosion

There is no significant association between boat speed and beach erosion at this inlet. However, wakes from boats are known to increase damage to poorly designed bulkheads and cause localized beach erosion. This issue was examined in the study by the University of Florida in 1984 (Buckingham, 1984). Bulkheads west of the Jupiter Inlet Colony club house as well as the Dubois Park beach are vulnerable to boat wakes. In addition, boat wakes are believed to cause bank erosion, e.g. in the vicinity of the lighthouse.

15.4. Impact on Interior Sedimentation

The role of boats in causing bank erosion has been established in this study in an indirect way. Regulating boat speed in the interior waters is considered to be important for example in reducing navigable depths the wider region of the Loxahatchee River estuary west of FECRR bridge (Region 3).

15.5. Ecological Considerations

Reducing boat speeds would have positive benefits to the manatees that use the inlet as a passageway. Throughout coastal Florida, many manatees are killed or injured by boats each year. It is possible that other organisms also are harmed by fast-moving boats, including sea turtles. By reducing boat speeds through the inlet, the potential for such injuries and deaths in Jupiter Inlet will be reduced. Idle speeds would be best, though any reduction in boat speed would have some positive effect.

VII. Outer Channel

16. Eastward Channel

16.1. Impact on Navigation Access

The 10 ft (3 m) deep eastward outer channel through the ebb shoal (Fig. 3.1) should enable better navigational access to vessels that require this much minimum depth and direction of passage. At Jupiter Inlet even the largest vessels presently plying the waters do not require such a deep channel, except where the ebb shoal restricts navigation, particularly during lower stages of tide. In such cases this channel will open up a new passage between the ocean and the inlet. The utility of such a channel will also depend on the future traffic growth including vessel draft.

16.2. Impact on Navigation Safety

The eastward channel should improve the navigational safety of vessels presently negotiating the inlet and expectedly reduce the chances of accidents which reportedly occur due to shallow depths over the ebb shoal.

16.3. Impact on Beach Erosion

Dredging of the eastward outer channel should be on the order of 20,000 yd^3 to 40,000 yd^3 (15,300 m^3 to 30,600 m^3) from the shallow portions of the channel. Maintenance dredging frequency is likely to be high; with dredging once a year in spring (e.g. in April or May), the channel may maintain itself through summer, but will undoubtedly fill up during the fall and winter months. The rate of infilling could be higher that of a southeastward outer channel. Dredging of the ebb shoal for this purpose will interrupt the littoral drift to some extent. Regular dredging (e.g. every April or May) and placement of the dredged material on the downdrift beach is a feasible option for maintaining fair weather (summer) access but the consequences of this operation to beach stability must be monitored, and the plan to maintain this channel discontinued if adverse effects with respect to shoreline stability are reported. The channel is not likely to increase wave action at the beach in any drastic way, and the net sand loss may not occur on an annual basis, unless for example dredging is also carried out during fall or winter.

16.4. Impact on Interior Sedimentation

The eastward outer channel is not likely to impact sedimentation in the interior of the inlet in any measurable way.

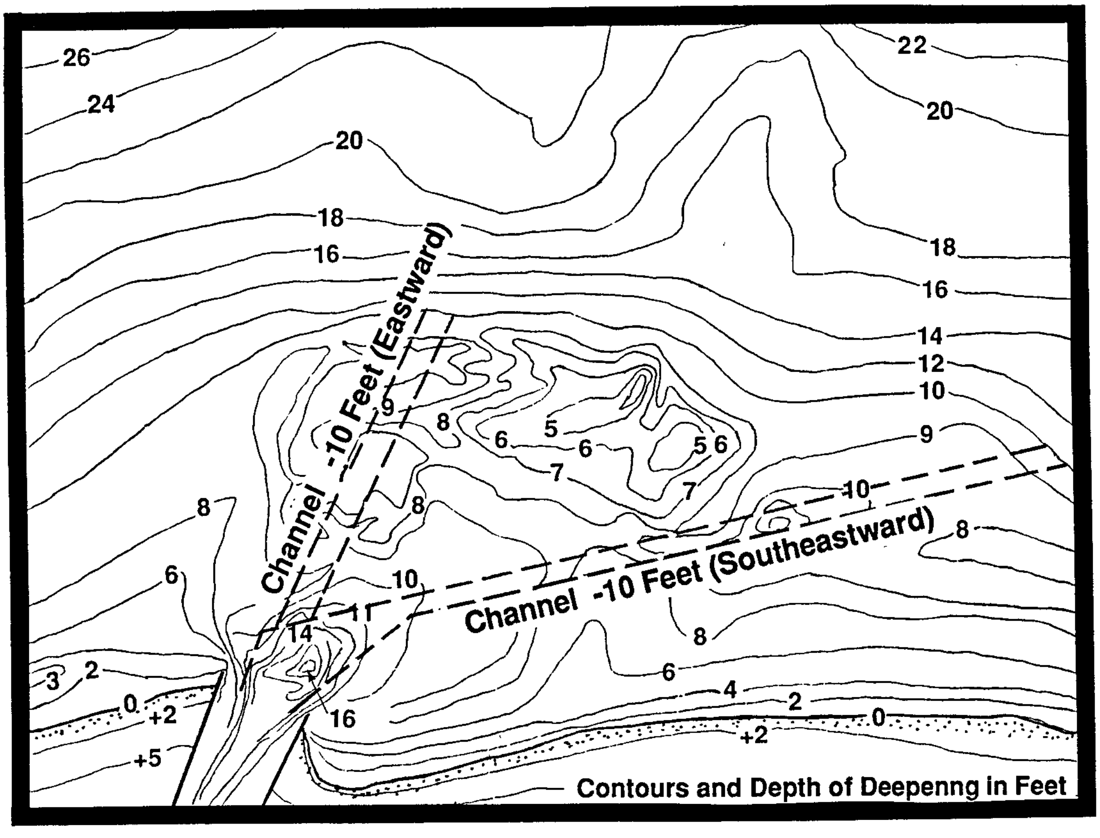


Figure 3.1. Inlet ebb shoal and offshore channel options.

16.5. Ecological Considerations

An eastward channel through the ebb shoal area should have minimal impact on nearshore rocky outcroppings, and sea turtle nesting, assuming initial and maintenance dredging do not occur during the turtle nesting season. If the channel affects the tidal prism, salinity intrusion and the ecological production and diversity of submerged and intertidal ecosystems in the Loxahatchee River estuary may be affected. However, channel dredging through the ebb shoal outside the inlet jetties is unlikely to measurably impact the tidal prism.

The process of dredging and maintaining such a channel will have the impacts of dredging and placement of material in proportion to the amount of dredging required. These impacts have been described in the relevant sections of this report.

17. Southeastward Channel

17.1. Impact on Navigation Access

A 10 ft (3 m) deep outer southeastward channel (Fig. 3.1) will not provide a new access route to the inlet as it is designed to be along the orientation of the present access. Dredging will be necessary only in certain portions where the littoral sand attempts to cross the channel. Dredging this access should not disturb the wreckage of an ancient vessel which is believed to be strewn along a path which is close to this channel.

17.2. Impact on Navigation Safety

Dredging out those areas (ebb shoal) where shoaling normally occurs should improve navigational safety, but the improvement may not be as significant as that at the eastward channel, since along most of the southeastward channel length the depths are adequate for navigation for presently negotiating vessels.

17.3. Impact on Beach Erosion

Capital dredging is likely to be around 30,000 yd^3 (23,000 m^3). This amount could be greater than that for the eastward channel. It is important to note, however, that the mass of sediment to be dredged is less unevenly distributed in the southeastward channel than in the eastward channel; in the latter case the smaller amount is concentrated over a smaller area and hence technically provides a greater barrier to navigation than in the case of the southeastward channel. As in the case of the eastward channel noted in Section 16.3, a summer channel can be maintained by dredging every April or May. The presence of this channel is not likely to alter wave action at along the affected beach south of the inlet, but the infilling rate of the channel may not be less than that of the eastward channel; hence no advantage may be gained during the fall and winter months. The presence of the channel coupled with regular dredging and placement of the dredged material on the south beach will increase shoreline oscillations but may not result in a net erosion on an annual basis, unless dredging is also carried out in fall or winter.

17.4. Impact on Interior Sedimentation

The southeastward channel is not likely to impact sedimentation in the interior of the inlet in any measurable way.

17.5. Ecological Considerations

While no channel would have the least ecological impact, because a southeastward channel will follow a natural flow pattern, it may require significantly less initial and maintenance dredging than an eastern channel, even though calculations do not point to any significant reductions. As with an eastward channel (see Section 16.5), a southeastward channel is not expected to measurably alter the tidal prism, and hence should not impact the ecological production and diversity in the interior of the estuary.

VIII. Offshore Dredging

18. Volumetric Rate of Dredging

18.1. Impact on Navigation Access

Sediment budget calculations suggest that the presence of the inlet results in some "loss" of sand in the sense that the net volume of sand moving southward as littoral drift on the annual basis is reduced as this sand bypasses the inlet. About 7,000 yd^3 (5,400 m^3) are not trapped by JID borrow area or the Corps of Engineers borrow area. A very approximate estimate suggests that about the same amount moves offshore. The latter amount may actually fluctuate from -7000 yd^3 (-5,400 m^3), i.e. a net onshore transport from the ebb shoal area or elsewhere, to perhaps as much as 21,000 yd^3 (16,100 m^3). On a long term basis (e.g. decadal) the total annual loss is thus estimated to be 1,4000 yd^3 (10,700 m^3). This amount represents an annual loss of sand equity to the beach south of the inlet.

Given the evidence which possibly suggests that the offshore bathymetry undergoes a decadal oscillation in the sand volume, as well as considering the cost of dredging, a practical approach would require that around 140,000 to 150,000 yd^3 (108,000 to 115,000 m^3) be dredged from the offshore to account for 100% sand bypassing requirement by JID. Dredging of this amount of sand should be carried out after identifying a suitable site which does not cause a measurable interruption of the littoral flow of sand, or is potentially harmful to the nearby beaches.

Note that an eastward channel corresponding to this sand volume would have to be about 250 ft wide by 22 ft deep (76 m x 6.7 m), which is too large to be justified for navigational needs, and is likely to pose a high risk as far as its impact on the beach south of the inlet is concerned. Therefore the required 150,000 yd^3 (115,000 m^3) should not be dredged from the ebb shoal by way of an eastward channel. The same general argument holds for the southeastward channel.

18.2. Impact on Navigation Safety

Dredging in the offshore area is not likely to impact navigational safety in a negative manner.

18.3. Impact on Beach Erosion

A potential exists for enhanced beach erosion depending on the selected site for dredging. As noted in Section 18.1 dredging 150,000 yd^3 (115,000 m^3) to create, for example, a channel through the ebb shoal is likely to cause a major adverse impact. Even if the dredged sand is placed on the beach, there is likely to be a significant oscillation of the shoreline position during the months following dredging.

18.4. Impact on Interior Sedimentation

Offshore dredging is not likely to impact sedimentation in the interior of the inlet in any measurable way.

18.5. Ecological Considerations

Dredging in the offshore shoal may help restore and maintain the beach to the south of the south jetty, although for a comparatively short period. If this action helps to maintain stable and gentle beach profiles during the sea turtle nesting season, this will have some positive ecological benefits. As with the trap dredging (see Section 2.5), however, other impacts also occur.

Ecological damage from sediment plumes during dredging may not be as likely in the offshore area as they are in the traps inside the inlet. The suspended sediment may be able to dissipate more widely, thus diluting any impacts to some degree. Furthermore, ecological communities in the immediate area are likely to be less productive than the seagrasses inside the inlet and are also likely to be more tolerant of shifting sediments, a phenomenon that occurs routinely in the sandy offshore areas. No seagrasses are likely to be in the immediate path of the plume, although this should be monitored and sediment screens employed if necessary. Dredging in the offshore area will not impact the tidal prism.

19. Frequency of Dredging

19.1. Impact on Navigation Access

As noted in Section 18.1, dredging in the offshore area may be carried out once every 10 years. A shorter interval may prove to be uneconomical as the amount to be dredged after n number of years is equal to 14,000 yd^3 (10,800 m^3) x n. There is also the concern for impacts on the beach due to the uncertainty in the behavior of the offshore bathymetry over shorter time intervals.

19.2. Impact on Navigation Safety

The frequency of dredging is not likely to impact navigational safety; however see Section 21.1.

19.3. Impact on Beach Erosion

As mentioned in Section 18.1, ebb shoal dredging to create a wide and deep eastward (or in some other direction, e.g. southeastward) outer channel can not be justified. The site ultimately selected for dredging should be in an area which is shown to have a relatively stable bottom. Site selection must be based on further searches for offshore sources of beach compatible sand, since the present data are inadequate for making a rational decision with regard to site selection. See also 21.3.

19.4. Impact on Interior Sedimentation

There is no significant relationship between the offshore dredging frequency and sedimentation in the interior region of the inlet; see however 21.1.

19.5. Ecological Considerations

Ecological considerations pertaining to the frequency of offshore dredging are the same as for the trap dredging covered in Section 2.5. More frequent dredging of smaller volumes per event may reduce local ecological impact, while allowing the collection of a sufficient volume of unstable sand. Less frequent dredging of a larger volume could require dredging more stabilized and ecologically productive sand communities in order to achieve the target volume. If sufficient unstable sand is available, the differences between dredging, for example, once ten years or once every year may not be particularly consequential.

20. Location of Dredging

20.1. Impact on Navigation Access

As noted in Sections 18.1 and 19.3, dredging of a major offshore access channel in the ebb shoal area is likely to impact beach stability and, furthermore, a wide and deep channel is not required at this inlet.

20.2. Impact on Navigation Safety

No strong correlation is expected between navigational safety and offshore dredging location as envisaged and noted in 18.1; see however Section 21.1.

20.3. Impact on Beach Erosion

As noted in Section 19.3 the offshore sand borrow site should be carefully chosen to minimize impact on the beach.

20.4. Impact on Interior Sedimentation

There is no significant relationship between offshore dredging frequency and sedimentation in the interior region of the inlet; see however Section 21.1.

20.5. Ecological Considerations

Although offshore dredging may reduce the necessity to dredge traps inside the inlet by an equal volume, it is not clear that the net ecological impact from dredging in the offshore area is any less. A beneficial impact may actually occur if sufficient quantities of unstable (mobile) sand are found at a suitable site which does not impact the beaches by increasing the wave energy reaching the beach. Furthermore, the location of the dredging site is of great importance. For the dredging in the offshore area to meet its main objective, dredged material must be suitable for placement on the beach. Therefore it must consist of sand of sufficiently large grain size and low organic content. For sand, low organic content is correlated to low ecological productivity. Thus dredging sand suitable for beach nourishment also reduces ecological impact at the dredging site.

To provide suitable sand for beach nourishment and to minimize damage to existing ecological communities in the offshore area, sand should be removed from the unstable parts of the bottom. Unstable areas, however, are likely to be those presently dissipating wave energy that would otherwise reach the beach or inlet. Hence the importance of selecting the optimal borrow site. Identifying the minimum-impact location on the offshore site also requires some ecological observation of the site.

21. Placement of Dredged Material

21.1. Impact on Navigation Access

Some of the sand placed on the beach immediately south of the inlet is known to be transported into the inlet around the south jetty. This transport decreases the depth at the JID trap more rapidly than desired, and can be construed as impacting on access to navigation, even though this effect is not thought to be highly significant. Note that the south beach is the most appropriate site to place beach compatible sand dredged from the offshore area. Modification of the south jetty for reducing interior sedimentation, as noted under Section 11.4, and reducing beach erosion as noted under Section 11.3 , are related to this issue.

21.2. Impact on Navigation Safety

The linkage between navigational safety and placement of sand dredged from the offshore area is not likely to be significant; however see Section 21.1.

21.3. Impact on Beach Erosion

The material dredged from the offshore area should be placed on the beach downdrift of the inlet. Note that this condition imposes an additional requirement for location of the offshore borrow area in terms of the compatibility of the borrow material as a beach fill. Material unsuitable for placement on the south beach should not be considered for dredging.

21.4. Impact on Interior Sedimentation

Calculations show, for example, that the net amount of sand transported per unit time is doubled if the median grain size is decreased from 0.50 mm to 0.20 mm. Thus for instance an annual, net sediment influx of 78,000 yd^3 (60,000 m^3) would increase to 166,000 yd^3 (127,000 m^3). Therefore finer the material, the greater the likelihood of increased sediment in the interior area.

21.5. Ecological Considerations

Assuming the nature of the material dredged from the offshore area is suitable for placement along the beach, the ecological considerations are the same as for the other aspects of beach nourishment. These are covered in Sections 5.5, 6.5, 7.5, and 8.5. If the offshore material is not suitable for beach nourishment, the main ecological advantage of offshore dredging will be lost. Furthermore, another site for disposal of the material will have to be found. This site must avoid covering offshore rocky outcroppings.

IX. Interior Trap Dredging

22. Location of Interior Trap

22.1. Impact on Navigation Access

Following a suggestion made during the mid-Seventies (Chiu, 1975), a third sand trap (i.e. in addition to the JID trap and the Corps of Engineers dredging site) may be created and located immediately eastward of the FECRR bridge. The earlier proposal called for a trap on the west side of the bridge which is a more suitable location than east of the bridge; however, the area west of bridge is now an aquatic preserve. The purpose of the third trap would be to control the accretion of littoral sand in the wider region of the Loxahatchee River estuary west of the bridge, i.e. in Region 3. Calculations indicate that at present about 1,000 yd^3 (800 m^3) of (0.50 mm) littoral sand is transported west of the railroad bridge. Note that the precise amount is not known; it is conceivable that at times the influx increases to as much as 2,400 yd^3 (1,800 m^3) of 0.20 mm sand. In so far as the trap is designed to control sediment buildup west of the railroad bridge, its impact on navigational access should be beneficial.

22.2. Impact on Navigation Safety

It is unlikely that the proposed trap location will impact navigational safety beneficially or otherwise in any significant way; there could be a minor positive impact on safety due to the availability of greater depths.

22.3. Impact on Beach Erosion

Dredging in this particular location will have little impact on beach erosion. Bank erosion in the vicinity is unlikely to be impacted in a major way, although the possibility of some impact cannot be ruled out.

22.4. Impact on Interior Sedimentation

As note in Section 22.1, the main purpose of the proposed third trap is to control the influx of littoral sand into the wide area of the Loxahatchee River west of the FECRR bridge. The location is thus appropriately selected to be at the eastern end of Region 3 where sedimentation is a matter of concern.

22.5. Ecological Considerations

Because the environmental portion of this study did not involve the area west of the Florida East Coast Railroad bridge, specific knowledge of the ecological impacts of trap location are not possible. In general, however, it is important to avoid dredging at sites that contain seagrasses or are in close proximity to seagrass beds. Dredging operations should perhaps employ the use of sediment screens to block sediment plumes from reaching seagrass beds. As stated in Section 2.5, suspended-sediment plumes temporarily reduce seagrass productivity through reduced light. Subsequent settlement of the plume may bury some organisms.

23. Dimensions of Interior Trap

23.1. Impact on Navigation Access

The considered trap dimensions are 500 ft (152 m) width centered laterally across the Loxahatchee River, 200 ft (61 m) length along the axis of the river and 12 ft (3.7 m) depth below NGVD. Such a depth is also maintained in the nearby Intracoastal Waterway. These trap dimensions do not suggest a strong positive or negative impact on access to navigation.

23.2. Impact on Navigation Safety

The proposed trap dimensions will not materially alter navigational safety in the area.

23.3. Impact on Beach Erosion

The proposed trap dimensions will not have any tangible bearing on beach erosion. However, there exists some possibility of local bank erosion; hence if and when the trap is dredged its stability must be monitored by periodic surveying.

23.4. Impact on Interior Sedimentation

The trap size is considered to be sufficiently large to contain a sizeable fraction of the incoming littoral sediment. Mathematical model calculations indicate that the net movement of sand further to the west should decrease by up to 50% relative to the present movement noted in Section 22.1. The degree of reliability of this assertion is, to a fair (but not the sole) extent dependent upon the model's ability to make accurate predictions. Since the model has been shown to yield reasonable results with respect to sand transport in the area of the JID trap as well as estimates of sand transport past (westward) of the FECRR Bridge, the basis for accepting model results does exist. On the other hand, at present the Intracoastal Waterway in the vicinity of the proposed trap does not seem to shoal significantly; an observation that seemingly counters model prediction. We must however note two mitigating physical factors: 1) the natural depths in the area of the proposed trap are somewhat lower than those of the proposed trap, and therefore there is likely to be a natural tendency to "fill up the hole", and 2) one is dealing with very small rates of shoaling of the trap in any event.

23.5. Ecological Considerations

Generally, interior traps of smaller surface area should carry less ecological impact than larger traps. Depth is less important. The majority of ecological activity in most estuarine sediments is found in the upper ft (30 cm) or so and diminishes considerably below that point. Since dredging will involve more than a ft (30 cm) of depth in any scenario (other than the no new action scenario), the impact of depth is ecologically relatively unimportant compared to the surface area of the trap. Smaller surface areas will yield lower ecological impact.

24. Volumetric Rate of Interior Trap Dredging

24.1. Impact on Navigation Access

The volumetric rate of trapping given the range of present rate of influx in Section 22.1 and trap efficiency given in Section 23.4 would range from 500 to 1,200 yd^3 (380 to 920 m^3). This trapping mode has no tangible bearing on navigational access. Dredging may be once every ten years.

24.2. Impact on Navigation Safety

The volumetric sand trapping rate in the proposed trap will have no measurable impact on navigational safety.

24.3. Impact on Beach Erosion

The volumetric sand trapping rate in the proposed trap will not impact beach erosion. The concern for some local bank erosion is noted in Section 23.3.

24.4. Impact on Interior Sedimentation

Calculations indicate that the rate of shoaling of the wider region of the Loxahatchee River west of the FECRR bridge (Region 3) has been decreasing steadily over the past two decades. Thus the possibility exists that with a continuation of this trend, coupled with an effort to trap more sand at the JID trap as noted in Section 2.4, could reduce the movement of sand into this area from the littoral drift, and hence diminish the need for maintaining the proposed trap.

24.5. Ecological Considerations

In general the comments about volumetric rate of trap dredging in Section 2.5 are applicable here. However, the material to be dredged is likely to contain a much greater number of biota (perhaps several orders of magnitude greater) that could be damaged by entrainment in the dredge. These are the estuarine epifauna and infauna: polychaete worms, clams, burrowing crustacea, and fish (e.g., certain gobies). The possible volumetric rate of about 10,000 yd^3 (7,600 m^3) in 10 years is relatively small compared to the dredging that occurs in the JID and Corps traps, however, the type of material to be dredged should be considerably more ecologically productive.

Results of the hydrodynamic model constructed as part of this study indicate no measurable impact of the proposed interior trap on salinity intrusion or tidal flows to the limits of the model boundaries.

25. Frequency of Interior Trap Dredging

25.1. Impact on Navigation Access

From Section 23.1 and the fact that the existing mean depth to the bottom at the site is less than the proposed depth means that the dredging interval can be shown to be on the order of a decade. Navigational access will be restricted only during those times when dredging is actually being carried out.

25.2. Impact on Navigation Safety

Any significant relationship between navigational safety and the frequency of dredging in the proposed trap is not evident.

25.3. Impact on Beach Erosion

No significant correlation is expected between beach erosion and the proposed trap dredging frequency. However, some local bank erosion may occur, for which monitoring will be required.

25.4. Impact on Interior Sedimentation

The decadal dredging frequency at the proposed trap would be more than adequate to maintain the up to 50% trapping efficiency of the trap noted under Section 22.1.

25.5. Ecological Considerations

The comments about the frequency of trap dredging given in Section 2.6 are applicable here also, but the intensity of the effects may be somewhat magnified since the ecological community in the sediment may stabilize and become very productive between dredging events. For estuarine sediments, the best option may be to allow an intermediate recovery between dredging events rather than either maintaining a high dredging frequency that is more continuously disruptive, or planning a lower frequency that produces a greater perturbation and a longer recovery time. This is presumably not as important an issue in the existing traps east of the Florida East Coast Railroad bridge, since they are composed of relatively unproductive, unstable sand that is unlikely to ecologically stabilize between dredging events.

Analysis of a dynamic ecological simulation model of infaunal recovery may help to determine inappropriate frequencies of dredging of interior traps. With additional research support, a model of a hypothetical infaunal community could be developed and so analyzed.

26. Material Placement

26.1. Impact on Navigation Access

Any significant relationship between navigational access and the placement of material from the proposed trap is not evident. Placement should be accomplished in such a way so as not to impact channels.

26.2. Impact on Navigation Safety

Any significant relationship between navigational safety and the placement of dredged material is not evident, as long as the material is not placed in the navigation channels or nearby.

26.3. Impact on Beach Erosion

No significant correlation is expected between beach erosion and the placement of dredged material. It is expected that this material will be unsuitable for beach nourishment.

26.4. Impact on Interior Sedimentation

The actual placement of the material should be accomplished so as not to allow material to impact channels, hence there should be no impact.

26.5. Ecological Considerations

Material may not be suitable for beach nourishment because sediment size may be too small and organic content too great. If so, alternative disposal sites will have to be found. Depositing the material on land may be expedient, but will not positively benefit the estuary. On the other hand, it may be possible to use this material to build shallow zones elsewhere in the Loxahatchee River estuary, possibly in Region 3, and plant seagrasses, marshes, or mangroves on them. It is necessary to assess the likelihood of success of such plantings in advance, however. Placement of material in the estuary, however, is likely to produce a large sediment plume. This could perhaps be adequately controlled by sediment screens, which should also be tested in advance.

4. RECOMMENDED ACTIONS, IMPACTS AND COSTS

4.1 Introduction

The decision rationale given in Chapter 3, coupled with practical engineering considerations relevant to Jupiter Inlet, were used to develop a series of individual recommended actions and associated costs. These actions are relative to the present coastal engineering protocol, which would require no new action. The individual actions and costs are listed in Table 4.1. Note that a given action may impact beach erosion, navigation as well as sedimentation in the interior. This interdependence between the three management characterizing (improvement) issues and the actions is shown by box diagrams in Figs. 4.1, 4.2 and 4.3. The costs are inherently approximate; in particular, the costs of such one-time purchase items as the sand fluidization system are uncertain. While annualization is based on a 50 year item life, even the expected life of a fluidization system is not quite known. Given these uncertainties as well as the questionability in projecting dredging and other annual costs in future at an appropriate interest rate (8% has been assumed here), the validity of the given costs beyond a 10 year period for dredging etc is speculative.

Two categories of "cumulative" actions for the proposed management plan are considered -- those that are interdependent and therefore must be carried out in a certain sequence or phases, and those that are mutually independent (Table 4.2). These are described next.

4.2 Recommended Phased, Interdependent Actions

P1. This action entails a revision of the sand dredging and placement protocol by JID, and a concomitant recommendation to the Army Corps of engineers to revise their dredging schedule. In order to minimize the south beach erosion problem, a minimum of 60,000 yd^3 (49,000 m^3) must be pumped to the south beach, each year. The actual amount, by way of combined total for the JID trap and the Corps trap, should not be allowed to decrease below this amount in a given year, assuming, of course, that this amount is available from the two traps.

Note that the recommended volume of 60,000 yd^3 (49,000 m^3) is the minimum for beach stability; the actual amount in the trap (or traps) may be larger, in which case the need to maintain a certain depth in the trap (- 20 ft or -6.1 m in the JID trap, and -12 ft or - 3.7 m in the Corps maintained Intracoastal Waterway) would mean that the actual volume pumped to the beach each year may be larger than the minimum, as often has been the case.

We also recommend that a sand placement plan that is different from that at present (Fig. 4.4) be tried as a way to increase the retention time of placed sand. A possible plan is shown in Fig. 4.5, in which the sand is shown to be spread out over a wider section of the public beach than the existing stretch. We suggest implementation of the proposed plan initially on a trail basis during a pre-summer (before the end of April) placement of sand. Monitoring of the beach subsequent to sand placement will provide grounds for making a decision as to the rate of success of the project. It must be borne in mind, however, that a single placement trial

Table 4.1: Individual actions investigated and costs.

Action Description	Cost ($)	Basis	Annualized Cost[a] ($)
JID Trap Expansion	500,000	One-Time	41,000
Dredging 60,000 yd^3/yr	250,000	Annual	250,000
			291,000
Raise Elevation of South Jetty	60,000	One-Time	4,900
Maintenance	3,000	Annual	3,000
			7,900
Raise Elevation of North Jetty	80,000	One-Time	6,500
Maintenance	4,000	Annual	4,000
			10,500
South Jetty Extension by 175 ft	500,000	One-Time	41,000
Maintenance	80,000	Annual	8,000
			49,000
North Jetty Extension by 400 ft	1,100,000	One-Time	90,000
Maintenance	12,000	Annual	12,000
			102,000
Fixed Sand Bypassing Plant	3,500,000	One-Time	436,000
Maintenance	150,000	Annual	150,000
	3,650,000		586,000
Fluidizer System	2,500,000	One-Time	204,000
Maintenance	100,000	Annual	100,000
	3,600,000		304,000
Offshore Dredging 150,000 yd^3	950,000	10 Years	143,000
Dredge Offshore Channel 40,000 yd^3/yr	620,000[b]	Annual	620,000
Navigational Aids	40,000	One-Time	3,300
Maintenance	5,000	Annual	5,000
			8,300
Additional Sand Trap 10,000 yd^3, Every 10 years	40,000	10 years	7,300

[a]One-time costs annualized at 8% interest, 50 year life.
[b]Capital plus maintenance dredging.

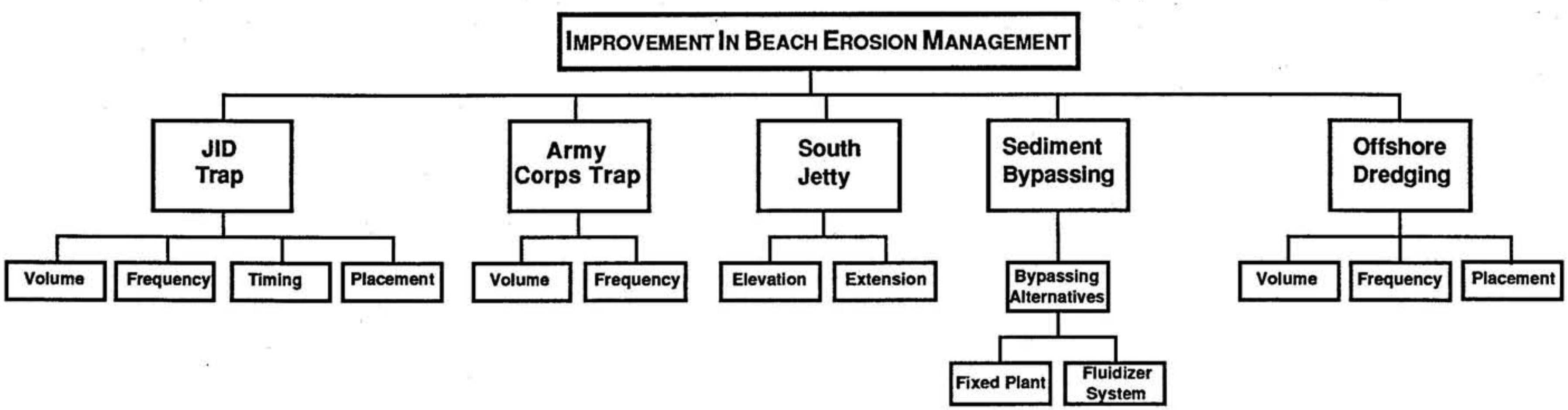


Fig. 4.1. Action categories considered in relation to improvement in beach erosion management.

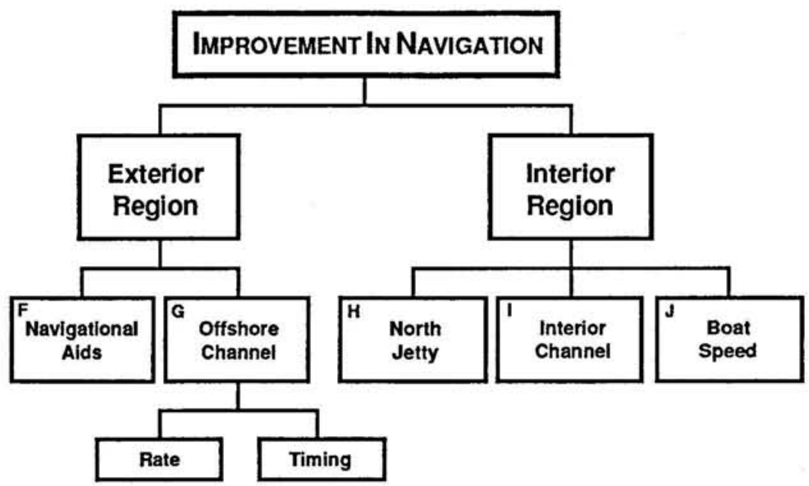


Fig. 4.2. Action categories considered in relation to improvement in navigation management.

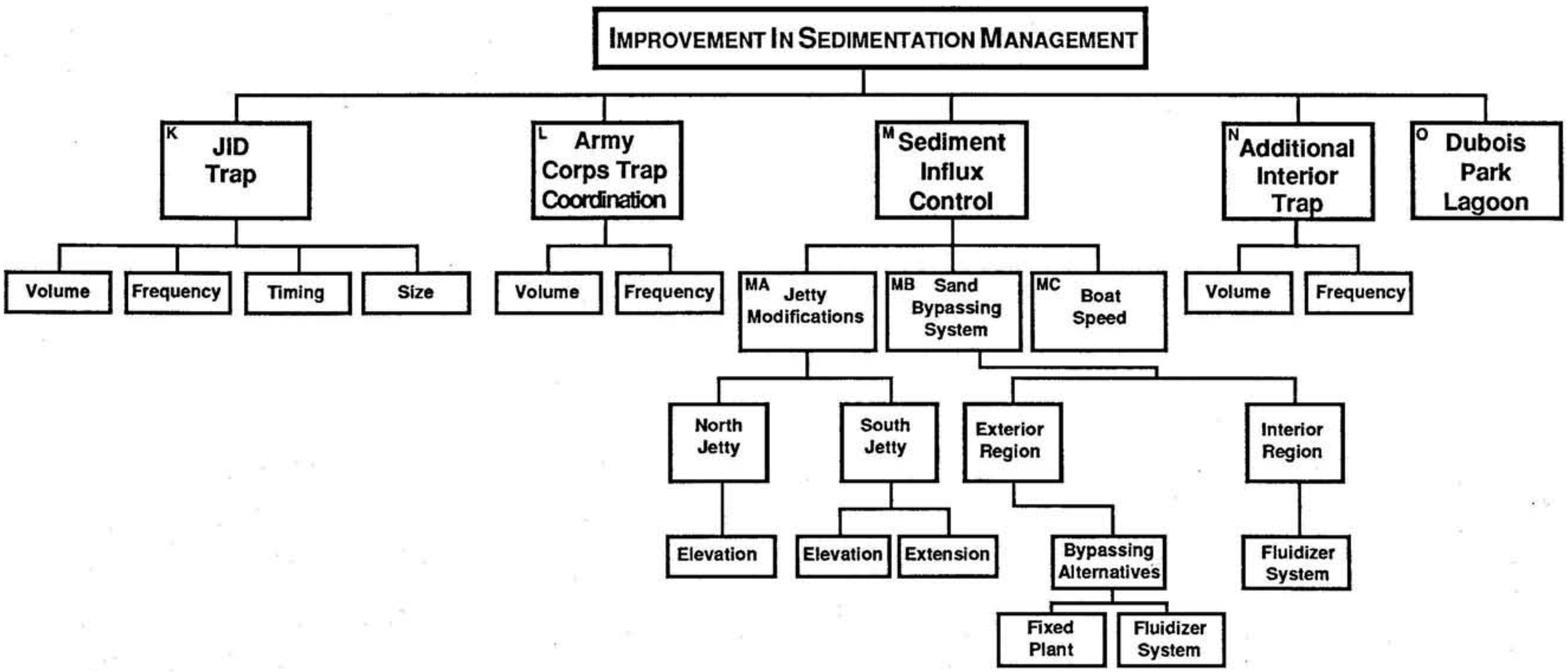


Fig. 4.3. Action categories considered in relation to improvement in sedimentation management.

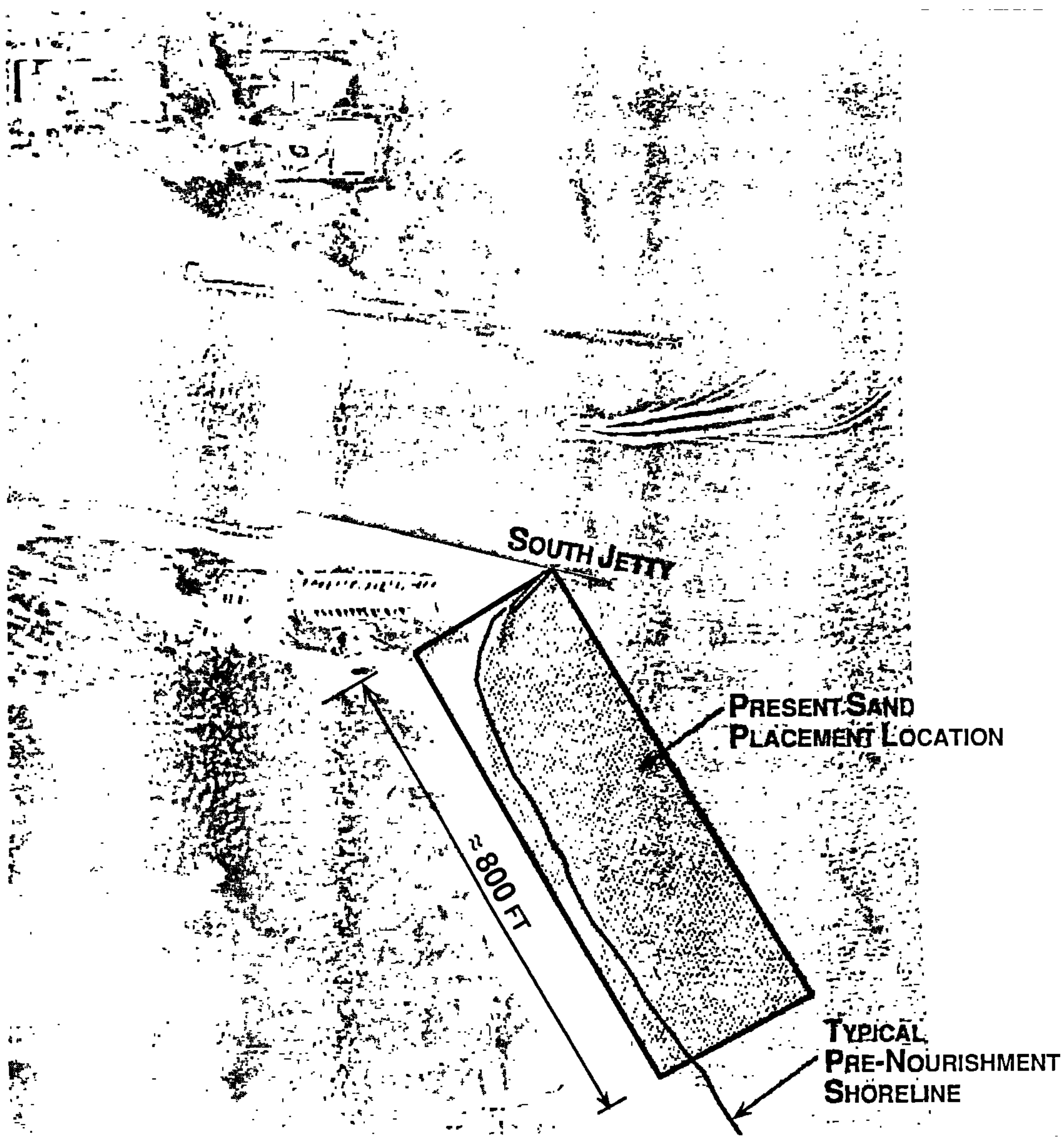


Fig. 4.4. Present sand placement plan.

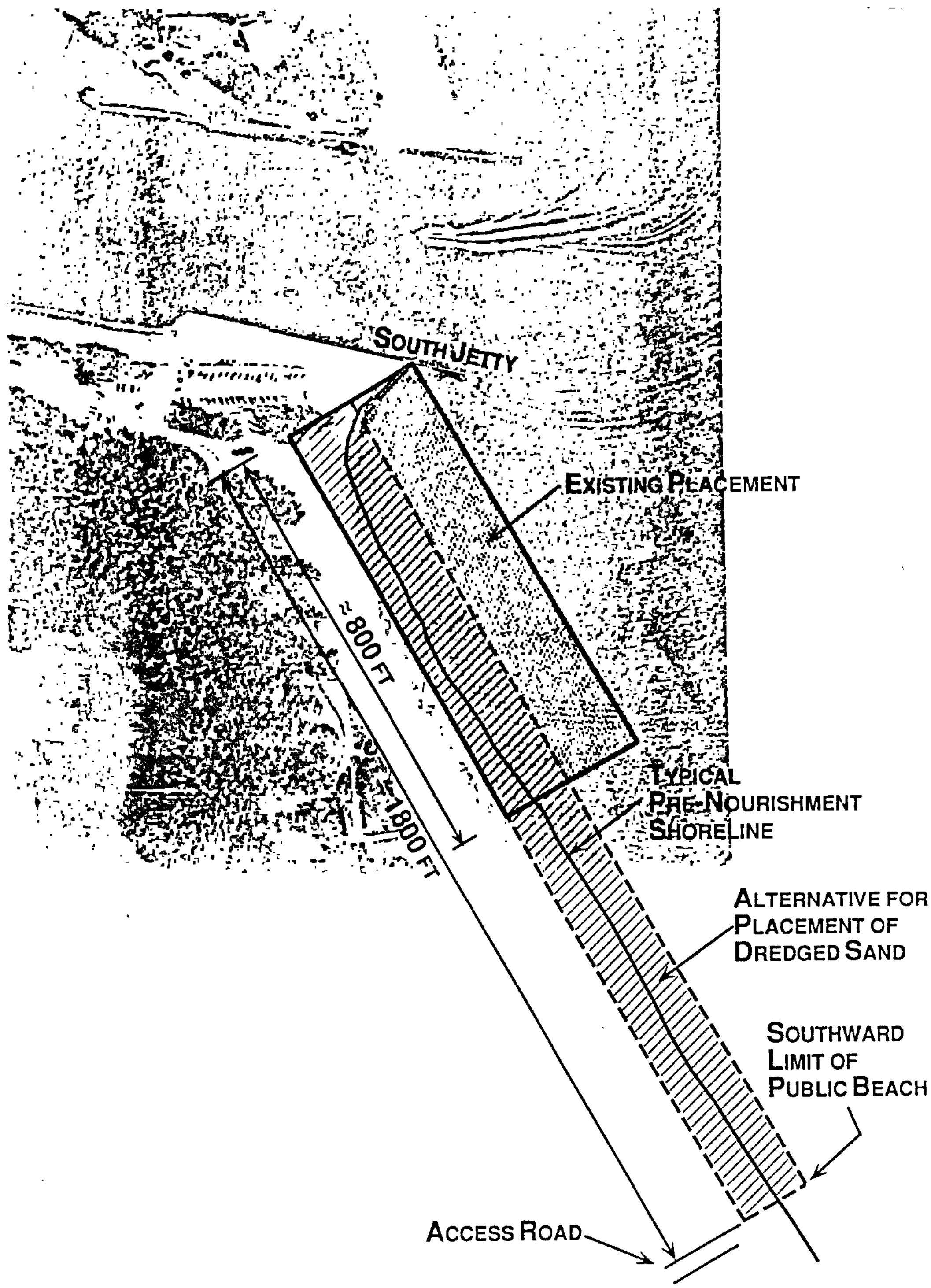


Fig. 4.5. A revised sand placement plan.

Table 4.2: Recommended actions.

Recommended Phased, Interdependent Actions	
P1	Trap dredging and sand placement protocol modification.
P2	P1 + raising north and south jetty elevations and extend south jetty.
P3A	P2 + north jetty extension and installation of beach sand bypassing facility.
P3B	P2 + Installation of a sand fluidizer system in the channel.
Recommended Independent Actions	
I1	Modification of Corps trap dredging protocol.
I2	Regulating boat speed.
I3	Placement of beacons.
I4	Dredging offshore navigation channel.
I5	Offshore dredging for sand equity.
I6	Interior trap dredging.

may not yield all answers, given the episodic nature of beach sand transport. Additional trials may therefore be required.

A possibility of enhancing the efficiency of sand trapping exists by expanding the size of the existing trap somewhat, as shown in Fig. 4.6. We recommend that the suggested length-wise expansion be carried out first, followed by width-wise expansion at a later date only if length increase does not show any measurable increase, e.g. around 15%, in trapping. If and when width-wise expansion of the trap is carried out, its impact on the stability of Dubois Park beach and the bulkheads in the area must be monitored. Furthermore, the trap should be consistently dredged to -20 ft (-6.1 m), even without any expansion. At the western end of the trap rocky bottom prevents dredging to full 20 ft (6.1 m); therefore these rocks must be removed by capital dredging, to "clean out" the bottom.

The JID trap should be preferably dredged by or before the end of each April, prior to the peak sea turtle nesting season. If at times insufficient sand accumulates in the trap for this dredging window, then dredging in early November may be carried out. The Corps is encouraged to dredge each November during those years when the JID trap is dredged in April. At other times, the Corps is encouraged to dredge before the end of April.

Since any action be the Corps would be independent of that by JID, we have also listed the above recommended action by Corps as independent action I1.

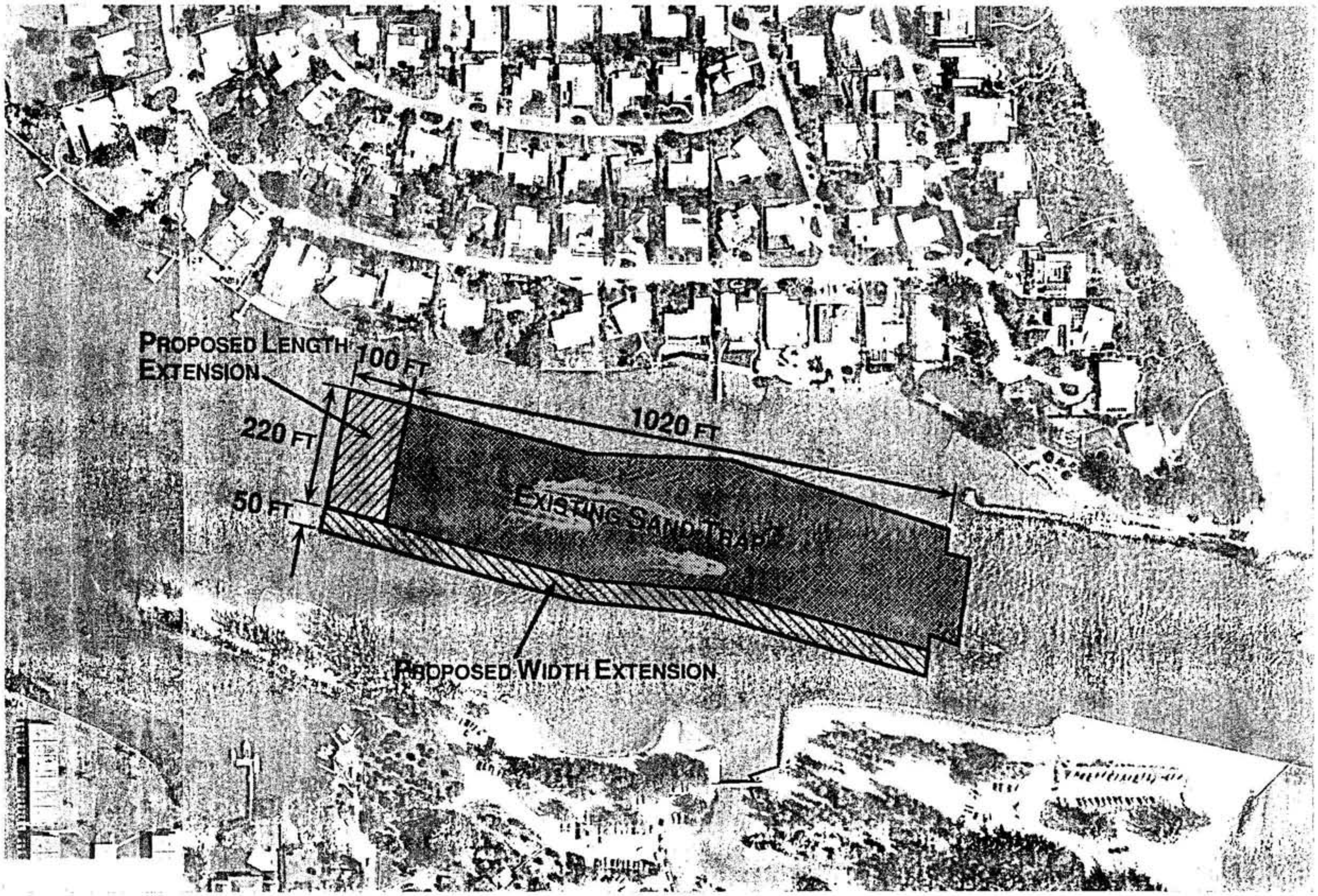


Fig. 4.6. A revised sand trap plan.

P2. This action is in addition to P1, and involves raising the seaward end of the two jetties by 3 ft (0.9 m), and lengthening the south jetty by 175 ft (53 m) (Figs. 4.7 and 4.8). Although these three actions can be implemented separately, it is recommended that they be carried out simultaneously. If for financial reasons for example, it is decided to carry out the works piecemeal, then we recommend that the north jetty be raised first (to reduce incoming sand from the north), then raise the south jetty (to reduce incoming sand from the south), and finally extend the south jetty as shown.

P3A. This action is in addition to P2, involving an extension of the north jetty by 400 ft (122 m) as shown in Fig. 4.9, coupled with the installation of a sand bypassing plant in order to prevent the extended jetty from causing further erosion of the south beach. In order to maintain the south beach, a minimum of 60,000 yd^3 (49,000 m^3) sand must be annually pumped to the south beach. The sand "catching" efficiency of the bypassing plant may not exceed about 75%. This being the case, dredging of the JID trap would not be eliminated entirely.

An alternative to the fixed sand bypassing plant is a fluidizer system shown in Fig. 4.10. The fluidization pipes will have to buried at least 6 ft (1.8 m) below the surface of the sandy bottom. The applicability of this system to this type of an environment is pending experiments presently being conducted at Oceanside Harbor, California, by the Army Corps of Engineers.

It should be noted that since it is unlikely that accumulation of sand in the interior will be entirely eliminated by way of this action, any decision concerning the need to remove the "access" sand from the trap will depend primarily on navigation considerations. However, a secondary consideration would be that an "empty" and larger trap will be more efficient than a filled, smaller trap in catching the fine sand that will continue to be transported past the trap, even though perhaps at a lower than present rate. Therefore the proposed protocol of dredging from a larger trap must be continued, even though the required frequency of dredging may be lower.

P3B. This action, involving the installation of a fluidizer sand bypassing arrangement in the general area of the JID sand borrow area (Fig. 4.11) must be considered as an alternative to P3A for practical reasons, since it would be impractical and costly to maintain more than one sand bypassing arrangement at Jupiter Inlet. This essential constraint means that P3A, which is meant to improve navigation via the extended north jetty, must be weighed against P3B, which is meant to better manage the south beach.

4.3 Recommended Independent Actions

I1. The recommendation to request the Corps to coordinate their dredging and sand pumping activity with that of JID is described under action P1. As noted there, since the Corps' activity has different objectives than JID, and inasmuch as the Corps is an independent entity, any action by the Corps to work with JID must be considered as an action that is jurisdictionally independent of the JID's management plan.

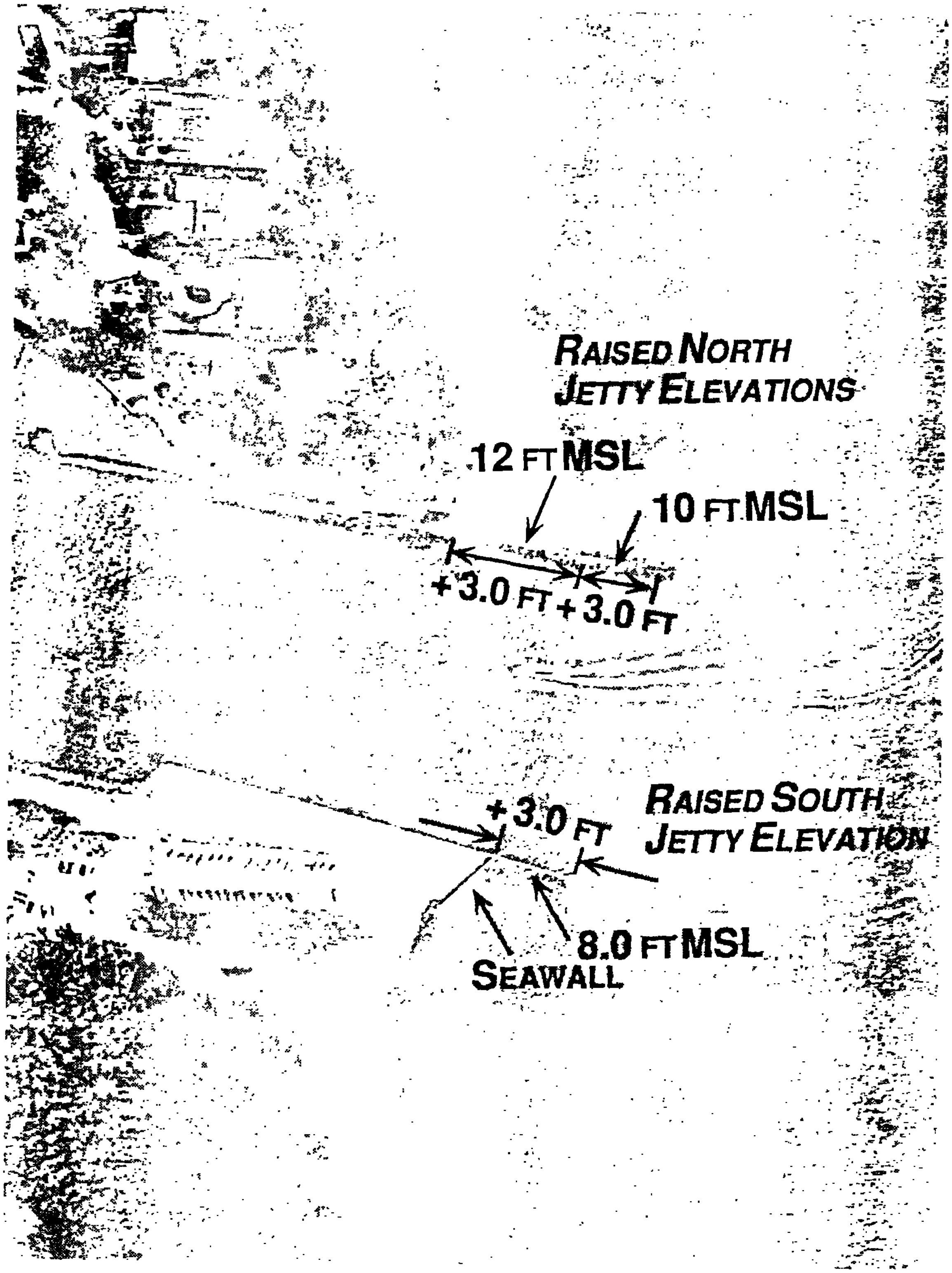


Fig. 4.7. Raising the elevations of the two jetties.

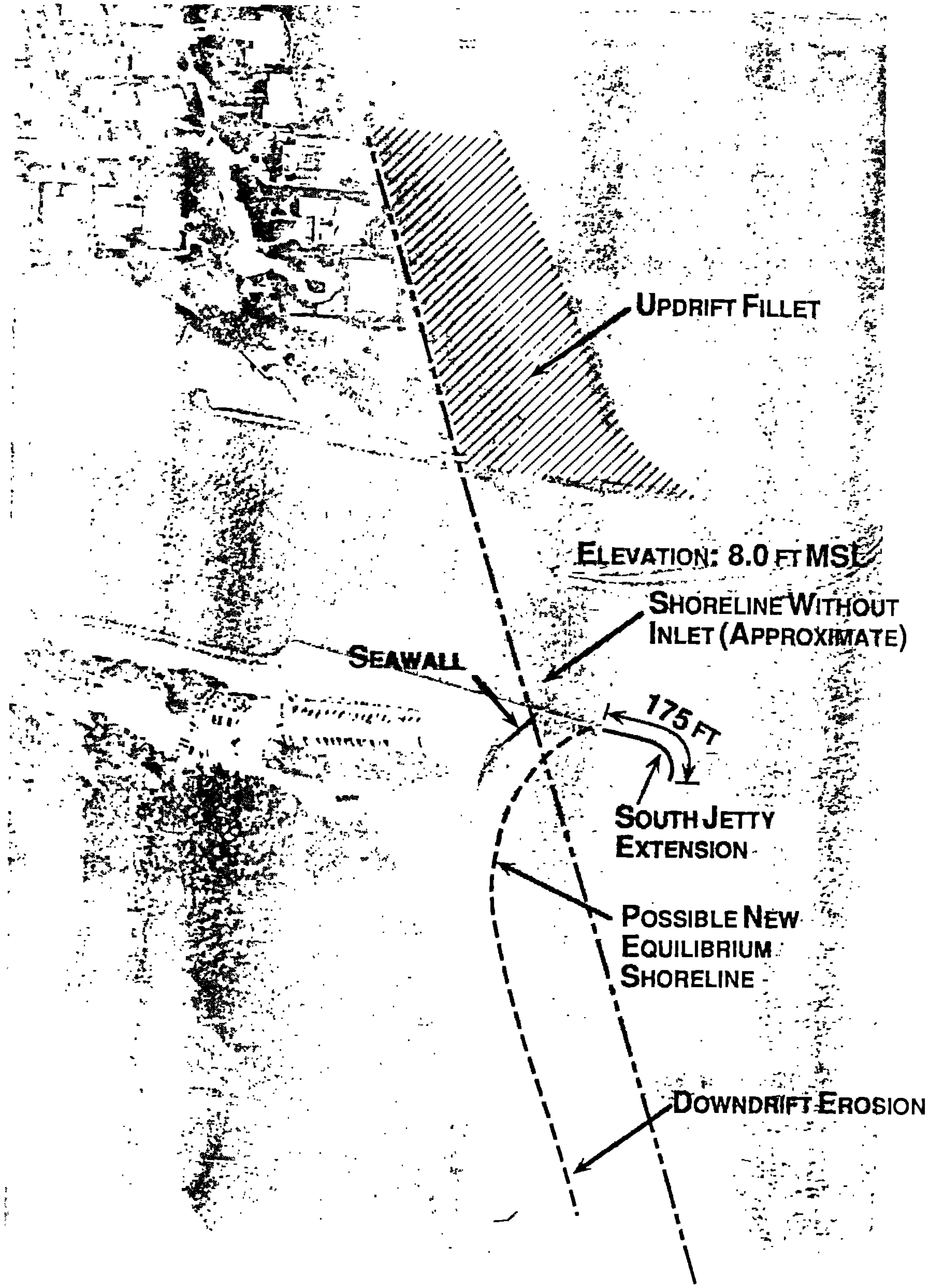


Fig. 4.8. Extended the south jetty.

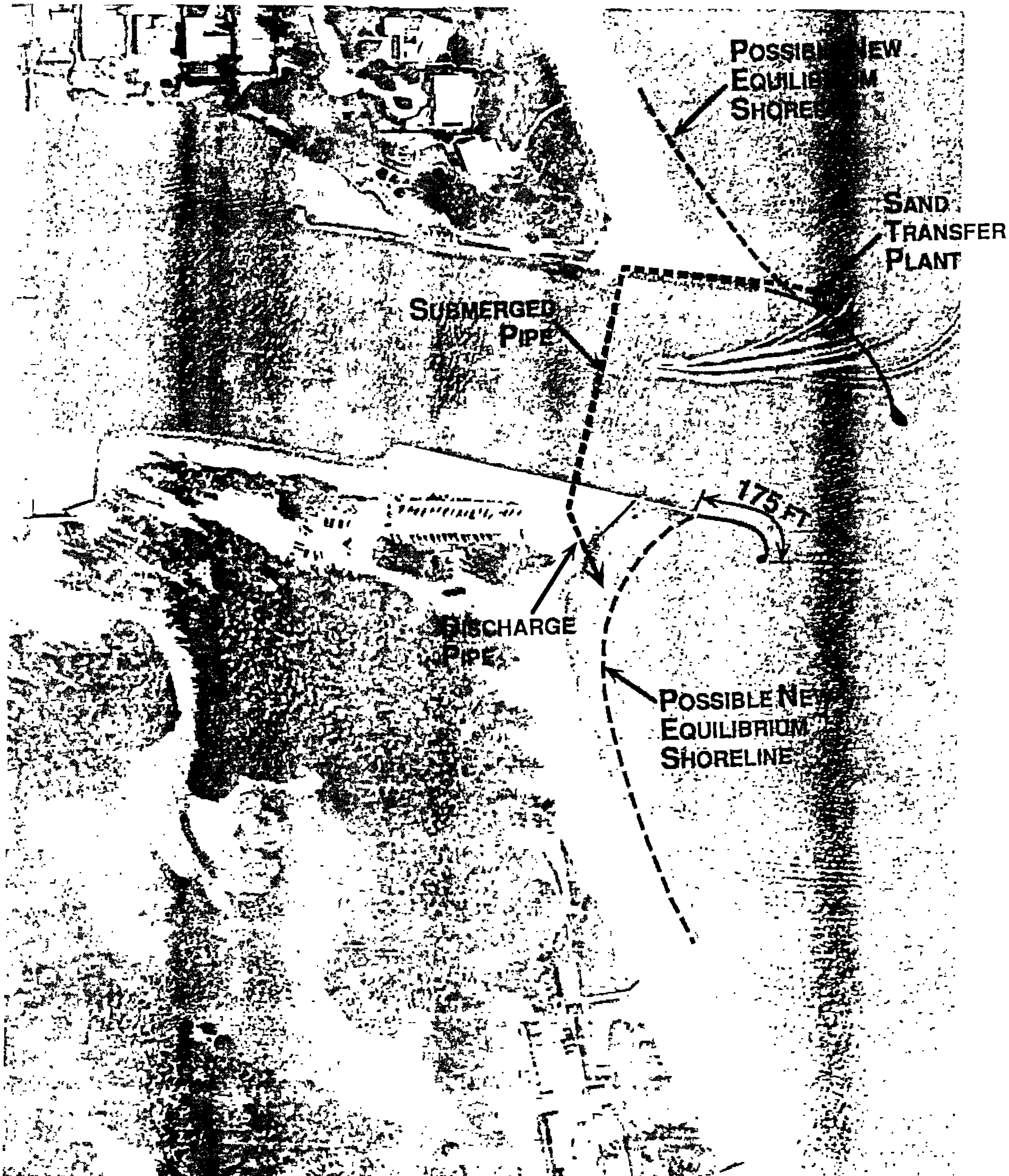


Fig. 4.9. Extended north jetty with a sand bypassing plant.

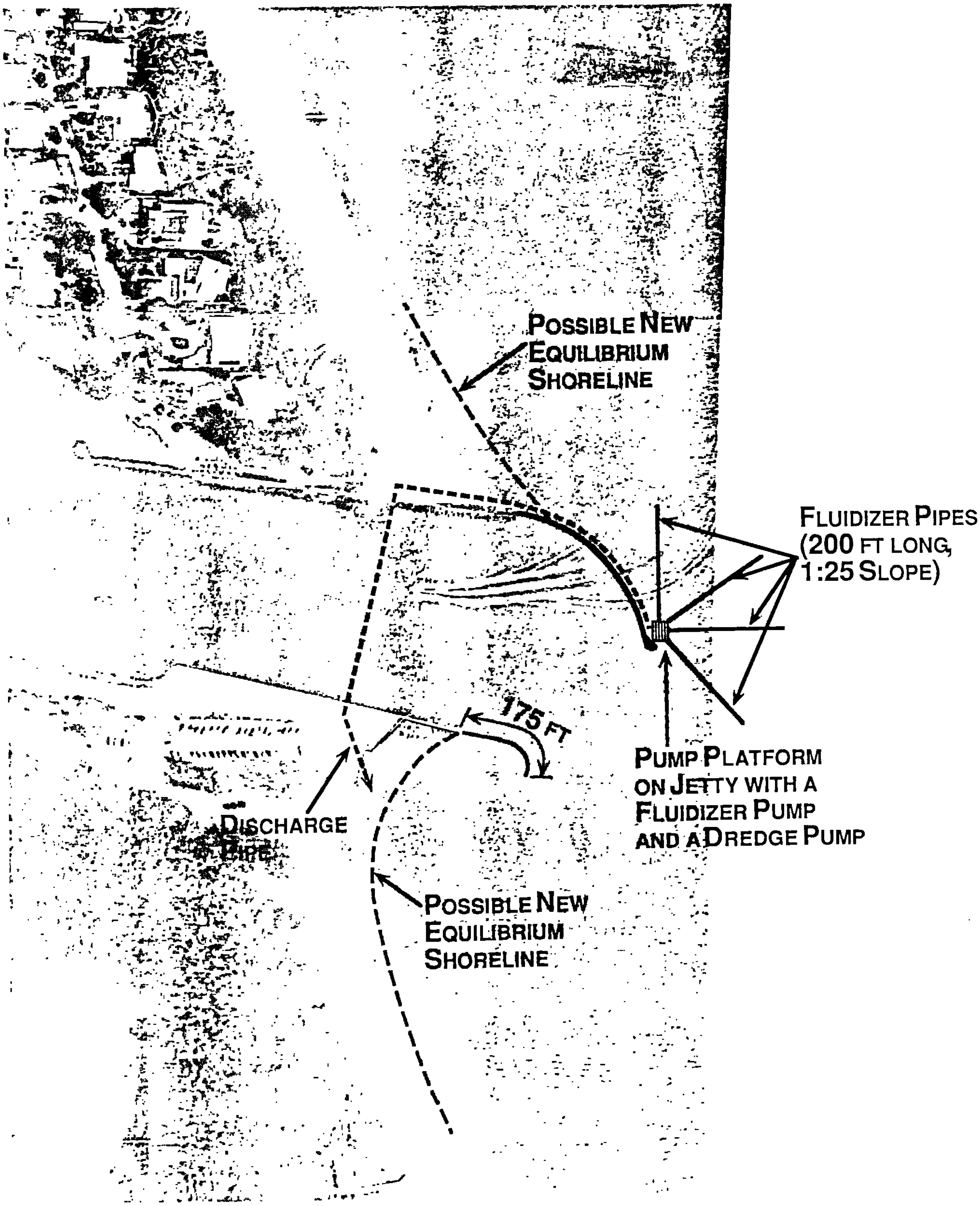


Fig. 4.10. Extended north jetty with an offshore sand fluidization system.

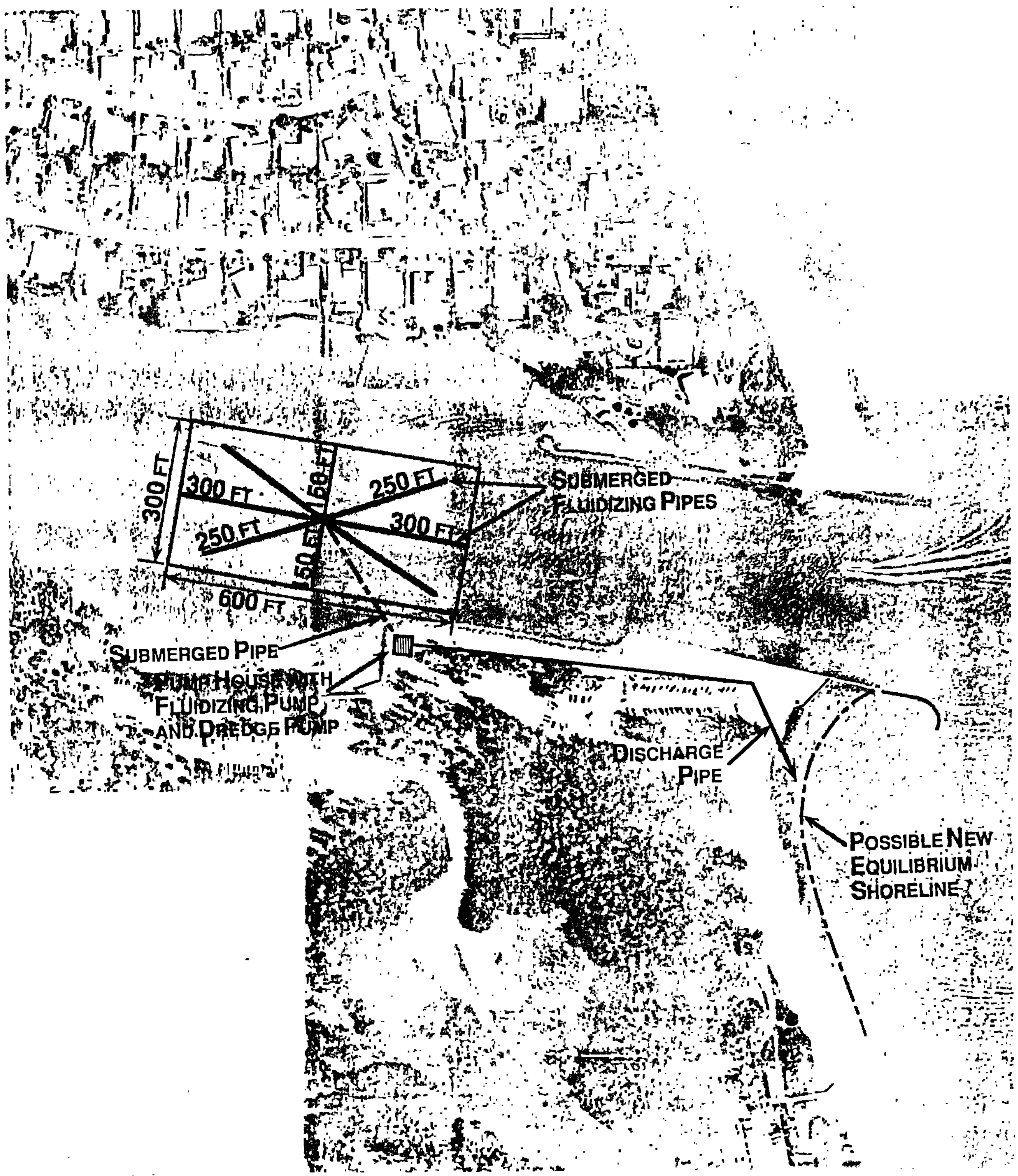


Fig. 4.11. A sand fluidization arrangement for the interior channel.

I2. Regulating boat traffic is within the jurisdiction of the Marine Patrol and the Coast Guard, hence it must be considered as an independent action.

I3. The placement of beacons on the jetty tips per Coast Guard specifications is recommended as shown in Fig. 4.12. Or, as an alternative, international danger signals on the north jetty. When the signals are lit the inlet would be closed to navigation.

I4. A possible configuration of the offshore navigation channel is shown in Fig. 4.13.

I5. Offshore dredging of 150,000 yd^3 (115,000 m^3) every 10 years to mitigate the loss of sand from the beaches south of the inlet is an independent action. Evidently, the sand must be beach quality.

I6. Dredging a third trap at the site shown in Fig. 4.14 can be considered independently of the plans for other dredging, jetty modifications or sand bypassing arrangements.

4.4 Impacts of Interdependent and Independent Actions

Table 4.3 (matrix) summarizes the recommended actions and their costs based on cost data given in Table 4.1. The impacts corresponding to the matrix "boxes" are noted in this section. Note that a number corresponding to a scale of -10 (extremely adverse impact) to +10 (extremely beneficial impact) is included within parentheses for each "box". These numbers are a semi-quantitative representations of the opinion of the authors. They should not be applied by other parties without due consideration to all of the rationale used in their development. This rationale is briefly summarized in the what follows, but is contained more completely in the earlier part of this report and particularly, the progress reports (see bibliography) and other communications with the JID during the course of this project.

P1.1 Revising the dredging and sand placement protocols will have no major bearing on the issue of navigation access, even though annual or bi-annual hydraulic dredging could, at least in principle, hinder boat traffic. A potential reduction in the sand being carried east of the JID trap would however have a slightly beneficial effect.

P1.2 Revising the dredging and sand placement protocols is unlikely to impact navigation safety in a measurable way, even though annual or bi-annual dredging could, at least in principle, "come in the way" of boat traffic.

P1.3 Modification of dredging and sand placement protocols should improve retention of sand on the south beach and hence reduce erosion. Improvement by revising the sand placement protocol is likely to be brought about by two factors: 1) less sand placed in an area where the "excess" sand is easily washed away by wave action in the vicinity of the south jetty, and 2) more sand placed in an area further south, where past records indicate retention

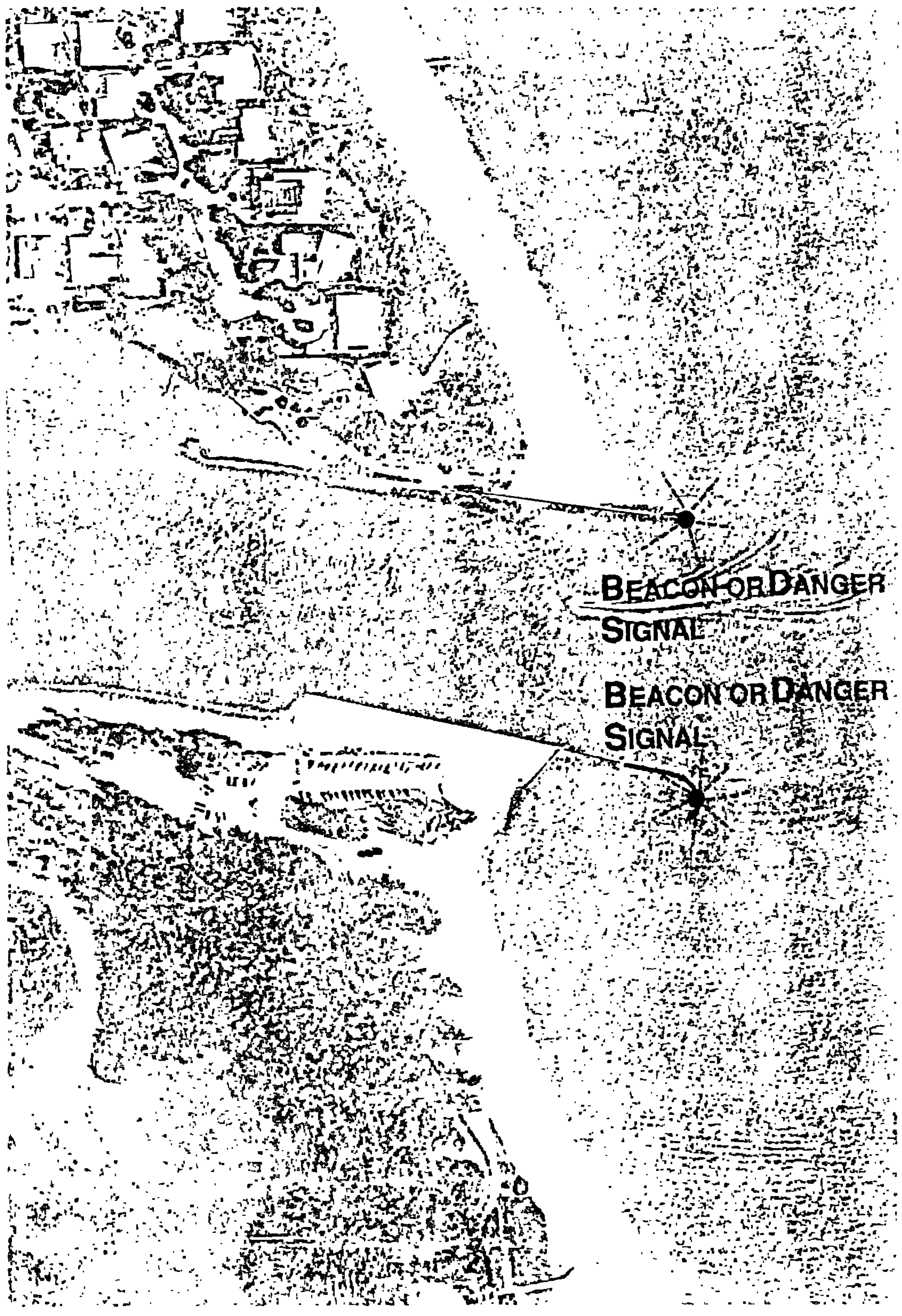
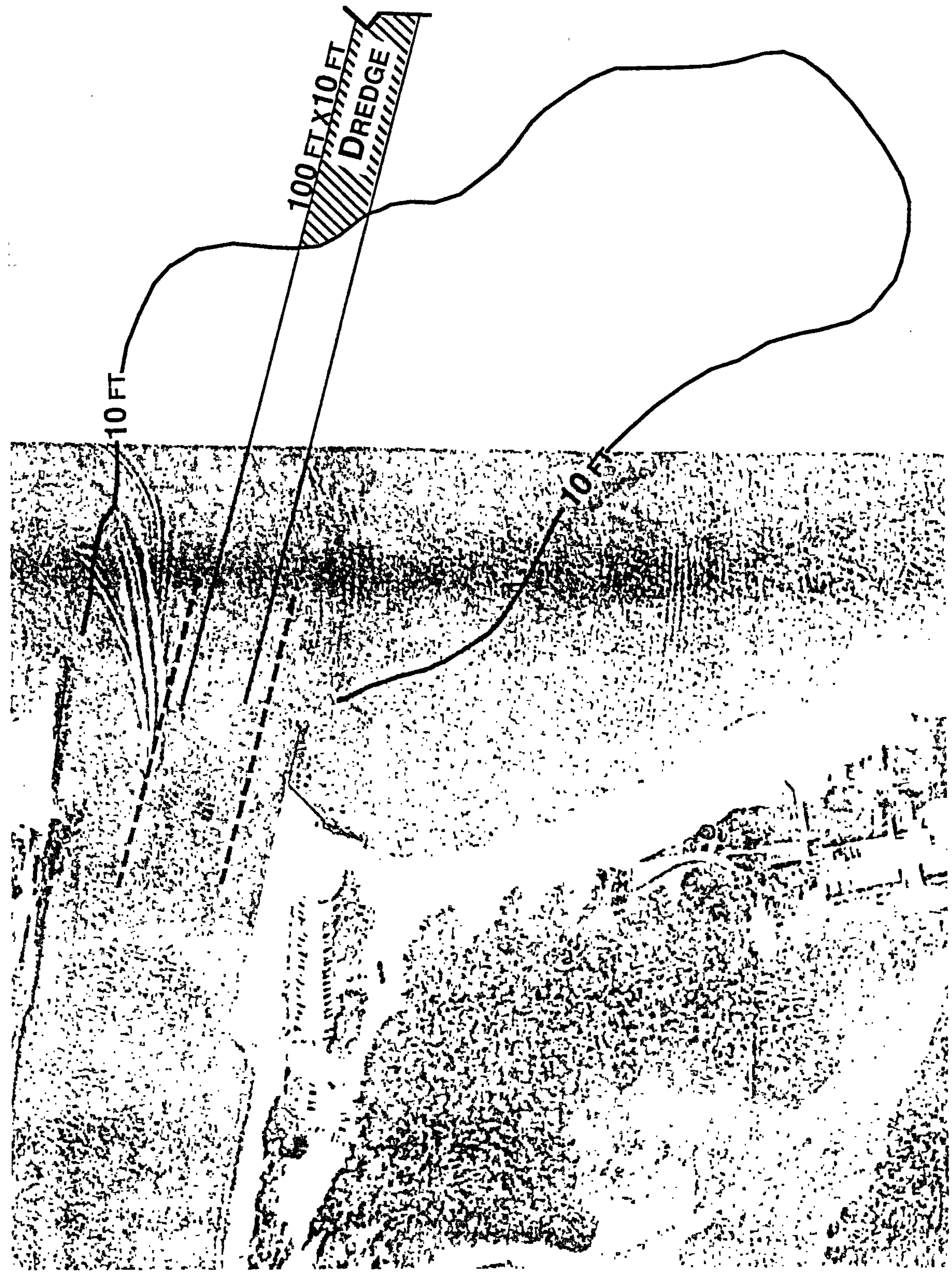


Fig. 4.12. Beacons or danger signals at jetties.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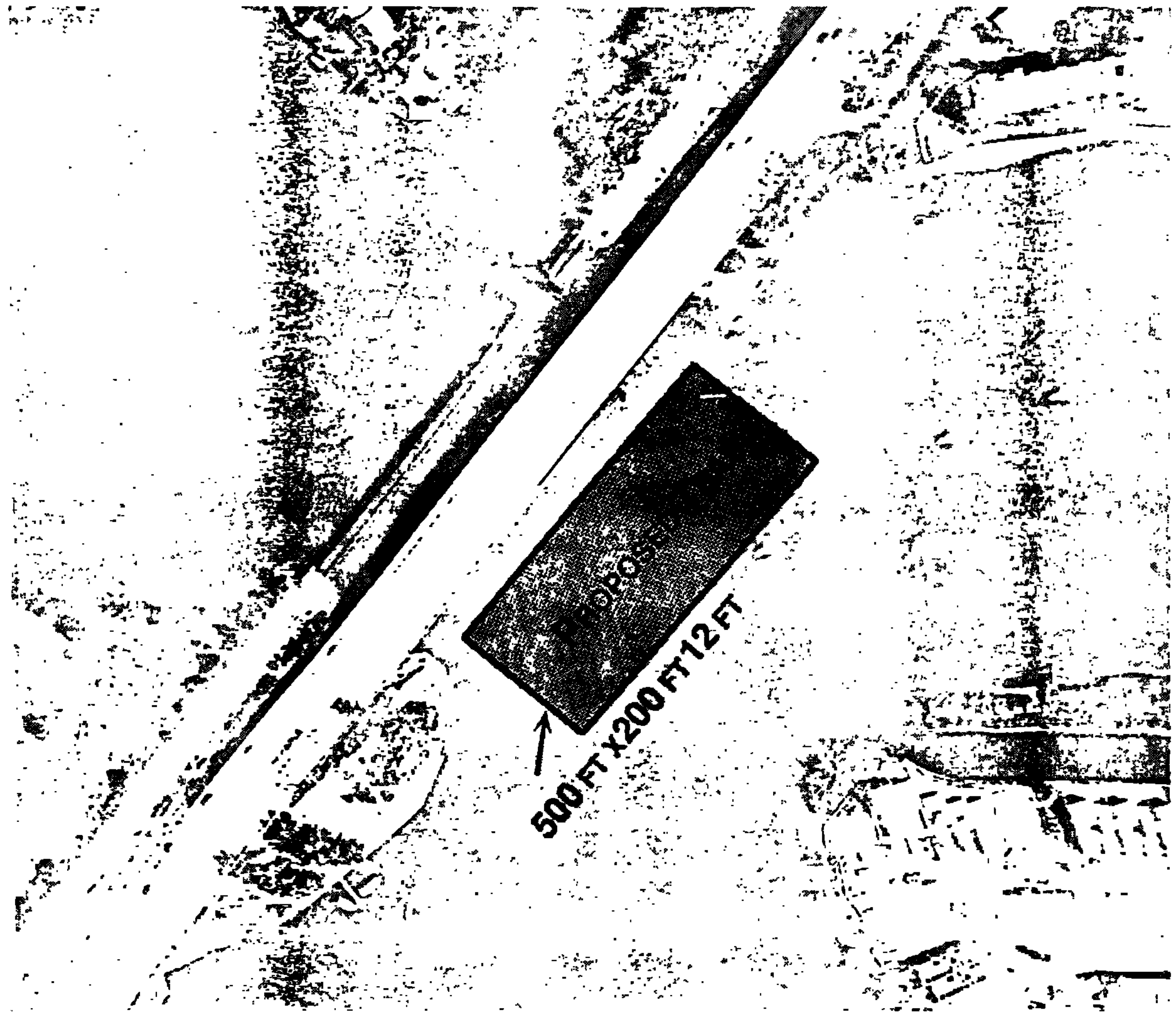


Fig. 4.14. Interior sand trap.

Table 4.3: Recommended actions, impacts and costs.

Actions	Impacts					Costs		
	Navigation Access	Navigation Safety	Beach Erosion	Interior Sedimentation	Ecological Considerations	Amount ($)	Basis	Annualized[a] ($)
P1	P1.1[b](+1)[c]	P1.2(0)	P1.3(+3)	P1.4(+5)	P1.5(+3)	500,000	One-Time[d]	41,000
						250,000	Annual	250,000
								291,000
P2[e]	P2.1(+1)	P2.2(0)	P2.3(+5)	P2.4(+6)	P2.5(+7)	1,140,000	One-Time	93,400
						265,000	Annual	202,000
								295,400
P3A[f]	P3A.1(+3)	P3A.2(+8)	P3A.3(+6)	P3A.4(+6)	P3A.5(+6)	4,640,000 (Fixed Plant)	One-Time	529,400
						415,000	Annual	352,000
								881,400
						3,640,000 (Fluidizer)	One-Time	297,000
						302,000	Annual	302,000
								599,000
P3B[g]	P3B.1(0)	P3B.2(0)	P3B.3(+5)	P3B.4(+6)	P3B.5(+10)	3,640,000 (Fluidizer)	One-Time	297,000
						302,000	Annual	302,000
								599,000
I1	I1.1(+1)	I1.2(0)	I1.3(+4)	I1.4(+2)	I1.5(+2)	N.A.[h]	N.A.	N.A.
I2	I2.1(0)	I2.2(+8)	I2.3(+3)	I2.4(+3)	I2.5(+3)	N.A.	N.A.	N.A.
I3	I3.1(+6)	I3.2(+5)	I3.3(0)	I3.4(0)	I3.5(-1)	40,000	One-Time	3,300
						5,000	Annual	5,000
								8,300
I4	I4.1(+5)	I4.2(+3)	I4.3(0)	I4.4(0)	I4.5(0)	620,000	Annual	620,000
I5	I5.1(0)	I5.2(0)	I5.3(+1)	I5.4(0)	I5.5(+1)	950,000	10 Years	143,000
I6	I6.1(+1)	I6.2(+1)	I6.3(0)	I6.4(+6)	I6.5(-2)	150,000	10 Years	22,600

[a]One-time costs analyzed at 8% interest, 50 year life.
[b]See comments on impacts for all such "boxes".
[c]On a scale of -10 (extremely adverse impact) to +10 (extreme benefit).
[d]This cost has been added for simplicity to the one-time costs of actions P2, P3A and P3B, even though these cumulative actions are not meant to be instituted at the same time; see Table 4.4.
[e]Saving of 15,000 yd^3/yr dredging.
[f]A fixed sand bypassing system or a fluidizer system are technical options.
[g]This action as an alternative to action P3A.
[h]Costs not applicable to JID.

to be more efficient. We do not anticipate shoreline recession in the critical zone to increase by virtue of the revised placement procedure over and beyond the present scenario; however, a major storm episode could cause drastic erosion irrespective of any selected sand placement protocol. If post-project monitoring of the beach suggests measurable adverse effects (in terms of retention time or shoreline position change), then this protocol must be revised again. Consistent annual (or bi-annual) dredging will provide a greater buffer against episodic events, and larger (over long term) dredging volumes, i.e. 60,000 yd^3/yr (49,000 m^3/yr) or more, placed on the beach should lead to larger beach volumes throughout the year. Dredging prior to the non-pumping (May-October) window should produce better summer beach conditions.

P1.4 This protocol will enable a more consistent maintenance of depths in the interior, and somewhat reduce sand deposition in the marina area. If as noted under action P1 the trap is increased in width, its impact on the adjacent banks, specifically the Dubois Park beach (which has been excessively hardened by concrete such that any sand deposited there is transported offshore by reflected wave action, thus causing the beach to lose the sand) and the bulkheads (many of which seem to have been poorly constructed and/or are in a poor state of repair) protecting private and public lands in the area must be monitored for any adverse impacts.

P1.5 The major ecological improvement here is on sea turtle nesting. Nesting turtles should benefit from greater quantities of sand per year added more frequently, at effective times of year, and spread out farther along the south beach. The sand derived from the JID trap (and the Corps trap) is typically suitable for sea turtle nesting. If nourishment is done according to the criteria for sea turtle nesting beaches outlined in Appendix G, sea turtles should benefit considerably from this action. An increase in death of biota via entrainment in the dredge will accompany any increase in dredging, however. This negative effect should be small relative to the positive effect on nesting sea turtles (based on biomass lost versus biomass gained). Spreading the nourishment farther alongshore may allow better retention of sand and hence a more stable and uniform beach profile for nesting sea turtles. If the design developed in this study is followed, the spreading zone will not extend far enough to the south to affect rocky outcroppings at Carlin Park. Increasing the JID trap dimensions in the manner described in this report should have no perceptible impacts on any of the ecological impacts that we have considered. The suggested new dimensions impact an area of high current and constantly shifting sand. Our model studies have indicated no significant effect of increased dimensions and dredging of the JID trap on ecologically important parameters in the interior.

P2.1 The recommended jetty modifications will not add to, or take away from, the present navigation access in any major way, but the reduction in sand influx should slightly improve access, e.g. in the marina area and the Intracoastal Waterway.

P2.2 The recommended jetty modifications should not measurably alter the present degree of navigation safety in the inlet area.

P2.3 Although elevation modifications to the north jetty are not expected to substantially change erosion patterns on the south beach, the lengthening and raising of the south jetty will reduce the sand influx from the south beach into the inlet. This reduction is estimated to be as much as 15% of the placement volume, and is particularly significant during initial profile adjustment following nourishment. The reduction in sand loss and the increased capacity of a lengthened south jetty, combined with improvements in placement protocol (Section P1.3), will tend to stabilize the south beach with an average shoreline position seaward of its present location. In Fig. 4.8, the approximate "no-inlet" shoreline taken from Fig. 2.2 has been plotted as a reference line. Note that even with the proposed extension the south jetty will extend less into the ocean than the north jetty. Given this factor, the proposed extension is unlikely to "intrude" into the littoral drift pathway, which will continue to be determined by the north jetty, particularly for the erosion-wise critical waves from the northeast. Note also the likely change in the vicinity of the "sea wall" connected to the south jetty by comparing shoreline positions in Figs. 4.7 and 4.8.

P2.4 There should be an annual saving of at least 15,000 yd^3 (11,500 m^3) of interior dredging, mostly from the JID trap, as a result of this action. The need to dredge the Corps trap (Intracoastal Waterway) could also reduce, especially if the saving is found to be greater than the minimum here noted. Therefore, the possibility of financial participation by the Corps in pursuing this option should be considered. Note also that action P.2 may reduce, but is unlikely to eliminate, the transport of fine sand into the marina area and into Region 3 past the FECRR Bridge. Therefore, a larger sand trap, as proposed under P.1, may have to be maintained simply because a larger trap will be able to better catch incoming fine sand than the present trap.

P2.5 Additional improvement on sea turtle nesting is expected from the increased sand bypassing and south beach stabilization to be expected from this option. Raising the south jetty should prevent sand from washing off of the south beach, which should improve the reliability of the south beach for nesting sea turtles. The "hooked" extension of the south jetty is the modification most favorable for nesting sea turtles. It should enhance the stability of the beach profile the now very unstable area immediately south of the south jetty. Presently, this area can become a death trap for incubating eggs because of being alternately attractive to nesting turtles, and washed out during incubation. Raising the north jetty by 3 ft (0.9 m) will reduce sand influx and hence should result in the need for less dredging and associated entrainment mortality of biota. Extending the south jetty will also add a small amount of artificial rocky habitat in the nearshore environment.

P3A.1 The 400 ft (122 m) extended north jetty should have a slightly beneficial impact on navigation access. This is because, even though the inlet ebb shoal will move slightly southward due the shift in the position of the inlet mouth, the present southeastwardly directed natural channel will be able to better self-maintain itself as a result of the focussed and concentrated tidal currents near the inlet.

P3A.2 The main purpose of north jetty extension is to improve navigation safety. This purpose will be accomplished in two ways: there will be a lesser likelihood of wave attack abeam, and within the inlet wave heights will reduce to one-half or less than at present. Also, the presence of a better self-maintained natural, southeastward channel should help improve safety.

P3A.3 The primary effect of a 400 ft (122 m) extension of the north jetty alone would be to greatly increase the south beach erosion due to the large retention and diversion of the net littoral drift by the jetty. Sand deficit due to shoreline recession will increase in the long run by at least 700,000 to 800,000 yd^3 (535,000 to 610,000 m^3) over the present. Recession will be most significant within a short distance south of the south jetty. Thus for example, at about 800 ft (244 m) south of the south jetty shoreline may recede by a distance on the order of 100 ft (31 m) relative to present. Similar recession may be experienced over an additional distance of 1,800 ft (549 m) at least. Therefore it is imperative that such an initiative be accompanied by a fixed bypassing plant (or a fluidizer system) at the north jetty. This combination can yield beneficial impacts on south beach erosion by providing a continuous sand bypassing system, allowing more effective and immediate control over the bypassing process by JID. For instance, bypassing rates can be increased following major storm events to mitigate further vulnerability, and subsequently reduced as necessary. However there are risks involved when relying on mechanical pumping facilities continuously exposed to the open ocean environment. Down time must be expected, and the potential for difficulties will also increase during storm events when dependable performance of the bypassing system is most needed.

P3A.4 The advantages gained by this action with respect to interior sedimentation would be about the same as those for action P2, since the addition of a long north jetty is not likely to materially reduce sand transport into the inlet around the north jetty, especially after the beach sand fillet on the north side establishes a new configuration commensurate with the new jetty design. It will be necessary for active "intervention", e.g. by the installation of a sand bypassing system, to reduce sand influx. For reasons cited in P2.4, the trap dimensions should be according to the plan per Fig. 4.6. See also description of action P1 for the recommended steps towards trap enlargement.

P3A.5 This option adds some significant ecological risks because of the presence of a long north jetty dependent on energy-using continuous pumping facilities to keep it from doing more harm than good. When the pumping facilities fail, the sand shadow created down drift along the south beach could cause greater erosion there than occurs now. Moreover, as the price for energy rises in the future, breakdowns may not be repaired, leaving behind a jetty with a net negative impact that cannot easily be removed. Furthermore, since the zone of influence of a long jetty on sand transport extends far downdrift, the rocky outcroppings at Carlin Park may expand or contract depending on the ultimate sand balance achieved with the jetty and associated sand transfer facility. Although a long extension to the north jetty will provide additional artificial rocky habitat, and the fixed bypassing plant (or the fluidizer system), when working, would likely benefit turtles from the more continuous supply of sand to the south beach (if the noise from the plant and moving sand does not discourage them), we feel that the ecological risks are too great to create an overall ecological improvement. Finally we must note that any mechanical arrangement close to Jupiter Inlet Colony must be so designed as to minimize engine noise and smell.

P3B.1 Without the north jetty, absent in this action, no measurable change will occur with respect to navigational access, as long as the sand fluidization system is non-intrusively installed in the channel.

P3B.2 As long as the sand fluidizer system is non-intrusively installed in the channel, no change will occur in the degree of navigation safety afforded by the inlet.

P3B.3 The benefits to beach stabilization in this case are analogous to those for P3A.3, that is, continuous bypassing and much more effective control over the sand transfer process. However, in this instance a fluidizer based in the present trap region provides a more sheltered environment for operation of the pumping system and an expected higher level of dependability than in action P3A.

P3B.4 Assuming the technical viability of the sand fluidizer system in the channel and low down-time, there are potential advantages of this action to controlling sedimentation in the interior, since the trap can be maintained at a desired depth, thereby: 1) maintaining adequate depths, and 2) increasing the efficiency of trapping, particularly if the depths in the trap are maintained at -20 ft (6.1 m). The marinas would benefit from this action. See also comments regarding trap dimensions in P3A.4.

P3B.5 The addition of an interior fluidizer bed and pumping system should provide the benefits to sea turtles of nearly-continuous pumping if: 1) the plant is reliable and not frequently out-of-service; and 2) the noises during the nesting season emanating both from the plant and from the discharge on the south beach, do not reduce nesting more than they enhance it. Habitat enhancement should arise from the more continuous availability of a beach of suitable profile and quantity of sand, and the more rapid restoration of the beach profile following events of extreme erosion. In addition to the possible improvement of sea turtle nesting habitat, we suggest that a decrease in dredging-entrainment mortality may result, though this has not been proven. Water-column organisms may be better able to avoid this system, while benthic organisms may be similarly affected, though this is by no means certain at this time. This is a superior option because it does not involve adding a long north jetty (see P3A.5).

I1.1 There is no strong relationship changing the Corps trap dredging and sand pumping protocols and navigational access seaward of the Corps trap in the Intracoastal Waterway; however, regularization of the dredging protocol should be slightly beneficial with respect to depths in the Intracoastal Waterway.

I1.2 This action is unlikely to impact navigation safety in any significant way.

I1.3 Although JID does not have the ability to dictate the actions of the Army Corps of Engineers, coordination can yield substantial benefit to the south beach. With the JID trap dredged prior to the non-pumping window (i.e. March-April), complimentary dredging of the Corps trap after the non-pumping window (i.e. October-November) and placement on the south beach can provide a significant buffer volume at the start of the winter season. Many major erosion events occur in October and November (e.g. Halloween Storm, 1991), and placement of sand on the south beach following such events will alleviate a vulnerable condition. In the absence of such early storms, the placed sand will provide an additional winter buffer for later storm events.

I1.4 Regularization of the Corps dredging and sand placement protocols would be beneficial, since a coordinated effort by JID and the Corps should reduce the possibility of placement of too much sand on the south beach; as the excess sand has the tendency to move back into the inlet.

I1.5 Coordinating with the Corps of Engineers' dredging should improve habitat for nesting sea turtles by adding more sand more often to the south beach. The sand quality from the Corps of Engineers' trap is adequate for nesting turtles, though slightly finer than that from the JID trap, so may become slightly more compact on the beach (see Appendix G).

I2.1 There is no relationship between boat speed (a human and mechanical element) and navigation access (a physical feature).

I2.2 The potential benefits of controlling boat speed to navigational safety are undoubtedly high.

I2.3 Boat speed regulation will not tangibly effect erosion of the south beach, but would reduce interior bank erosion associated with boat wakes.

I2.4 Less boat wake-induced bank erosion (see also I2.3) also means less sedimentation, e.g. in Region 3 west of the FECRR bridge.

I2.5 Although the effect of regulating boat speed seems negligible for many included ecological considerations, we heartily recommend reducing boat speeds because of the side-benefit of helping to diminish the potential for mortality to manatees from boat collisions. There would also be a lower risk of damage to the intertidal vegetation due to smaller boat waves.

I3.1 Since the main purpose of beacons or danger signals would be to mark navigation access, the potential advantage of this action is evident. However, see I3.2.

I3.2 Beacons should in general improve navigation safety. However, if they do serve to lure unwary mariners to cross the offshore bar at night without knowledge of channels, a safety problem could be created. While a danger signal may be more appropriate, similar safety hence liability issues may occur for JID.

I3.3 Beacons or danger signals will not affect the south beach.

I3.4 Beacons or danger signals will not impact sedimentation in any way.

I3.5 Jetty lights conceivably could disorient a small number of both adult and hatchling sea turtles that appear very near to the jetties. We believe, however, that if lights are installed in the manner indicated in this report and with appropriate consideration of Florida Department of Natural Resources Sea Turtle Protection Plan guidelines for permanent lighting, this effect will be negligibly small and permissible.

I4.1 The main purpose of the offshore navigation channel is to provide an eastern access through the ebb shoal. However, since this channel will tend to close each Fall and remain closed during the subsequent Winter and part of Spring, the benefit will be less than that for a year-round channel.

I4.2 Navigation safety should improve during those time when the depths in the channel in critical areas are greater than at present, on a seasonal basis.

I4.3 Regular offshore dredging of an offshore channel may mitigate south beach erosion only if the dredged material is placed on the beach, increasing sand volumes by a moderate amount. It is expected that such channel material will be suitable beach sand. Nevertheless, potential adverse impacts remain uncertain. Tentatively we ascribe no benefit to beach erosion by way of this action.

I4.4 There is unlikely to be any change to interior sedimentation as a result of this action.

I4.5 It is difficult to predict what effects a channel straight out offshore may have on the quantity of beach sand and the stability of the beach profile, two important factors in sea turtle nesting. If increased wave energy on shore results from dredging this channel, greater beach erosion could result, thereby increasing the risk to sea turtles. Since any dredged channel will rapidly fill in, however, any negative impacts on sea turtle nesting habitat should be easily reversed by discontinuing channel maintenance. Therefore, we recommend monitoring the effect on the beach in the event this channel is constructed. The material dredged from the channel, if placed on the south beach in a manner consistent with the needs of nesting sea turtles, could improve sea turtle nesting habitat in proportion to the amount nourished (see Appendix G). On the other hand, dredging entrainment mortality should also increase in proportion to the amount dredged. Since the quantity of added material will likely be small, we consider these positives and negatives to be offsetting.

I5.1 Since dredging for this purpose must be done in an area that does not impact the beaches or the inlet, no relationship can exist between this operation and navigation access.

I5.2 No impact on navigation safety will accrue as a result of this action.

I5.3 Offshore dredging can benefit the beach erosion difficulties provided that the placement is made on the south beach <u>and</u> the dredged material is of suitable beach quality. Very fine material will be quickly lost offshore and provide minimal benefit. Note however that dredging of large quantities of sand from the ebb shoal region can reduce the shoal height, thus increasing wave action on the beach and resulting in a potentially negative impact.

I5.4 This action will not alter the present mode of sedimentation in the interior.

I5.5 Dredging from an offshore site that does not affect the wave energy reaching the beach in and of itself will not positively or negatively affect any of the ecological aspects considered except by increasing dredging-associated entrainment mortality of biota. No offshore rocky outcroppings presently occur within a kilometer of the ebb shoal. A ten year frequency of offshore dredging has no known positive or negative effects compared to any other reasonable frequency. Placing the dredged material on the beach, if done with sensitivity to the needs of nesting sea turtles could improve sea turtle nesting habitat in proportion to the amount nourished (see Appendix G).

I6.1 The interior trap will not provide any additional access, but increased depths would mean a slight benefit.

I6.2 Navigation safety may improve marginally.

I6.3 Dredging of an additional interior trap will not affect the south beach erosion since, in general, material in the interior region proposed is considered too fine to make suitable beach material.

I6.4 The trap should help reduce the rate of sedimentation west of the FECRR bridge. However, influx of sand in Region 3 will not be entirely eliminated.

I6.5 Although the proposed site for the interior trap has no submerged vegetation, dredging an interior trap just east of the aquatic preserve boundary as described in this report could negatively impact nearby seagrasses (primarily from sediment plumes during dredging) and will cause entrainment mortality of biota during dredging. The method of disposal of material dredged from this trap is also an important issue that must be resolved. It will be too fine for beach placement. This material could conceivably be used to construct new areas of submerged and intertidal vegetation, or supratidal habitats. Dredging this new trap every ten years as proposed in this report will mean fewer but larger sediment plumes. Overall impact of dredging frequency on entrainment mortality of biota and reduction on seagrass production is unclear. Dredging smaller volumes more frequently may not offer any advantage in these regards. During each 10 yr event, however, a large volume of material will be in need of disposal. This volume may be sufficient for creating intertidal, submerged, or supratidal habitats in the vicinity of the trap. Such use of this material could mitigate any negative impacts from interior trap dredging.

4.5 Comments on Management Options

If one were to add the impact numbers in Table 4.3 row-wise, the totals would be: P1 = +12, P2 = +19, P3A = +29, P3B = +21, I1 = +9, I2 = +17, I3 = +10, I4 = +8, I5 = +2 and I6 = +6. Several observations can be made with respect to these very approximate, subjectively based quantities. Firstly, all totals are positive, which is not surprising since situations that would potentially lead to net negative impacts were eliminated from further consideration at the technical stage of action evaluations (see progress reports and other correspondence with JID). Secondly, if all actions are to be carried out (choosing however between P3a and P3B), the implementation time schedule given in Table 4.4 is recommended, allowing adequate time periods between certain actions for monitoring impacts.

Thirdly, having said the above, we note that the high nets (benefits) for actions P3A and P3B depend on the underlying assumption that, by the beginning of the sixth year when these actions are recommended (see Table 4.4), quality technology for sand bypassing will be available. If this does not turn out to be the case, then the benefits may be marginally positive or even negative. In general therefore, actions P3A and P3B, which are also estimated to be costly, warrant consideration only at a future date.

Finally, our strongest recommendations are for P1, followed by P2, I1, I2, I3 and I5. In recommending P1 as the first choice over P2 we note that while P2 may be technically more beneficial than P1, practical considerations dictate that we first attempt to fine-tune the existing protocol (P1) before considering more permanently regime altering solutions (P2). I3 offers overall advantages, but places more management responsibility on JID with respect to operation of beacons or danger signals. Certain liability issues may arise as a consequence, and these must be taken into account. Thus while we recommend I3 on a technical basis, its implementation may require further considerations by JID. I5 does not have a high net benefit by way of the evaluation procedure selected in Table 4.3, but we consider it to be an entirely necessary action in the context of Florida's beach management. High cost may preclude I4. I6 has a low net benefit, partly due to the negative ecological consequences; nevertheless it may become essential, although without further action, specifically dredging west of the FECRR Bridge, the sedimentation problem there will not be solved.

4.6 Monitoring

JID has been duly conducting necessary beach and bottom surveys related to their dredging and sand transfer program. For every relevant new action planned, further surveying and sediment sampling must be carried out in accordance with the requirements to be determined by the State of Florida Department of Natural Resources. On the other hand, JID has presently instituted no ecological monitoring effort, which we recommend.

The following ecological monitoring plan for the vicinity of Jupiter Inlet and the Loxahatchee River Estuary is non-destructive, extensive, and cost effective. Many of the routine tasks can be accomplished by trained volunteer

Table 4.4: Implementation dates of actions.

Action	Implementation Date Beginning Start of[a]
P1	First year.
P2	Third year, after the impacts of P1 (and I1) are monitored.
P3A	Sixth year, after ongoing technological developments in sand bypassing elsewhere are monitored.
P3B	Sixth year, after ongoing technological developments in sand bypassing elsewhere are monitored.
I1	First year.
I2	First year.
I3	Third year, if desired, after a decision is made as to whether or not to implement P2.
I4	Fifth year, if desired, after monitoring impacts of P2. To be discontinued if P3A or P3B are implemented, if a self-flushing channel is maintained by virtue of P3A or P3B.
I5	Tenth year.
I6	Fifth year, if necessary, after monitoring impacts of P2.

[a]Relative to the year in which management plan is initiated.

observers. An economic trade-off occurs in monitoring programs between extensive sampling, in which many sites are observed frequently, and intensive sampling, in which each site is characterized as thoroughly as possible. For tracking large-scale changes in this dynamic environment, extensive sampling is imperative. Thus, the intensity of sampling at each site is reduced to enhance cost-effectiveness, without sacrificing the ability to detect temporal and spatial changes in the set of simple parameters. Any modification of this plan should, above all else, preserve the spirit of extensiveness of observations, or the utility of the plan for its intended purpose of tracking ecological changes in the estuarine and the vicinity of the inlet will be compromised.

Nearshore rocky outcroppings. The purposes of this phase of monitoring are: 1) to determine the frequency of burial by sand and subsequent re-exposure of nearshore rocky outcroppings in the vicinity of Jupiter Inlet; 2) to detect any significant trends in sand coverage over time; and 3) to evaluate the consequences of burial and re-exposure on the ecological development of the bottom. To evaluate the ecological significance of any changes that may be caused by future inlet, shoal, or beach alterations, it is necessary to describe the routine variability in sand coverage and judge the routine stability or instability in bottom communities in the vicinity of the inlet. To evaluate the ecological significance of any changes that seem to occur in conjunction with such alterations should be compared against the spectrum of natural changes in the vicinity. To this end, extensive (rather than intensive) monitoring is required. With limited funds, simple observations done frequently at many sites are therefore preferable to sophisticated or complex sampling that can only be afforded at a few sites. With this trade-off in mind, the following plan is offered. Some elements of this plan could be adequately accomplished by citizen volunteers. The dimensions given in this plan are suggestions that may require modification in light of actual field experience with the plan. A pilot program is recommended.

Walk the beach north and south of the inlet for two kilometers once per week at low tide and record where rocks are exposed in the intertidal zone or visible in the surf. Snorkel once per month on a calm day along multiple transects from the low tide surf zone to 250 m offshore. Snorkelers should record the nature of the bottom every 5 m to give 50 observations points per transect. Ten transects north and ten south of the inlet should be snorkeled. Transects should be spaced 200 m apart. Records at each observation point should include whether the bottom was sand or rock (hard bottom) and should include a quick estimate of the biotic development on the sand or rock. Biotic development should include the degree of vegetative cover (little or none, moderate, heavy) along with a description of the one to three most prevalent forms of vegetation. The brief check should also include the degree of cover by the more slowly growing attached colonial animals. This could simply be a rapid check of presence or absence of hard corals, soft corals, sponges, mat-anemones, colonies of worm rock, colonial tunicates, etc. in a square meter centered on each observation point. These observations of biotic development are not intended to fully describe the biotic community, but rather to broadly assess the ecological development and stability of hard and sand bottom in the vicinity, and the ecological recovery of any re-exposed hard bottom that presents itself over the course of the monitoring.

Sea turtle nesting. The objective of this phase is to determine the frequency and success of sea turtle nesting as a function of beach profile and beach stability in the vicinity of Jupiter Inlet. Again, a high frequency of sampling is required both to characterize the relationship and so that any changes thought to be caused by inlet and beach alterations can be compared to routine changes in the beach profile . Thus, for feasibility, simple descriptors of beach profile are needed. The following program is suggested. Once again the suggested quantities may require alteration with experience.

Walk the beach 1000 km to the north and south of the inlet each morning during nesting season (April through November) recording each successful crawl and each false crawl (the turtle returned to the sea without depositing eggs). Observers can be trained by experienced personnel to distinguish these differences. At each successful and false crawl, record major characteristics of the beach profile. These characteristics should include a rough estimate of the slope from mid tide to the nest and any major irregularities in the profile (steep scarps or other obstacles to turtles such as large rubble or driftwood, massive driftline materials, etc.). The observers should also record any sudden or otherwise noticeable changes in beach profile at marked sites along the beach (see next paragraph).

At the beginning of the nesting season and monthly thereafter through the season, beach profiles should be surveyed within 30 m from the jetties and every 100 m north and south to give 10 monthly beach profiles north and 10 south of the jetty. Iron pipe markers should be installed at the mean sea level mark and at the dry sand berm at each profile. This will be used to measure changes in the beach profile among the monthly surveys, and therefore track the stability of the beach profile. The markers will also be used by the daily observers to estimate the beach profile at turtle crawls as indicated above. The markers will be moved monthly when required to keep up with changing beach profiles.

Intertidal vegetation (marshes and mangroves). The objective of this phase is simply to check for large changes in the extent and production of marshes and mangroves in all arms of the Loxahatchee River Estuary, including the Dubois Park Lagoon and one kilometer inside the north and south arms of the intracoastal waterway. Routine changes in these components are not as rapid as those involving sand transport along the beach, so the frequency of monitoring can be less. The following plan is suggested.

Take aerial photos initially and annually thereafter that are suitable for distinguishing intertidal marshes and mangroves from upland vegetation. Provide copies of these photos to observers who will visit all sites monthly to inspect for noticeable changes in the extent or production of the intertidal vegetation. Such changes include expansion or contraction of the aerial extent of intertidal vegetation, appearance or disappearance of the dominant type of vegetation, or changes in the dominant vegetation (discoloration, extensive replacement of major species by other species). In addition, any incidental observations of use of the site by vertebrates (birds, mammals, reptiles, amphibians, fish) should be noted on these visits.

At least five sites that have considerable mangroves within the region (including the Dubois Park Lagoon as one of the sites), at least 30 mangrove trees should be randomly chosen among all sizes over one meter tall and identified for growth measurements. The common foresters measurement of diameter at breast height (DBH) is not consistently possible with mangroves because they often do not grow straight. Hence, a spot should be marked on the tree trunk one meter from its base, but halfway between any branches to try to avoid the swelling of the trunk common adjacent to branches. The diameter of the trunk should be measured every other month at that spot to the nearest mm. This will provide a record of growth, which should be sensitive to environmental changes.

As with the rocky outcroppings, the purpose of this mangrove monitoring is not to fully characterize the ecological communities at these sites, but rather to effectively monitor major ecological changes. With a limited budget, effectiveness means sacrificing intensive characterization, for extensive diligence and ability to use volunteer help.

Seagrasses (submerged vegetation). As with the mangroves, the purpose of this phase is to track changes in the extent and general nature of beds of submerged vegetation. Seagrasses and other submerged vegetation are more difficult to monitor than intertidal vegetation, but they are perhaps one of the most useful indicators of changes in water and sediment inside the estuary. They are not only very important habitat for fishes and manatees, but are also dependent upon the quality of the water and sediment to grow. They are sensitive to changes in light, depth, salinity, and temperature and sediment type. Thus, to be able to detect the influence of various specific happenings around the estuary (such as canal discharges, inlet modifications, construction activities, etc.) it is important to capture routine changes in the type and extent of major beds of submerged vegetation. The response time of seagrasses to routine changes in the environment may be on the order of months, though sudden changes (such as a sudden freshening) could conceivably cause damage within days. With this in mind, the following monitoring plan is suggested again with the caveats of the plans above.

Three times per year the extent of major seagrass beds should be mapped by snorkelers. Within at least five major beds (including the Dubois Park Lagoon bed), at least 30 sites should be randomly chosen and marked for monthly inspection by a snorkeler. Upon inspection, the most dominant species should be recorded, along with an estimate of the average length of its blades (nearest cm), width of the blades (nearest mm), and shoot density (using an internodal length estimate). Water depth (relative to mean sea level) should be measured at each inspection station three times per year. To be useful for repeated inspection, care must be taken not to damage vegetation at the inspection stations.

A few water quality parameters should be monitored generally at each site (but not at each individual inspection station) on each monthly visit. This will give an idea about the environmental variation at each site. These parameters should include salinity, water temperature, and light penetration (measured as the distance required for a white pole to disappear when viewed underwater by a snorkeler).

To assess bottom vegetation more generally throughout the estuary, monthly inspections of the bottom should be made to at least 50 permanent inspection stations randomly chosen among the submerged areas throughout the Loxahatchee River Estuary that are not within the seagrass beds mapped above. This will help to track the appearance and disappearance of ephemeral bottom vegetation (seagrasses and algae). The most dominant (and second most-dominant if obvious) species of vegetation should be recorded along with an estimate of the overall percent cover by all vegetation (nearest 10%, 0 to 10 scale) within a square meter frame centered on each station. Again, to be useful for repeated sampling, care must be taken not to damage the vegetation at the site.

Salinity intrusion. The purpose of this phase is to track salinity and the impact of salinity changes in the upper reaches of each arm of the Loxahatchee River Estuary. Salinity in these areas is highly variable depending on the frequency and intensity of rainfall and on freshwater releases from the C-18 canal. To be able to attribute changes in salinity to specific events requires a thorough evaluation of the routine variation. Thus frequent, or ideally, continuous salinity sampling is required. By also regularly monitoring species shifts both in low-elevation vegetation (in swamps and marshes) and in littoral vegetation along the edges of each arm, major ecological consequences that may be caused by salinity intrusion can be documented. The following monitoring plan is offered.

Install continuous salinity recorders 1 or 2 km inside the North and Northwest arm of the Loxahatchee River Estuary, another inside the Southwest arm halfway to the canal lock, and another at the railroad bridge. If these recorders cannot be afforded, then weekly measurements of salinity by trained volunteers would offer valuable information.

In addition to salinity monitoring it is imperative to monitor the progress of salt tolerant species of vegetation up the arms and any losses or regression of freshwater species. Monitor swamp, marsh, and littoral vegetation at the edges by visiting each arm three times per year to identify the zone of change from saltwater to freshwater vegetation. Look for the presence of specific indicator species such as saltmarsh cordgrass (*Spartina alterniflora*), giant cordgrass (*Spartina cynosuroides*), mangroves, and cypress trees, and saltwater and freshwater submerged vegetation present in the shallow edges, if any. Mark sites of transition with permanent poles or other markers to detect shifts in the zones of transition from saltwater to brackish and brackish to fresh between sampling trips.

APPENDIX A: COASTAL AND ENVIRONMENTAL ENGINEERING MANAGEMENT ELEMENTS FOR SANDY TIDAL INLETS

A1. Introduction

Management of a sandy tidal inlet for maintaining a navigable channel has been an issue to contend with since the early days of waterborne commerce. In recent years this issue has taken on new dimensions as a result of the problem of recession of the contiguous shorelines, and ecological damage that may accrue from corrective measures. In consonance with the nature of the problem for example along Florida's sandy shoreline, the focus here will be on Florida inlets. In what follows a perspective based on coastal processes and environmental imperatives is developed (Mehta and Montague, 1991).

A2. Shoaling due to Littoral Sand

Two relevant questions are: 1) what is specifically meant by tidal inlet management?, and 2) why is it required? In these contexts it is worth reviewing the general nature of sand transport and budget along a relatively straight barrier shoreline punctuated by tidal inlets, say every 15 to 30 km, as shown in Fig. A.1. Consider a micro- or mesotidal environment having a dominant direction of wave approach and associated alongshore sand transport over a relatively narrow nearshore column of water bounded by the shoreline and the depth of closure, say on the order of 9 m. This alongshore transport, coupled with shore-normal sand transport within the water column leads to the development of a longshore sand bar whose configuration is modified near each inlet. This modification primarily amounts to the occurrence of the ebb shoal, while in the interior tidal waterway flood shoals occur.

Consider the net rate of littoral drift (equal to the difference between the gross rates of drifts in the two directions shown by arrows) applicable to barrier segments of the shoreline. Reported values of the net drift rates obtained from accumulations at the updrift jetties of inlets tend to decrease, in many instances, from segment to segment in the downdrift direction. With respect to the difference in the net drifts between two adjacent shoreline segments, say A and B, i.e. $10^5 - 6\mathrm{x}10^4 = 4\mathrm{x}10^4$ m^3/yr, it follows that the mass of sediment corresponding to this volume difference must deposit each year either in the nearshore waters of barrier segment B, or inside the inlet between segments A and B. Assume barrier B to be 20 km long having a width of 200 m between the shoreline and the depth of closure. The area available for sand deposition will be $4\mathrm{x}10^6$ m^2. Let the inlet channel between barriers A and B be 100 m wide and 0.5 km long. Thus the deposition area of the channel will be $0.5\mathrm{x}10^5$ m^2. Further assume that only 10 % of the depositing littoral drift sand, i.e. 4,000 m^3, settles in the inlet each year. Then, say over a 10 year period, the depth in the inlet will decrease by 80 cm which is measurable, while the beach bottom, assuming sand deposition to be uniform over it, will rise by only 9 cm, which is comparatively small. This simple illustration shows why shoaling of inlets can become a problem for navigation, while deposition of a much greater total quantity of sand over the beach bottom may remain undetected.

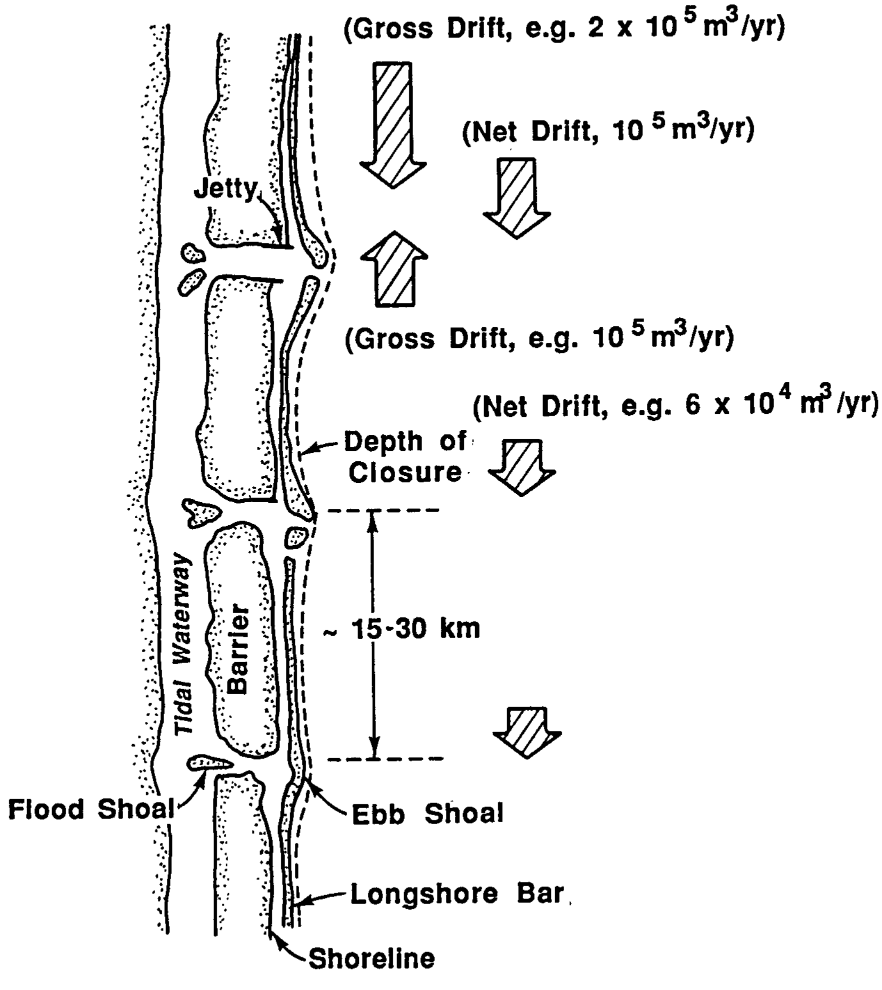


Fig. A.1. Barrier shoreline with sandy tidal inlets and littoral sand transport.

Since the ingress of sand into the inlet channel is a manifestation of littoral sand drift it follows that, inasmuch as the role of each inlet in influencing the regional inventory of sand goes well beyond the beaches in the proximity of the inlet, a regional management approach based on morphologically identifiable segments of the shoreline is far more desirable than one based on physical limits dictated by institutional constraints.

A3. Elements in Inlet Management

Consider the sediment pathways near an inlet as shown in Fig. A.2. The updrift and downdrift shorelines have been modified by the presence of the inlet as well as its training by jetties. The updrift accretion or fillet, may or may not be balanced by downdrift loss of sand depending upon a number of controlling physical parameters. Even in cases where it is balanced, accretion is usually localized over some distance updrift which depends on the jetty length, wave intensity and approach direction etc., while the effect of erosion is often felt over much longer distances downdrift, occasionally over most of the downdrift barrier beach. About 85 % of beach erosion in Florida over the past century has been attributed to effect of this type (Dean, 1988).

Of the two natural sediment pathways based on the net drift concept shown in Fig. A.2, one characterizes (net) sand bypassing which occurs over the ebb shoal, while the second indicates (net) sand influx. At point A the two pathways diverge, while at point C the first pathway reattaches itself to the shore-parallel sand bar. The region of primary concern is between points B and C, the main area of sand deficit. The cause of this deficit is insufficient net supply rate of sand in relation to its rate of depletion by local waves and currents. A navigation channel cut through the ebb shoal may measurably intercept the first pathway thus exacerbating the deficit, while at the same time this channel may experience significant shoaling in the interior as a result of the second pathway.

The need to alter natural sediment pathways to maintain adequate channel depths and minimize downdrift erosion leads to the following three elements in inlet management: 1) Maintenance of the navigation channel to allow safe passage of vessels under non-extreme climatic conditions, 2) restoration of the sand flow to mitigate the downdrift deficit, and 3) maintenance of ecological balance while fulfilling the requirements of the first two elements.

Elements 1 and 2 can pose competing requirements, since the ideal solution for meeting the second requirement would be to close the inlet, and this has been done in cases where the need of maintaining shoreline stability is overwhelming. In general however, it is essential that technology be provided to address the issues of navigation and erosion simultaneously, without damaging the environment in the process.

A4. Creation of Artificial Pathways

Simultaneous fulfillment of the first two, coastal engineering elements is conventionally achieved by creating artificial pathways shown in Fig. A.3, in order to alter sand "sharing" at the inlet. Consider first the natural pathways. Pathway 1 is the same as that in Fig. A.2, while pathway 2 is now considered to represent the *total* influx of sand. Pathway 3 implies transport of sand to the so-called passive part of the ebb shoal from which, by definition,

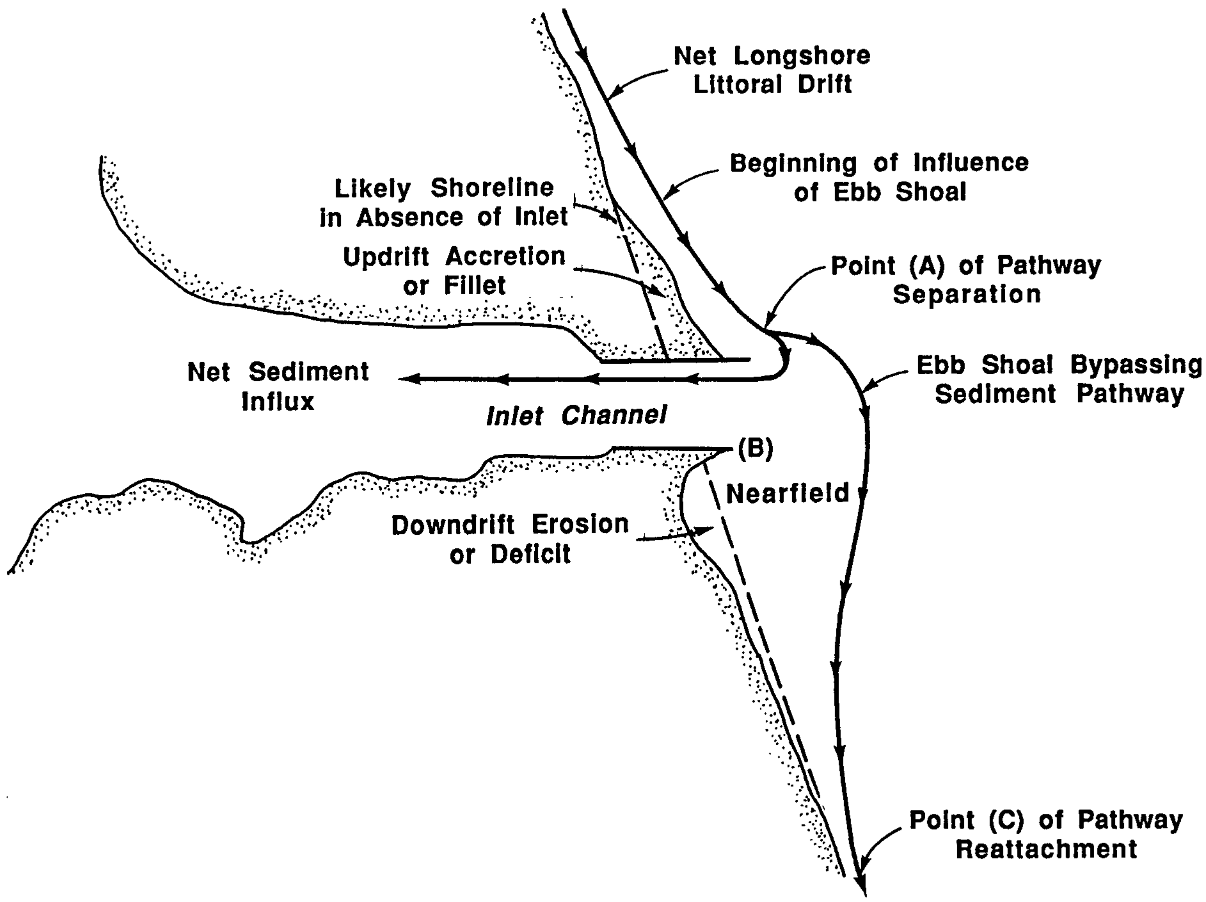


Fig. A.2. Interception and modification of the littoral sand pathway by an inlet.

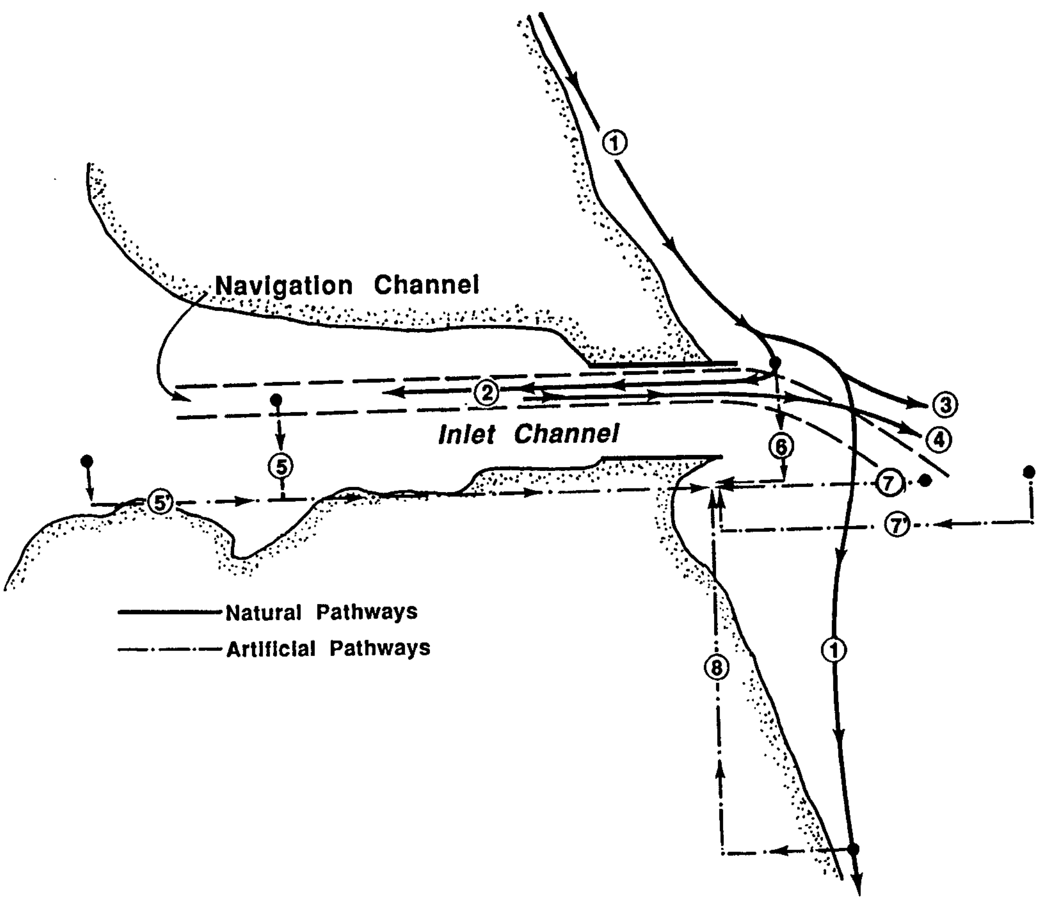


Fig. A.3. Natural and artificial sediment pathways in the inlet nearfield and channel.

the deposited sand does not return to merge with pathway 1. Pathway 4 is that portion of the sand which is also transported out to the passive part of the shoal by ebb currents.

Inherent to the described role of pathways 3 and 4 is the assumption that the ebb shoal, at least the passive portion, is in a state of growth, however small the growth rate might be. This can only be the case if the bathymetry surrounding the inlet has not attained equilibrium with the ambient hydrodynamic environment. Consider for example navigable inlets along the east coast of Florida, most of which have been "newly" opened or trained by jetties in the last 100 years. New inlets develop ebb shoals which are previously absent, while training causes stronger currents to push existing ebb shoals into deeper offshore waters. Since however the controlling depth over the shoal is determined largely by wave action, the shoal grows in planform. The rate of growth is rapid in the initial years, but steadily decreases as the shoal size approaches equilibrium. Many of the ebb shoals along the east coast of Florida are known to be growing presently albeit at slow rates, decades after new inlets have been opened or natural ones trained.

While natural pathways operate over time-scales of tides and are episodically influenced by wave action due to storms and hurricanes, the time-scales of artificial pathways vary widely, dependent as they are on the technology used. Pathway 5 is the most common means of "resharing" sand for example by hydraulic dredging of the interior channel. Pathway 5' includes cases in which the flood shoal is dredged independently of the navigation channel, e.g. at Sebastian Inlet. Pathway 6 is typically instituted by use of sand transfer plants, e.g. at Palm Beach Inlet, or by related systems that essentially achieve the same purpose. Pathway 7 involves dredging of the offshore channel, which for example is customary in Federally maintained navigation channels. In those cases in which the dredged material is found to be compatible, it is transported to the beach. Alternatively the ebb shoal may be mined for sand through an operation not related to navigation (pathway 7'), and the material transported to the downdrift beach, as at Redfish Pass.

Given these artificial pathways, and having the technology to utilize them as and when needed for purposes of continuous or near continuous transport, thus amounting to 100 % sand bypassing, the two coastal engineering management elements can be fulfilled simultaneously.

Inherent to the development of artificial pathways is the need to establish a sand budget based on the natural pathways within a control region. In Fig. A.4 such a region is shown, whose designation requires the determination of the different flux boundaries, i.e. boundaries with zero net flux, or boundaries through which the fluxes are known. The last condition occurs at the shore-normal boundaries 1 and 3, given the littoral drift rates. Zero flux boundary 4 can be established up estuary provided no sediment arrives by river. If it does, there is the likelihood that the riparian sediment is of different composition than the marine material crossing the boundary upstream. In the latter case fluxes in both the directions must be considered.

In the absence of the inlet, the depth of closure would practically suffice as the zero flux boundary 2, especially over comparatively short term time-scales e.g. on the order of 25 year design life of a sand sharing project, during which shore-normal transport may be negligible. In the area of the ebb shoal however, the depth of closure typically diverges from the boundary delineating the offshore extent of the shoal. Between these two

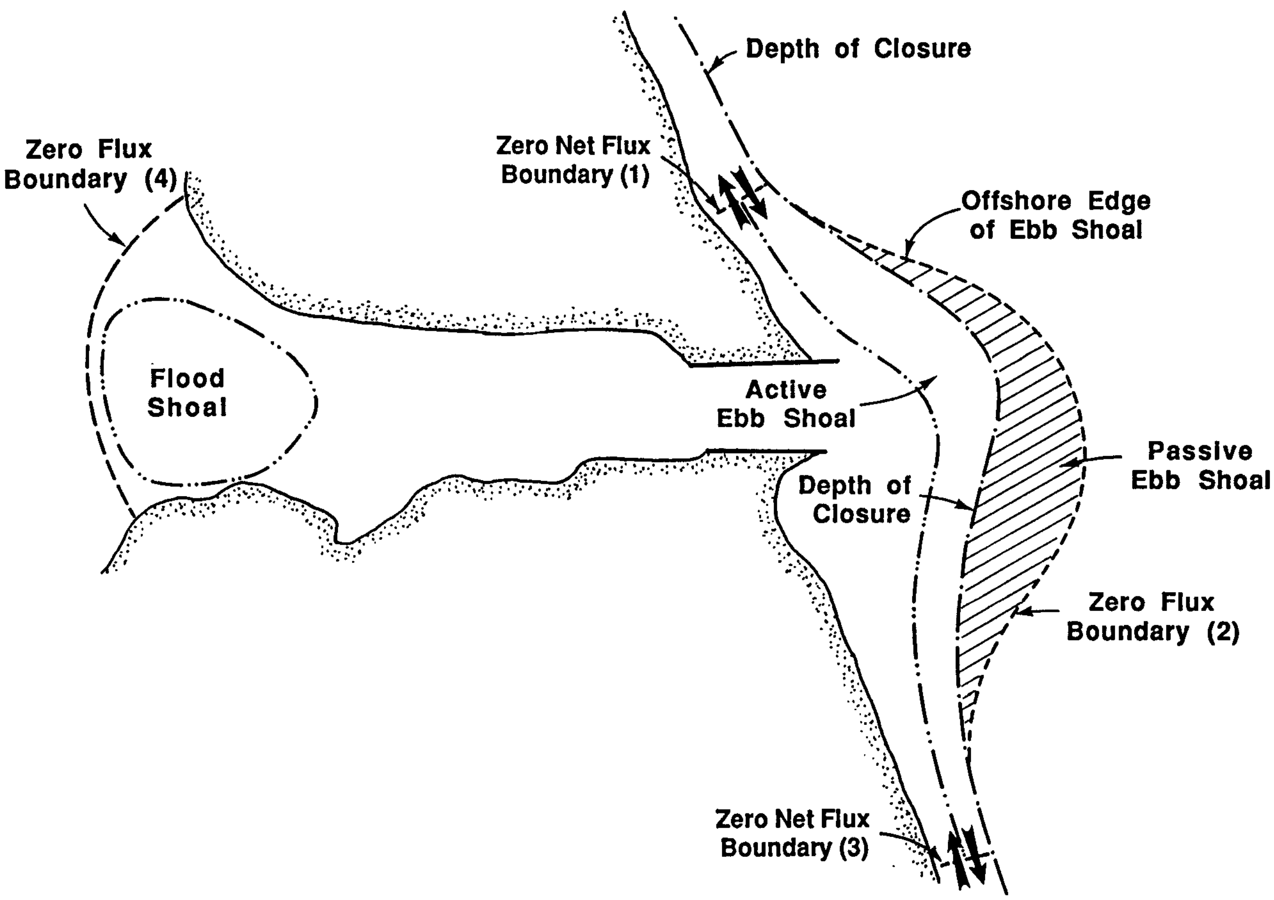


Fig. A.4. Control water area identifying the passive ebb shoal.

boundaries lies the passive ebb shoal. The zero flux boundary in this area is therefore defined by the offshore edge of the passive ebb shoal. The points at which the two boundaries merge essentially defines the extents of upstream and downstream influences of the ebb shoal, and therefore boundaries 1 and 3.

In a hydrographic investigation for determination of natural sediment pathways, shoal boundaries and sand budget it is technically advantageous to follow a "hybrid" approach involving a combination of a field study to measure the governing parameters *in situ*, a laboratory study with the help of a physical model to reinforce and extend the results from the field, and a mathematical study which, together with field data and physical model results, can assist in developing management options. The hydrographic investigation should sequentially focus on: 1) the nature of bottom topography, and the composition and stratigraphy of the bottom material within the control region, 2) inlet nearfield and channel hydrodynamics including the wave-current interaction, 3) effect of changing water density between the interior and the exterior water bodies on the flood and ebb flow distributions, and interaction between river discharge and salt water ingress up the channel, and 4) location of sediment pathways, shoal boundaries and sand budget for the control region. Once the sediment budget is developed, selection of appropriate technology for the creation of artificial pathways becomes feasible. For example if the ebb shoal is to be dredged for beach sand, it is essential to identify the passive part of the ebb shoal, since any extensive dredging of the ebb shoal that is not passive can lead to potentially serious problems for the stability of the beaches due to increased wave penetration and reduced sand bypassing.

A5. Effective Bypassing

The requirements to achieve 100 % bypassing of sand by artificial means, commensurate with the maintenance of a navigation channel and control of downdrift erosion, are contingent upon the availability of resources and dedicated technology. Problems occur in implementing bypassing technology in most cases due to inadequacies associated with these two factors. Additional constraints can arise if the sediment required to be bypassed is either unsuitable for beach placement, or if there are possibilities of damage to benthic habitats.

Effective bypassing solutions can be "passive" or "active" or, as commonly the case, a combination of these two modes. Passive solutions are based on construction of structures including jetties, sometimes extended linearly and sometimes with a certain curvature, or in some cases having non-parallel orientation to control sand influx, while attempting to minimize the blockage of sand transfer from the updrift to the downdrift side.

Long jetties were constructed at St Mary's Entrance and St John's River Entrance to cut off sand influx completely, but given the concern for downdrift beach erosion that this may cause, such an option may be precluded from consideration. Curving one (usually the updrift) jetty, such as at South Lake Worth Inlet, can actually serve two purposes. First, it allows a somewhat smoother pathway for natural sand transfer from the updrift to the downdrift side. Secondly, it provides a certain degree of protection to vessels against beam waves as they enter the inlet. Non-parallel jetties converging towards the sea, such as at East Pass, are meant to accentuate the difference between inlet nearfield ebb and flood flow patterns. The ebb jet is separated from land boundaries and is flanked by induced flow eddies which tend to transport beach sediment towards the inlet. The jet interacts with the wave-induced cross flow via lateral entrainment and mixing. On the other hand flood flow "sinks" into the inlet without any drastic boundary separation. By causing the converging jetties to "shoot" the flow seaward, the ebb shoal is formed in deeper waters than under weaker ebb currents, thus requiring lesser amount of dredging for the offshore channel than for parallel jetties. On the other hand, sand entering the channel during flood is likely to settle out quickly once inside the entrance, since flow expansion there causes the velocity to drop. The material can therefore be trapped in a designated borrow pit, from which it can be transferred to the downdrift beach. Providing a weir section in the updrift jetty such as at Ponce de Leon Inlet, thus deliberately allowing the jetty to "leak", accomplishes a similar sand trapping purpose.

Active solutions would ideally consist of continuous mechanical transfer of sand in order to mitigate downdrift erosion by the placement of sand from the updrift, nearfield or the interior areas. With respect to bypassing by dredging the nearfield (e.g. offshore navigation channel or the passive part of the ebb shoal), practical considerations dictate that dredging be carried out on an "as needed" basis. The same can be said of bypassing of material in the interior, where vessel traffic and shifting shoal patterns as well may preclude continuous bypassing. Hence the question of continuous bypassing at desired (variable) rates typically arises mainly in transferring sand from the updrift to the downdrift beach. This question deserves fuller examination, because of the need to feed sand to the deficit area on a more continuous and efficient basis than at present.

In selecting a sand bypassing system, four criteria must be evaluated: 1) proven long-term, field tested ability to transfer the desired amount of sand in the type of physical environment for which the system is needed, 2) commercial availability of the system including terms for maintenance and repair, 3) capital and maintenance costs, and 4) availability of necessary physical infrastructure for operation and repair. At present there are real constraints in all four areas, which makes the issue of sand transfer one that requires considerable additional technical development.

A6. Environmental Considerations

Inlet management protocols today must consider a broad suite of environmental consequences. Alterations to improve navigational safety may affect critical habitats in the vicinity of an inlet. These effects not only include the historically recognized problem of downdrift beach erosion, but also impacts on habitats near the ebb shoal and inside the inlet. The opportunity has arisen to develop criteria for management both of nearby ecosystems and of species of special concern. These criteria can be used not only to minimize impact, but also to restore or create critical habitats, thereby enhancing the survival of particular animals and plants that may be threatened with extinction, or be fundamental to the continuation of a productive fishery.

A6.1. The Inlet as a Passageway

Many animals migrate through inlets. Most adult fishes of commercial and recreational importance spawn offshore, yet the juveniles of most species are found in estuarine nursery grounds. Inlets are the pathways both by which larvae pass into estuaries and later by which adults leave to spawn. Some fish, such as striped bass (*Morone saxatilis*) and salmon (*Oncorhynchus spp*), migrate from the ocean to freshwater to spawn. Freshwater eels (family Anguillidae) migrate from rivers to the ocean to spawn. In Florida, a mammal -- the endangered West Indian manatee (*Trichechus manatus*) -- is a frequent user of inlets. It migrates northward in summer and southward in winter passing through inlets to feed on submersed vegetation in estuaries along the coast. An artificial inlet that has been stabilized for many years may have become an important migration pathway for many animals.

A6.2. Rocky Outcroppings

Critical habitats outside of an inlet include rocky outcroppings near the ebb shoal and near both updrift and downdrift beaches. Submerged rocks develop a living surface consisting of rich and sometimes very diverse communities of attached plants and invertebrate animals. Offshore rocky outcroppings are habitat for both spawning and non-spawning fishes. If exposed to repeated scour or burial by sand, the attached biological community will develop poorly if at all. Such perturbations are a natural consequence of close proximity to beaches or shoals. The time required for maximum community development on unperturbed rock is perhaps years to decades, though considerable development may take place within a year. Manipulation of inlets may reposition shoals and alter the pattern of sand accumulation along beaches. Nearby rocks with well-developed biological communities may be buried or scoured with greater frequency. Conversely, rocks used in jetty construction are also well-utilized by fishes and develop rich biological communities within a period of one or two years (Hay and Sutherland, 1988).

A6.3. Beach Habitats: Sea Turtle Nesting

Some beaches and dunes are habitat for species threatened with extinction. The beaches of the Atlantic coast of Florida, for example, are among the most heavily used in the world by nesting loggerhead sea turtles, *Caretta caretta* (Ross, 1982). During the main nesting period (March through November), more than 200 nests are laid per km in many stretches of beach, along with nests of other sea turtles. Because of the Federal listing of these species as threatened or endangered, beach nourishment activities are heavily restricted. Female sea turtles are easily discouraged when they come ashore searching for a nest site. Lights, noises, and many unknown factors discourage them. Beach construction activities are not allowed during the nesting season. Eggs deposited during or prior to construction activities would likely be destroyed before hatching so they must be relocated to safer sites.

Although the criteria for developing a successful nesting beach are not completely understood, good nesting beaches are characterized by a gentle profile without steep scarps, a wide (perhaps 20 m), wet-sand intertidal zone, and a gently-sloping, drier berm of compaction less than 350 t/m^2 to a depth of one meter (Nelson, 1985; Nelson and Dickerson 1988). Sea turtles will not dig nests in sand that is too compact. Some constructed beaches are initially suitable, but later become too compressed or erode during the nesting season. Incubating eggs exposed by erosion do not survive and new nests will likely not be laid on eroded beaches. Maintaining a suitable profile may require continual sand pumping or repositioning of jetties. Selection of dredge material of a grain size distribution similar to that found on nearby natural beaches prevents compaction.

A6.4. Inside the Inlet: Critical Estuarine Habitats

Inlet alterations may subtly affect intertidal and submersed vegetation inside the inlet. Changes in inlet width or depth can alter tidal amplitude, mean water level, patterns of circulation, transport of salt and sediment, and turbidity. These factors can affect salinity intrusion into freshwater supplies and habitats and determine the extent and productivity of intertidal and subtidal estuarine ecosystems. Intertidal and submersed vegetation traps and stabilizes sediment. Vegetative detritus comprises the main food for estuarine food chains and provides cover for numerous estuarine animals, including the juvenile stages of commercially valuable fish and invertebrates (Montague and Wiegert, 1990). Moreover, submersed vegetation is eaten directly as a main component of the diet of the green sea turtle, *Chelonia mydas*, and the West-Indian manatee, *Trichechus manatus* (Zieman, 1982).

A6.5. Intertidal Habitats

Intertidal vegetation occupies the low wave-energy, intertidal zones of estuaries and lagoons (Montague and Wiegert, 1990). Gentle slopes and higher tidal ranges increase the extent of the intertidal zone and therefore the area suitable for growth. Rises in mean water level will shift the position of the intertidal zone landward, falls will shift it toward the center of channels. Since slopes may increase toward channels, falls in water level may result in smaller intertidal zones. Intertidal vegetation traps suspended sediments, which can cause expansion or vertical growth of the intertidal zone. If sediment supplies are large, sediment trapping could eventually offset any decreases in width caused by altered water level.

A6.6. Submersed Vegetation

Management of submersed vegetation is more complex because it involves a variety of plant species each with particular responses to changes in salinity, temperature, nutrients, light, current, and other factors (Zieman 1982; Fonseca and Kenworthy, 1987). Inlet modifications may alter water level, tidal range, bathymetric slope, currents, wave energy, and water clarity. Where currents are sufficiently low to allow bed development (probably less than 150 cm/s), submersed vegetation will likely occur between the limits of exposure to air on the shallow side of the bed and lack of light on the deep side. The bathymetric slope between these extremes is then the major determinant of the size of the bed. Gentle slopes and continually high water-clarity should allow extensive coverage of subtidal areas by submersed vegetation. Growth increases as current increases from 2 cm/s to perhaps 50 cm/s or more and as light increases from 5% to 70% or more of surface irradiance. A minimum average light for habitat development is perhaps 15%.

A complex positive feedback loop exists among available light, submersed vegetation, current, and suspended sediment. As beds develop, drag increases, current slows, and suspended sediments are trapped and held by the vegetation, thereby decreasing turbidity (Fonseca and Fisher, 1986). Beds can then expand both into deeper waters and into areas formerly with higher currents. Removal of the beds can upset this loop and make it "snowball" in the other direction: sediment destabilizes, turbidity increases, and submersed vegetation at the edges of remaining beds both erodes away and dies from lack of light. Control of this feedback loop is a significant management challenge.

A7. Sea Level Rise Effects

The relative sea level rise during the years 1940-80 in Florida has ranged from 1.2 to 1.9 mm/yr (Marine Board, 1987). Studies have shown that during this period the effect of this rise on the shoreline, if any, has been masked by effects of inlet modifications (Dean, 1988). The exception perhaps is the entrance to Nassau Sound, which is in its natural state. Here, in keeping with sea level rise, the volume of the ebb shoal increased by 6.3×10^6 m^3 during 1871-1970, since there the controlling depth over the shoal has been primarily determined by wave action which most likely remained unchanged in the mean over this period (Mehta and Cushman, 1989).

In a scenario with a relative sea level rise that is, say, ten times greater than in Florida, as has been the case in recent years along coastal Louisiana, inlets, particularly those backed by shallow bays and extensive wetlands, may be significantly modified. This is because the increased water storage volume in the bay will widen the channel to accommodate the increased tidal prism. Furthermore, enhanced entrapment of sand by the ebb shoals may accelerate the rate of beach erosion. Also, jetties could become less effective, but in most cases they can be modified easily to counter inundation. It is likely that more serious consequences will actually be encountered in the interior areas having low relief. In many parts of Florida for instance interior banks are fronted by homes with land elevations that are less than say one meter at Spring high tides. Storm damage at higher than present water levels and associated wave action in such areas is indeed a matter of potential concern. Interestingly enough, in shallow areas in which the effect of bottom friction on the flow is strong, a higher water level will reduce the friction effect thereby reducing the naturally occurring head difference (superelevation) between the sea and the interior waters (Mehta, 1990). This reduction would counter the effect of sea level rise to some extent.

Some of the habitat criteria outlined above can be applied to an understanding of the effects of a rise in sea level. Beaches, for example, will lose dunes and nesting habitat for terns and sea turtles as a result of increased beach erosion. Residential and commercial developments are likely to be protected by revetments that will exacerbate these losses. Likewise inside the inlet, rising water levels will shift vegetated intertidal zones toward steeper land or revetments, reducing intertidal area, unless sediment supplies allow intertidal vegetation to grow vertically to keep up with rising water levels. If not, subtidal habitats may expand into the former lower-intertidal zone. Water on the deep sides of submersed vegetation beds will become even deeper, however, so vegetation there will die from lack of light, releasing any trapped sediments and perhaps beginning the "snowball" effect described earlier. Saltwater intrusion into freshwater supplies and habitats will also increase, requiring relocation of pumps and wells, and killing or dislocating freshwater animals and plants. Saltwater intrusion may eliminate all the freshwater wetlands within small, low relief, coastal-plain watersheds. Some of these contain unique or endangered freshwater biota. These wetlands would be replaced by saltwater wetlands, thereby reducing the diversity of coastal zone wildlife.

A8. Concluding Comments

While our knowledge and understanding of coastal processes in the vicinity of sandy tidal inlets has been gaining ground, technology for bypassing sand must be developed further to allow for flexibility in terms of locations of sand catchment, control over the timing and rate of bypassing, and installation, operation and maintenance requirements.

Environmental protection and habitat restoration can and should be incorporated into the design or redesign of inlets. Design criteria that are focused on critical habitats are presently crude compared to other engineering criteria. Nevertheless they can now be used and improved as needed. As is true of all management of natural and living systems, the most relevant information needs will be more efficiently identified and researched through attempts to use the criteria. Environmentally improved inlet designs will then be forthcoming.

APPENDIX B: ENVIRONMENTAL SEDIMENTOLOGY OF THE LOWER LOXAHATCHEE RIVER ESTUARY AND JUPITER INLET

B1. Summary

The purpose of this work, reported more extensively in Mehta et al. (1990b), was twofold: 1) to develop a sediment distribution map for the interior water area of Jupiter Inlet, and 2) to attempt to explain recent depositional trends for coarse and fine-grained sediment fractions in the study area. An extensive set of surface grab samples and five vibracore samples comprised the material upon which this work was based. Sediment distribution maps included sediment median diameters, sediment sorting, sediment skewness (based on Trask parameters) and sediment texture (Shepard, 1954 classification). The bottom texture was quite coarse at the inlet mouth and became progressively finer and less well-sorted inland in the Loxahatchee Estuary. A prominent flood tidal delta occurs in the estuarine embayment, at the confluence of the Southwest, Northwest, and North Forks of the Loxahatchee River. This wedge-shaped deposit, consisting of at least 80 cm of very fine-grained, well-sorted sand, overlies a muddy, less well-sorted substrate containing brackish-water fossils, and appears to be extending itself into the Northwest Fork.

Several areas show significant sediment mixing and high organic matter contents. Both the Southwest Fork and the reach above Pennock Point in the Northwest Fork contain sediments having organic matter contents in excess of 20% (dry weight basis). These reaches could easily become anoxic if tidal circulation patterns were to change and cause less well-oxygenated conditions.

Sediment appears to originate from two sources. On one hand, sediment comes from the fluvial Loxahatchee, bypassing the freshwater delta at the head of the tide, and working its way seaward, probably during periods of increased runoff. On the other hand sediment appears to be supplied from seaward, entering the inlet from the longshore current system on flood tides. A lesser ebb flow volume leaves some of this material within the estuary. Fine-grained, well-sorted siliciclastic material appears to enter the inlet when the longshore drift is from the north. Shelly sand, distinctively different in appearance, appears to enter the inlet when the longshore drift is from the south. Both sediment types mix within the inlet, but only the siliciclastic sands are transported into the estuary. A third source of sediment appears to be coming from unprotected banks which are being undercut and eroded by wave and boat wake energies.

Sediment is presently being retained and redistributed within the estuary and these conditions are likely to persist for the foreseeable future. If *Global Warming* is a valid scenario for the future, then accelerated sea level rise will compound the present adverse sedimentological effects in the Loxahatchee Estuary.

B2. Introduction

Jupiter Inlet is one of many small tidal inlets that have developed in the eastern United States coast line to allow access of small boats to the interior rivers, lagoons, and intracoastal waterway system. These inlets have an erosion/deposition history, most of which have been well documented, that often strongly reflect a cultural influence. This project originated as part of a comprehensive management plan for the Jupiter Inlet in Palm Beach County, Florida, such plan to serve as a guideline for coastal management for the next 25 years.

B3. The Problem

This study focuses specifically upon the problem of excessive sedimentation in the Loxahatchee River Estuary, in the region adjacent to the convergence of the Northwest, Southwest, and North Forks of the estuary. It is here that a significant flood tidal delta has formed and impedes navigation. The project involves the development of a sediment distribution map of a specified portion of the estuary (based upon literature review and extensive bottom sampling), and attempts to explain the observed distributional trends.

B4. Background

The Jupiter Inlet and its immediate environment has a long and rich history of change, extending back to 1892 when the St. Lucie Inlet was artificially cut through the barrier island, about 10 km north of Jupiter. A comprehensive review of these changes has been prepared by Parchure (Mehta et al., 1990a). It seems redundant to include that material in this report inasmuch as it is readily available. Accordingly, the reader is referred to that report for background information.

B5. Field and Laboratory Work

The field work consisted of two and a half days of bottom sampling from a small boat, using an Ekman-type grab sampler for soft fine-grained sediments and an Ekman bottom dredge for coarser materials. Locations were chosen to provide thorough coverage, with certain areas receiving greater attention. Positions were determined by line of sight orientation on recognizable structures and plotted directly on an enlarged set of aerial photographs from which a base map was made (Map 1). Long cores (>1 meter) were taken with a vibracorer, designed and manufactured by the University of Florida (Kirby et al., 1989). Grab samples were collected, photographed, described into a voice recorder on deck, and placed in sample bags for analysis in the laboratory. The vibrcores were taken, capped, and returned to the laboratory for further analysis. In the laboratory, sand samples were rinsed free of salt water, dried in a 105°C oven, and, using a Ro-Tap sieve shaker, each sample was sieved through a nest of sieves (1/2 phi intervals) for 15 minutes. The amount remaining on each sieve was weighed and a cumulative distribution curve was plotted. Sample statistics were calculated according to Trask (1932). Mixed sediments (sizes smaller than 62 microns) were analyzed first with a hydrometer, then the residue sieved as above (Bowles, 1970). A cumulative curve was constructed from which percentages of sand, silt and clay were determined, the sample classified according to Shepard (1954), and Trask estimators calculated, where applicable. Organic matter was determined by loss-on-ignition in a 400° C oven for 24 hours (Davies, 1974).

B6. Data Analysis and Interpretation

Following the particle size distribution analyses of the samples collected in the field, a set of maps were constructed, based upon the particle size parameters, i.e., median diameter (in phi units), sorting, skewness, and sediment texture (based upon the classification of Shepard (1954). The central tendency estimators used were those of Trask (1932), used primarily to facilitate comparison with the work of Buckingham (1984). Median diameters are reported in both millimeters and phi units (Appendix III, Table 1 in Mehta et al., 1990b), but the map (Map No. 2) was constructed using the phi units as textural contours. Sorting and skewness are ratios of quartile measurements and are dimensionless numbers and are easily mappable. Textural classification concentrates on fine discrimination within the sand sized material, using the terms "very fine" (0.063 to 0.11 mm), fine sand" (0.13 to 0.21 mm), etc (Appendix III, Table 2 in Mehta et al., 1990b). When sediment became mixed with finer silt and clay-sized material, they were mapped as "mixed" sediment, but classified more descriptively in Fig. B.1.

B6.1 Median Diameter - Map 2

Median diameters (phi units) show several distinctly different patterns through the estuary/inlet complex. Within the area studied, two reaches of fine-grained sediments are observed, the most obvious being the segment of the Southwest Fork extending 3000' from the entrance to the C-18 canal toward the main body of the estuary. Sizes range from medium silt (6 phi - 0.016 mm) to fine sand (3 phi - 0.125 mm) in this reach, the finer material being concentrated toward the entrance to the canal. A second area of fine-grained sediment occurs in the Northwest Fork, upstream from Pennock Point. A patch of coarse silt (5 phi) is found in a restricted area, approximately 2000 ft^2, and appears sharply isolated from the lower and upper portions of the estuary. Sands of varying textures dominate the remainder of the map, falling into the categories of fine to very fine sand (3 to 2 phi -0.125 to 0.25 mm). The central sand bar (flood tidal delta) is distinguished by a coarsening to a medium sand (2 phi - >0.25 mm) but exists as an isolated textural island within a larger sea of finer grained material. Coarsening occurs toward the mouth of the inlet, with median diameters changing from 3 phi (0.125 mm at the southern extension of the Intracoastal Waterway) to -1.2 phi (2.2 mm) within the mouth of Jupiter Inlet. Fine sand (3 phi - 0.125 mm) extends up the North Fork of the Loxahatchee to the bridge at Tequesta Drive, where it coarsens to a medium sand at 2 phi - 0.025 mm.

B6.2 Coefficient of Sorting - Map 3

As expected, the degree of sorting of the sediment reflects the size distribution of the sediment, e.g., the wider the distribution, the poorer the sorting and the reverse. Two regions of poorly sorted sediments are seen, one occurring in the Southwest Fork of the Loxahatchee River, the other occurring in the Northwest Fork. In the former, sorting coefficients greater than 4.0 result from the incorporation of fine material derived from the C-18 canal and the lack of significant tidal circulation in the reach (cul de sac) which keeps the sediment in place. The latter region shows sorting coefficients exceeding 5.0 located within the center of the enlargement of the stream, between 26°57' and 26°57'30" N latitude and 80°07' and 80°07'15' W longitude. The situation here seems quite

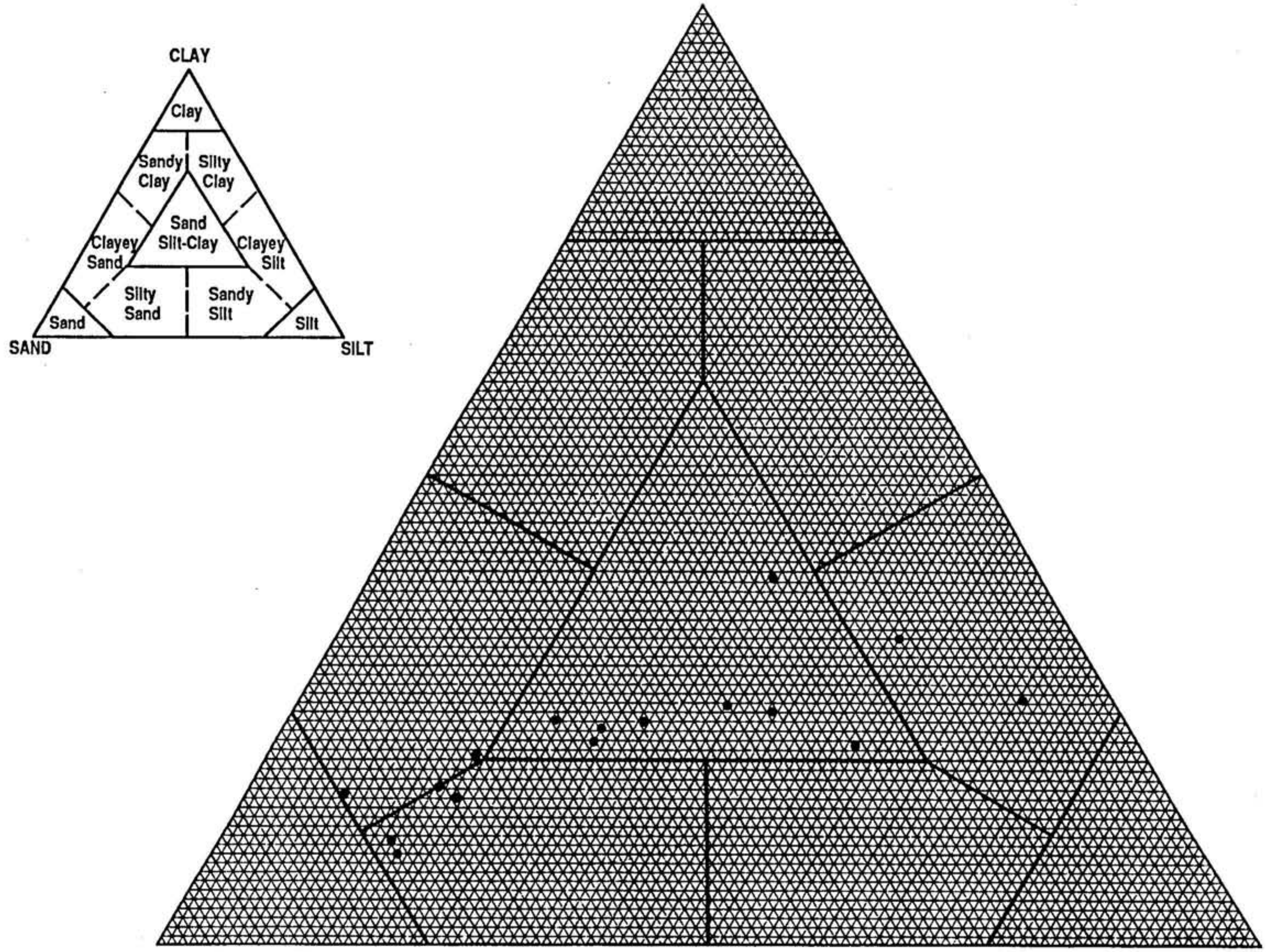


Fig. B.1. Textural classification of Loxahatchee Estuary and Jupiter Inlet bottom samples (Shepard, 1954). Inset shows the descriptive terms. Sixteen samples (Appendix III - Table 1, in Mehta et al., 1990b) did not plot within the 'sand' category and are shown on the diagram. These are designated as 'mixed' samples in the text.

different from the preceding inasmuch as the reach experiences normal tidal circulation. The abrupt occurrence of this material appears related to the sediment trapping phenomenon and will be discussed more fully in a later section. A third area of poorly sorted sediments occurs in the Northwest Fork at the very top of the mapped area. While not being of particular importance to this work, it does signify additional influences of the estuarine circulation pattern.

A dramatic change in sorting becomes very apparent below the reach previously discussed and extending seaward through the Jupiter Inlet. The remainder of the area is characterized by sediments which show Trask sorting coefficients between 1.0 and 1.4. In order to discern sorting differences, the area was contoured in 0.2 contour interval units. Thus, a qualitative aspect to sorting is introduced to the map, e.g., a sediment with a 1.41 sorting coefficient is less well sorted than a sediment with a 1.01 sorting coefficient. However, the sorting interval between 1.0 and 1.4 is still considered to represent a well-sorted sediment. Sorting within the enlarged central portion of the Loxahatchee Estuary, between 80°06' and 80°07'is well-sorted, with the best sorting occurring in a belt parallel with the shorelines. The poorest sorting of the sands occurs in the vicinity of the flood tidal delta deposit (based on only one sample). Sorting decreases somewhat east of the southern arm of the Intracoastal Waterway. As shown on the map, a central band of sediment with coefficients exceeding 1.4 extends to the month of Jupiter Inlet. The situation is somewhat complicated by the fact that this bottom is composed of a shelly sediment, derived from the erosion of the Anastasia (Pleistocene) Formation.

B6.3 Coefficient of Skewness - Map 4

Skewness is a measure of the asymmetry of a distribution. Its significance to sedimentation processes has long been debated and the jury is not yet in. Since skewness measures the abnormality of the sediment distribution, i.e., does it have more fine- or more coarse-grained particles than expected, it is presented here as an aid to interpretation of sedimentary processes. The values used to construct this map represent a semi-quantitative estimate of the shape of the size distribution, based upon the central 50% (tails of the distribution are not included in the Trask skewness parameter).

Two distinct fields of finely-skewed sediment occur west of a line drawn north and south of Pennock Point in the Southwest and Northwest arms of the Loxahatchee River. This boundary is very sharp and must surely reflect the oceanographic conditions within the estuary. The central portion of the estuary is characterized by normally-skewed sediments, perhaps slightly dominated by a coarse sediment mode. Normally-skewed sediment exists in the northern Intracoastal Waterway and on the northern side of Jupiter Inlet.

A strip of coarsely-skewed sediment extends from the north bank of the Loxahatchee, from its intersection with the north branch of the Intracoastal Waterway, through the central portion of the Loxahatchee, and up the North Fork. This strip is quite distinctive and is shown on the map. It seems unlikely that this particular distribution would occur by chance in the sampling scheme used. [note: the beginning of this strip coincides with the erosion of the bank on the north branch of the Intracoastal Waterway. It looks as if the fines have been winnowed out from the North Fork and possibly deposited in the confluence with the main stem, to be further transported up the main stem on flood tides].

B6.4 Sediment Distribution - Map 5

As noted earlier, the dominant sedimentary deposits within the Loxahatchee-Jupiter Inlet system are sands. Coarse to medium (0.25 to 0.84 mm) sands are found from the inlet mouth, extending landwards to the southern extension of the Intracoastal Waterway. Very fine- to fine-sands (0.063 to 0.21 mm) occupy the central reach between the ICW and the divergence of the Northwest and Southwest Forks from the central basin. A band of very fine- to fine-sand occurs along the western shoreline of the Northwest Arm, but mixed sediments fill the remainder of the channel. [note: mixed sediments refers to the various clayey silts, silty clays and SaSiCls that result from the Shepard Classification]. The eastern portion of the map shows an obvious sediment gradient, with coarse sand giving way to very fine sand within 2700 m of the inlet mouth. Very fine sand dominates the interior basin of the estuary, merging with the 'mixed' sediments occurring in both the lower Southwest and upper Northwest Forks. The exception to the expected sediment distribution occurs in the North Fork. Here, very fine-sand grades into medium sand, thus reversing the expected distribution.

B6.5 Analysis of Vibracores

Five vibracores were taken to provide some information concerning the nature and thickness of the flood tidal delta shoals. The general stratigraphy of each core is presented in Appendix II in Mehta et al. (1990b). This stratigraphy is based upon examination *in liner*.

Core VC1A90 was taken in very shallow water (61 cm) on the flat part of the shoal immediately east of the channel. This site was selected specifically because the lobate, tongue-like shape of the body seemed to state that it was a site of active accumulation and apparent up-estuary migration. The core penetrated 81.3 cm of fine sand and entered an underlying, dark brown silty sand with a distinct shelly zone.

Core VC2A90 was taken in deeper water (1.2 m) from the up-estuary terminus of the flood tidal delta. This also appeared to be a site of active sediment accumulation and extension. It seemed reasonable to expect that the core would penetrate a thin sand layer migrating up-estuary over the present estuary bottom. Although a short core (38.1 cm), it penetrated a 20.3 cm thick fine sand layer overlying a dark brown, silty sand containing shell fragments.

Core VC3A90 was taken in shallow water (61 cm) from the northern shoal of the flood tidal delta at the intersection of the North Fork with the Northwest Fork of the Loxahatchee River. This also appear to be an area of active accumulation and, in this case, extension into the North Fork appears to be indicated. The core penetrated 80 cm of fine sand, thus giving a minimum accumulation.

Core VC4A90 was taken in shallow water (61 cm) from the southern shoal, directly across the deposit from the preceding core site. It was taken from the delta-shaped deposit that appears to be transferring sediment into the lower portion of the embayment. The core penetrated 43.2 cm of fine sand before entering a dark brown, silty sand (no shells were observed through the core liner).

Core VC5A90 was taken in deeper water (1.2 m) immediately downslope of the preceding core. It penetrated 48.3 cm of fine sand and rendered a dark brown, silty sand containing shell fragments.

6.6 Summary of Vibracoring

Two clearly defined layers occur within the immediate region of the flood tidal delta (FTD). The deposit is a composite feature, showing evidence of very fine- to fine-grained sand accumulating to considerable thickness (approximately 1.5 meter) in the shallowest reaches, thinning outward and toward the channel as the deposit extends itself further up the estuary. This sand deposit conformably overlies a silty sand which contains an abundance of shells and most probably represents sediment which normally accumulates on the bottom of the Loxahatchee Estuary. It is, in fact, the *bioturbated mud*, described by Wanless et al. (1984) as "homogenized organic-rich mud containing a small amount of sand" which reflects intense bioturbation and forms the bottom of the modern estuary.

B7. Sedimentary Types and Sources

Examination of the various sediment samples indicated that only two major sediment types are involved in this study. On the one hand, we see several variations of siliciclastic material, generally defined as very-fine, fine, and medium grained sand. This material is composed of clean quartz grains, low in organic matter, and often containing small amounts (up to 3%) of calcium carbonate shell debris, generally small fragments of thin-shelled molluscs, some complete juvenile *Macoma(?)* clams, and some unidentifiable gastropods. Wanless et al. (1984) present a faunal listing of the shelly material and state that they are representative of a shallow, brackish-water fauna. Consequently, it is believed that material of this composition was produced directly within the Loxahatchee River Estuary, perhaps as sandy material which mixed with the brackish water fauna as it worked its way down-estuary from the upper fresh-tidal reaches. In general, this material is unimodal, with the modal diameter falling between 110 to 150 microns (3.25 to 2.75 phi). This modal diameter prevails in the upper portion of the estuary where mixed sediment types occur, being quite distinctive in the size analysis. Consequently, it appears that the same sand exists throughout the estuary, being cleaner and more narrowly sorted in the lower portion of the estuary than in the upper portion. There, because of the estuarine circulation pattern which creates a sediment trap, it becomes mixed with finer-grained material (organic matter, diatom frustules, foraminiferal tests, and clay particles) to form the mixed sediments, e.g., silty sands, sandy silts, and SaSiCls.
[note: this sediment is also found offshore]. The late Pleistocene Pamlico Formation which covers older formations (Miami and Anastasia) to thicknesses up to 60 ft (Hoffmeister, 1974) is a likely source of sand for the Loxahatchee River. The offshore sand may have had multiple sources, e.g., submerged early Holocene beaches and dunes which are being transported shoreward as sea level continues to rise. This would include the Pamlico Formation.

The second type of sediment is the coarse, shelly material, which is found in the entrance to the Jupiter Inlet (Area B) and in coastal waters on the south side of the inlet (Area C). This material appears to be derived from the Anastasia (Pleistocene) Formation which comprises the bedrock from Palm Beach to Jacksonville, Florida, and occurs offshore in numerous shallow water outcrops. The formation is often called a 'coquina', being composed nearly completely of fragmented calcium carbonate shell material cemented by a siliceous or calcareous cement. The shell fragments vary in size, are dominately molluscs, and usually have a distinctive orange-reddish color which makes the material easily recognizable. It is difficult to find a sediment sample which does not contain some Anastasia fragments due to the ubiquity of the formation within the region. However, the presence of local underwater outcrops provides a significantly larger portion of Anastasia material for the Jupiter Inlet (Area B) than for the sediments in the Loxahatchee. Indeed, it is believed that samples without Anastasia-derived material originated and were transported within the fluvial/estuarine environment whereas those samples containing recognizable Anastasia fragments represent material eroded from the offshore outcrops which have been transported inland on flood tide.

A third sediment type which has been found in minor amounts, is the fine-grained, organic-rich deposit which accumulated in the low energy, canal-linked arms of the estuary, specifically the Southwest Fork of the Loxahatchee River. Classified as SaSiCl's, clayey silts, and silty sands, they also occur in a restricted area of the Northwest Fork above Pennock Point (Map 5). Organic matter contents are varied, ranging from 2.23% (9A90) to 29.45% (27A90) -Appendix III, Table 3 in Mehta et al. (1990b). yet no evidence of anoxic conditions due to oxidation of this material was observed during the sampling period. It seems unlikely that such conditions could often occur due to the shallow depths of the estuary and the vigorous tidal currents. However, the energy levels in the Southwest Fork of the estuary seem conducive to the development of anoxic bottom conditions and it would not be unexpected to see such conditions occur during summer months.

Several local sources of sediment to the Loxahatchee River were observed during this sampling period. Generally speaking, the shoreline is well armored, with rip-rap and pilings installed to prevent erosion of the shoreline. However, a significant slope failure was occurring on the west side of the north bank of the Intracoastal Waterway. A second area of significant erosion was the shoreline of Dubois Park, just inside the Jupiter Inlet. These failures, operating over time, would provide a substantial amount of sediment to be redistributed within the system.

B8. Patterns of Sediment Transport

Two general patterns of sediment movement seem to be operating in this environment. 1) There is likely to be episodic movement of sand from the fresh tidal portion of the Loxahatchee River to the lower flood tidal delta where it becomes incorporated into the deposit. Wanless et al. (1984) observed lenses and laminae of fine sand in the mixed sediments of the middle estuary deposits. Their hydrologic data indicates that near bottom current velocities sufficient to transport sand-sized material up to 500 micron diameters exist throughout the Northwest Fork. The fresh tidal delta that exists at the head of the estuary contains 25% of sand less than 200 micron in diameter. Storms and other meteorologic events could winnow these finer sands out of the deposit and they could be transported as suspended material down-estuary to the flood tidal delta. 2) Two different sediment populations (siliciclastic and shelly) are being transported from offshore into the inlet. The siliciclastics are introduced on flood tide whenever the longshore currents flow from north to south. These are clean, very fine- to fine-grained, unimodal (0.11 to 0.15 mm) sands, practically indistinguishable from those being carried down the Loxahatchee River, except for a small amount of recognizable Anastasia fragments in their coarse fraction. These sands can be transported deeply into the estuary, probably as suspension load (Wanless et al., 1984). Vibracores taken through the flood tidal deposit reveal it to be a wedge-shaped deposit, tapering up- estuary and composed of this siliciclastic material. This strongly suggests that sediment is being introduced from the offshore through the Jupiter Inlet.

Sediment derived from the Anastasia Formation is transported into Jupiter Inlet as bedload and saltation load and is deposited within the narrow channel of Area B. A few smaller shell fragments may be carried into Area A on flood tides, but the majority of the sediment is confined within the eastern part of Area B. Carrying capacity of the flood tidal flow diminishes when it enters the enlargement at the confluence of the North, Northwest and Southwest Forks of the Loxahatchee River. Sediment is naturally deposited in a flood tidal delta which is further modified by winds, surface currents, and boat wakes. This process has been occurring at least since 1940 (McPherson et al., 1982).

B9. Conclusions

The flood tidal delta which is located at the intersection of the Southwest, Northwest, and North Forks of the Loxahatchee River is extending itself into the mouth of the Northwest Fork, causing shoaling and a general deterioration of the access channel for small boat traffic. It is not absolutely clear where the sediment is coming from, however, both the longshore sand transport system and the fluvial transport system appear capable of making significant contributions. Shoreline erosion offers an additional, as yet unquantifiable contribution to the supply of sediment. These conclusions are based upon the similarity of textural parameters in the different deposits, the availability of sufficient tidal energies to transport this material, and the evidence of significant shoreline erosion in two specific areas.

Sediment maps show that sediment textures become finer up-estuary, beginning as coarse sand/granules at the mouth of Jupiter Inlet, grading into mixtures of sand, silt, and clay in the Southwest Fork and above Pennock Point in the Northwest Fork. Sediment is generally very well-sorted in the eastern and central reach, becoming poorly sorted in the western portion of the Northwest Fork and the Southwest Fork. This reflects the availability of wind and tidal energy to rework and winnow the material with less reworking occurring in the poorly sorted reaches. The estuarine sediment trap occurs in the Northwest Fork, above Pennock Point, and results in a reach dominated by mixed, organic-rich sediment in the center with progressively better sorting occurring along the shallow margins. Coarse and fine-skewed reaches occur adjacent to each other in the central and western portions of the mapped area. A band of coarsely-skewed sediment 'appears' to outline a channel or pathway down the North Fork into the main portion of the estuary. The Southwest Fork is finely-skewed, the Northwest Fork above Pennock Point is also finely-skewed. The central portion of the estuary is normally-skewed, and, except for the strip down the center of the North Fork and through the estuary to the north bank of the inlet, the remainder is finely-skewed. It is noted that the flood tidal delta is finely-skewed, possibly due to sea grasses which would tend to retain fine-grained material due to a baffling effect.

Studies by Sonntag and McPherson (1984) indicate that tidal flow into and out of the estuary is much greater than freshwater flow from the tributaries. Measurements during the 1980 'wet' season showed the freshwater inflow to be 1.15×10^5 m^3, only 1.5% of the ebb tidal flow of 7.65×10^6 m^3. The corresponding flood tidal flow was 8.26×10^6 m^3. During the study period, the freshwater inflow per tidal cycle averaged about 2% of the average tidal flow through Jupiter Inlet. While important in maintaining the estuarine environment, increasing the magnitude of fresh water flow in the Loxahatchee will have little effect on determining sediment import or export. Further reduction of the freshwater flow of the Loxahatchee River will occur as long as the present drought conditions exist. It is concluded that the flood tidal delta will continue to extend into the central basin of the estuary until such time that the net ebb tidal volume exceeds the net flood tidal volume and causes net ebb tidal sediment transport to occur. Accelerated rise of sea level, occurring as a result of *Global Warming*, will drive the estuarine circulation pattern toward a Type A (salt-wedge) configuration, with the null point occurring farther up-estuary. Thus, high density salt water capable of carrying sediments will progress further up-estuary. The flood tidal delta, so well-developed in the lower reaches of the estuarine Loxahatchee, will continue to migrate up-estuary.

B10. Recommendations for Future Work

In order to more fully understand the processes operating in Jupiter Inlet and the Loxahatchee River, it is suggested that the following projects be initiated. If the postulated *Global Warming* event is really occurring, then we can expect sea level to increase between 4.8 to 17.1 cm by year 2000 (Hoffman, 1984). This is an unprecedented rise in global sea level, undocumented in human times, and can be expected to result in some immediate and dramatic changes to the coastline. Some of the effects will include a loss of coastal wetlands due to inability of marshes to match the rate of sea level rise (Hackney and Cleary, 1987), significant shoreline erosion and property losses arising from storms with increasing duration accompanied by wave heights in excess of 5 m (Dolan et al., 1990), and an increase in the landward transport of sedimentary material as the salt water prism moves up the estuary. The Jupiter Inlet area will certainly be affected by these events.

1. We must begin a regular period of monitoring of sediment accumulation. In particular, we must be able to assess the seasonality effects (summer/winter storms) and periodic and episodic meteorologic events, e.g., Hurricane Hugo, on sediment accumulation. This will require the installation and monitoring of sediment traps, designed specifically for shallow water, microtidal, episodically high energy, estuarine systems.

2. We must begin a program of sediment tracing, using fluorescence dyed-particles which will indicate the direction of sediment transport under various conditions of storms, tides, and reduced or enhanced freshwater flow. Different colored tracers should be used to differentiate the fresh tidal sand deposits from the longshore sand deposits.

3. Assess the effectiveness of shoreline erosion by wind waves and boat wakes in contributing to the supply of sediment available for deposition in the flood tidal delta.

MAP CAPTIONS

Map 1 - Grab sample locations are shown by a closed circle, vibracore locations are shown by closed triangles. Area west of the railroad bridge is designated *Area 'A'*. Area east of the railroad bridge, including the mouth of Jupiter Inlet, is designated *Area 'B'*. Marine samples come from *Area 'C'*.

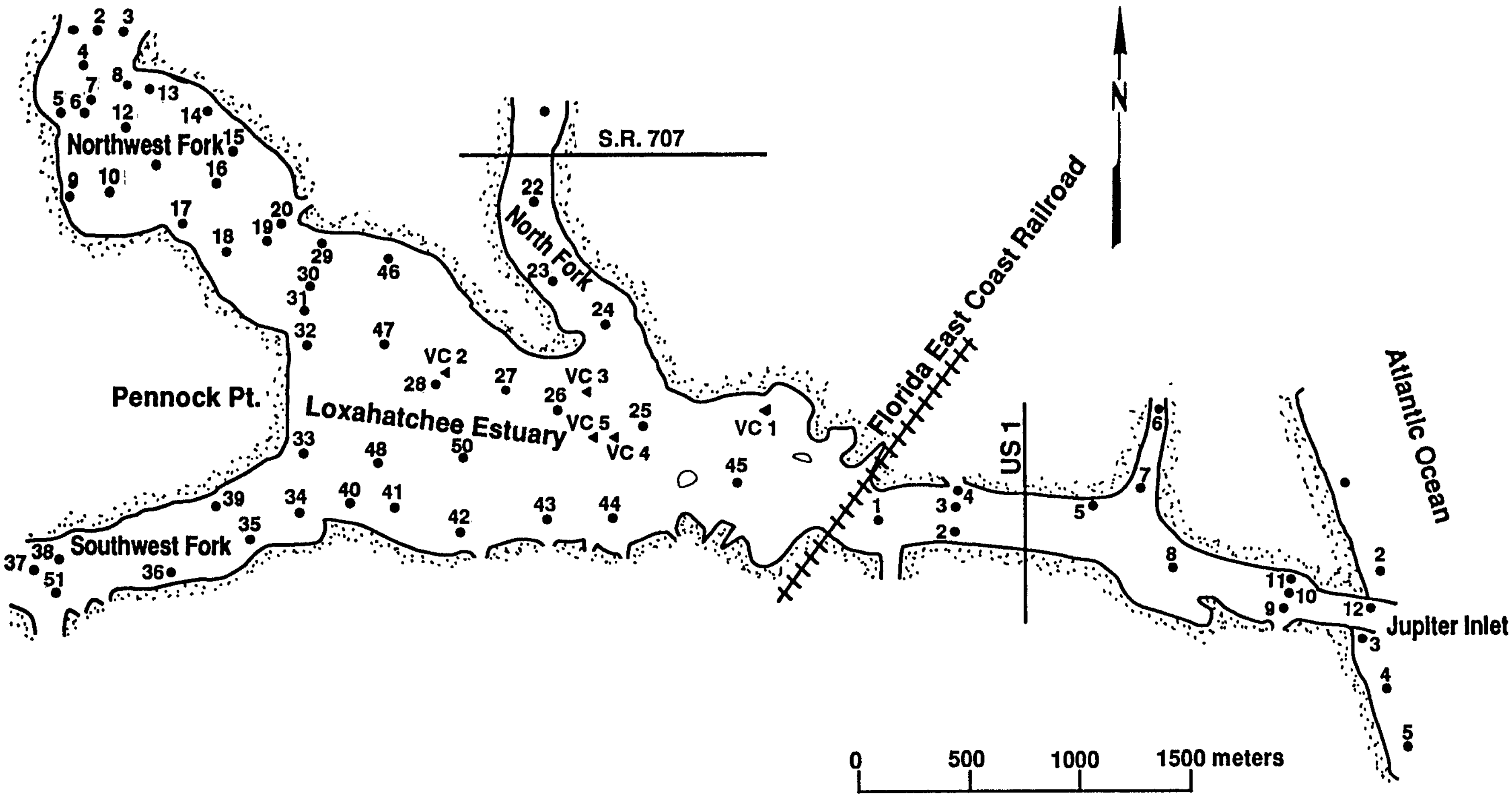
Map 2 - Distribution of sediment median diameters, contoured in phi units. Since phi units bear an inverse relationship to metric units, areas outlined by large phi values show fine-grained material and low phi values show coarse-grained material. Fine-grained material is found in patches in the Northwest and Southwest Forks of the Loxahatchee Estuary and on the flood tidal delta in the central portion of the estuary. Median diameters increase generally from the center of the estuary through the mouth of Jupiter Inlet.

Map 3 - Distribution of Trask sorting coefficients. Several areas of poorly-sorted sediment occur in the Northwest and Southwest Forks and 1.0 unit contour intervals were used to delineate these areas. The remainder of the estuary and tidal inlet was contoured in 0.2 unit contour intervals to emphasize small differences of sorting within generally well-sorted material.

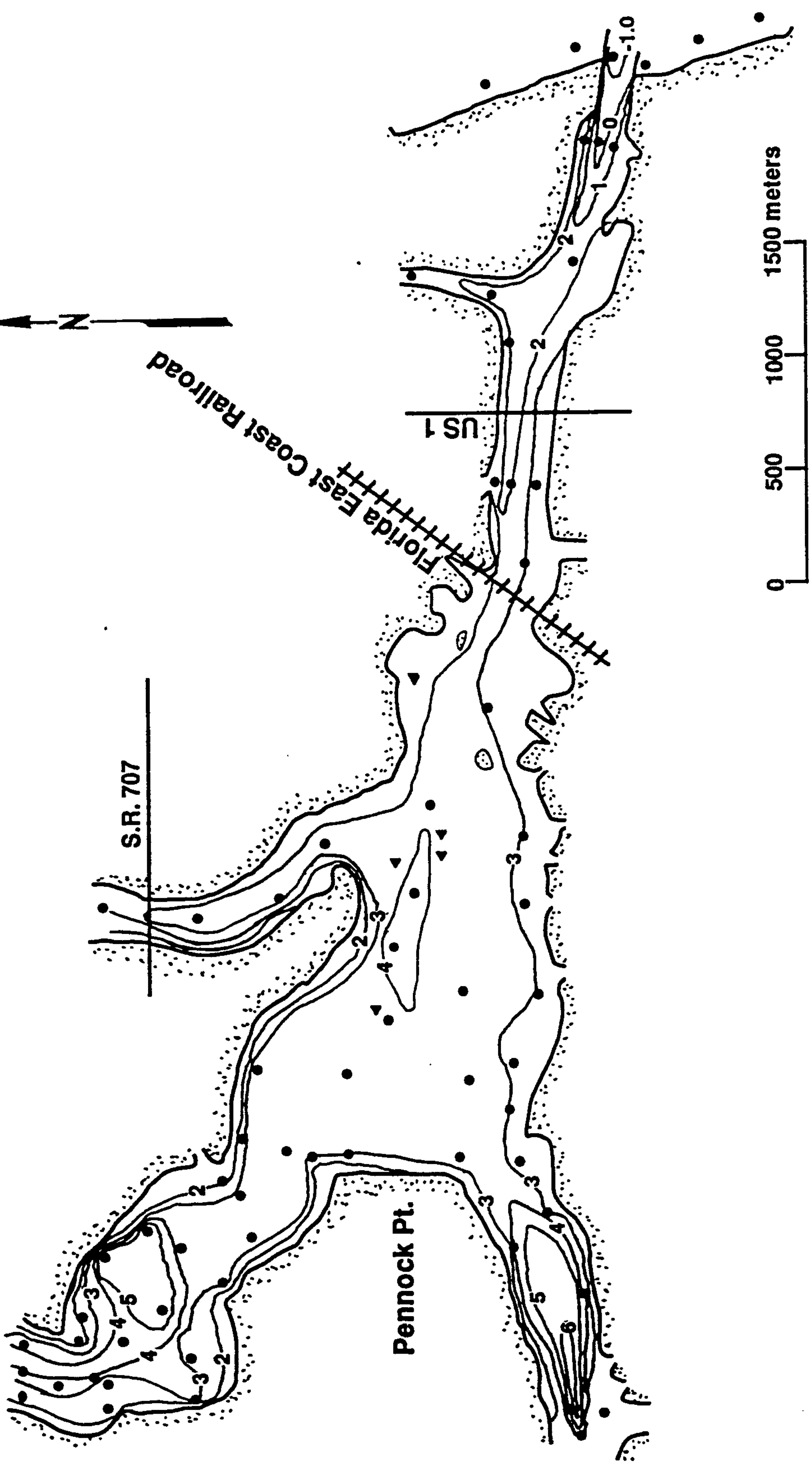
Map 4 - Distribution of sediment skewness, e.g., degree of abnormality of sediment distribution. Values less than 0.9 indicate an excess of material smaller than the modal diameter (finely-skewed). Values greater than 1.1 indicate an excess of material larger than the modal diameter (coarsely-skewed). Normal skew is shown by values between 0.9 - 1.1. The Northwest and Southwest Forks are finely-skewed and the central portion is normally-skewed. A small patch of finely-skewed sediment occurs off the entrance to the southern portion of the Intracoastal Waterway, and a coarsely-skewed region exists offshore to the south of the inlet mouth. A band of coarsely-skewed sediment extends through the North Fork eastward to the north branch of the Intracoastal Waterway.

Map 5 - Textural distribution of bottom sediment types, classified according to Shepard (1954 - Fig. B.1).

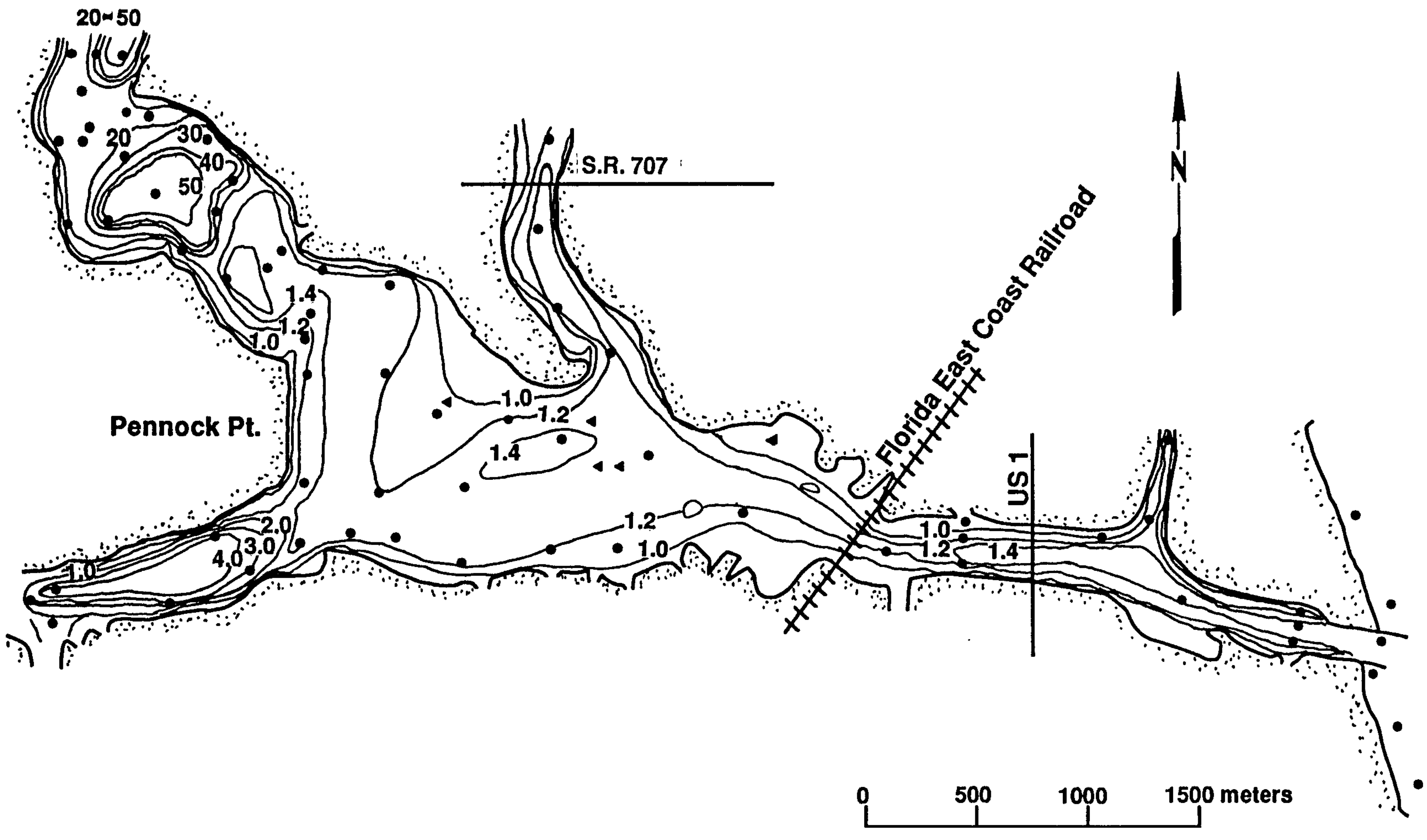
MAP 1 - Sample Locations



MAP 2 – **Median Diameters**



MAP 3 - **Sorting Coefficients**



APPENDIX C: LITTORAL DRIFT AND SEDIMENT BUDGET

C1. Littoral Drift

C1.1 Previous Estimates

The quantity and the rate of movement of littoral drift along Jupiter Island has not been determined through direct measurements; however, various estimates, which have been made in the past from time to time, are given in Table C1:

Table C1: Some estimates of annual littoral drift near Jupiter Inlet.

Source	New Drift Cu.yd./year Quantity	Direction
1. U.S. Army Corps of Engineers	230,000	South
2. DeWall and Richter (1978)		
a) Das	536,200	South
b) S.P.M.[a]	673,600	South
3. University of Florida	250,000	South
4. Bruun (1990)	225,000	South
5. Aubrey and Dekimpe (1988)	200,000	South

[a]Shore Protection Manual of the Army Corps of Engineers.

For purposes of this report, it is estimated that the net littoral drift at Jupiter Inlet is southwards with an average rate of 230,000 cubic yards per year. This is based on the analysis of dredging data and wave data as described in the subsequent sections. See also Harris (1991).

C1.2 Dredging Data Analysis

Dredging has been carried out in two areas inside Jupiter Inlet:

i) Sand trap

The sand trap is located about a quarter of a mile west of the inlet (Fig. C.1). Dredging is done by JID through contractors as and when necessary, usually at intervals of 2 years. The dredged material is transferred to the south beach.

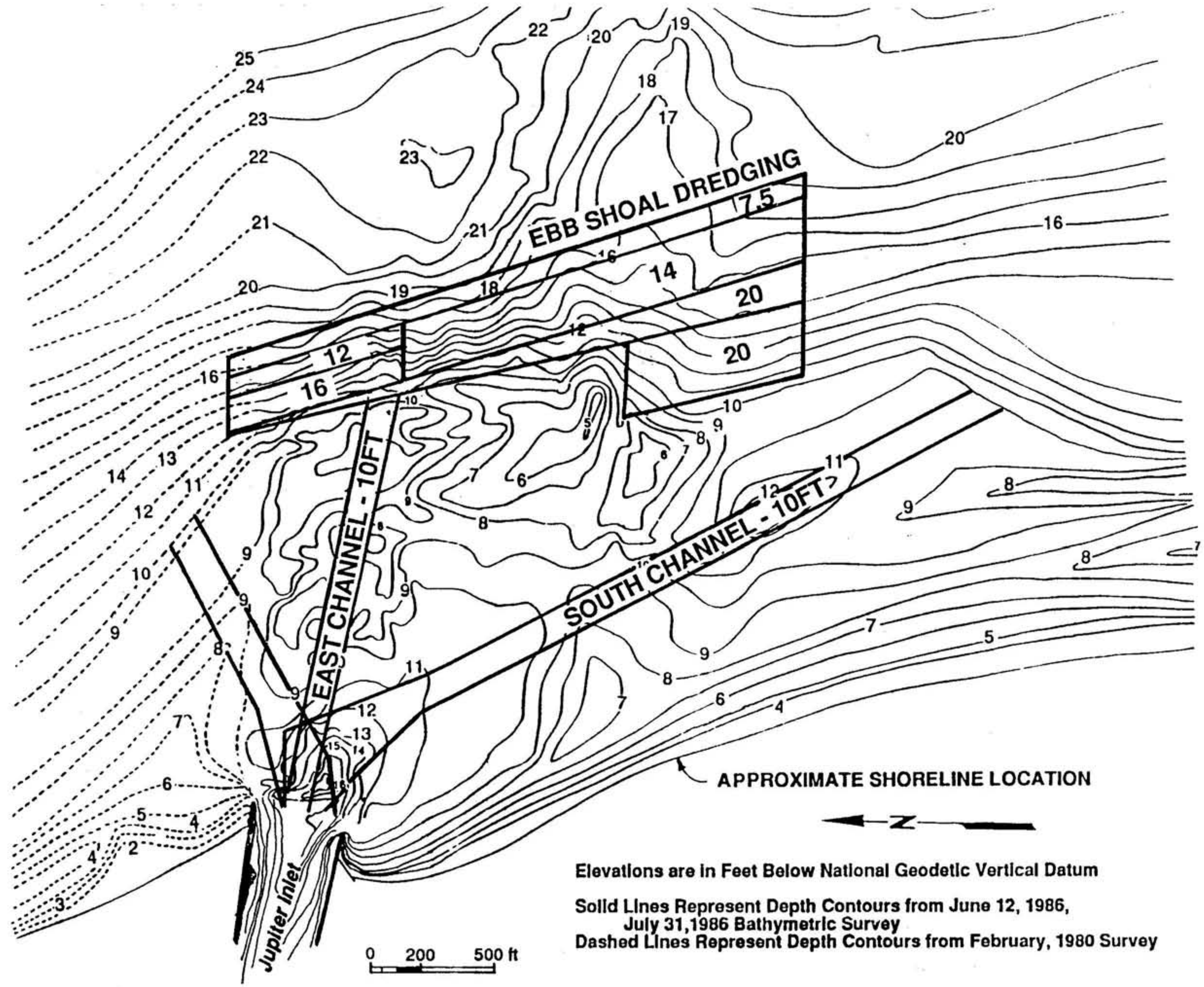


Fig. C.1. Proposed developments at Jupiter Inlet. The south channel shown has also been referred to as the southeast channel elsewhere.

ii) Intracoastal Waterway

This dredging has been carried out mainly at two locations which are shown in Fig. C.2. The material dredged from the sand trap located at the confluence of northern and north-western arms of the Loxahatchee River is transferred to the southern beach. Sediment dredged from a small area inside the northern arm is transferred to the beach north of Jupiter Inlet (Fig. C.2). This dredging is carried out periodically by the Army Corps of Engineers. Since this is an independent operation, it does not necessarily coincide with the dredging of the main sand trap.

Data on the dredging quantities in both the areas are given in Table C2. The average quantity of sand dredged from the Intracoastal Waterway by the Army Corps of Engineers during the years 1963 through 1988 works out to 41,180 cubic yards per year. Data on the amount of sand transferred to the south beach out of this total dredging are not available. However, it is believed that more material has been placed on the north beach than on the south beach. Assuming that about one third of the material was placed on the south beach on the average, the estimated quantity would be of the order of 13,000 cubic yards per year. This estimate is later used for working out the sand budget.

Data on the placement of dredged material on the shoreline south of Jupiter Inlet are given in Table C3 (Continental Shelf Associates, 1989a). The quantities given in the table cover a period of 37 years from 1952 to 1988. Although the sediment was transferred from two areas, namely, the main sand trap and the sand trap of Intracoastal Waterway, data on the breakup of quantities are not available. From the data presented in Table C3, the average amount of sediment transferred to the south beach works out to 43,513 cubic yards per year.

C1.3 University of Florida Study

C1.3.1 General

The University of Florida used the following data for estimating wave energy at Jupiter:

1. U.S. Naval Weather Service Command - Summary of Synoptic Meteorological Observations (SSMO); use of existing ship wave data in the Atlantic.
2. Wave hindcast using wind data at West Palm Beach Airport.
3. U.S. Army Corps of Engineers' Wave Information Study (WIS): Hindcast model.

Data were obtained over a 20 year period from 1956 to 1975. Average monthly distributions of wave heights and wave directions were determined and wave energy calculations made. The relationship between wave energy and rate of littoral transport suggested in the Shore Protection Manual of the Army Corps of Engineers was used to determine the rate of longshore drift.

C1.3.2 Estimated Annual Drift

The estimated annual longshore transport for the years 1956 through 1975 is shown in Table C4. The table gives the quantity of southward and northward drift separately, along with the net drift. It may be noted that the net drift was southward during this entire 20-year period. Quantity of net drift worked out for the year 1975 appears

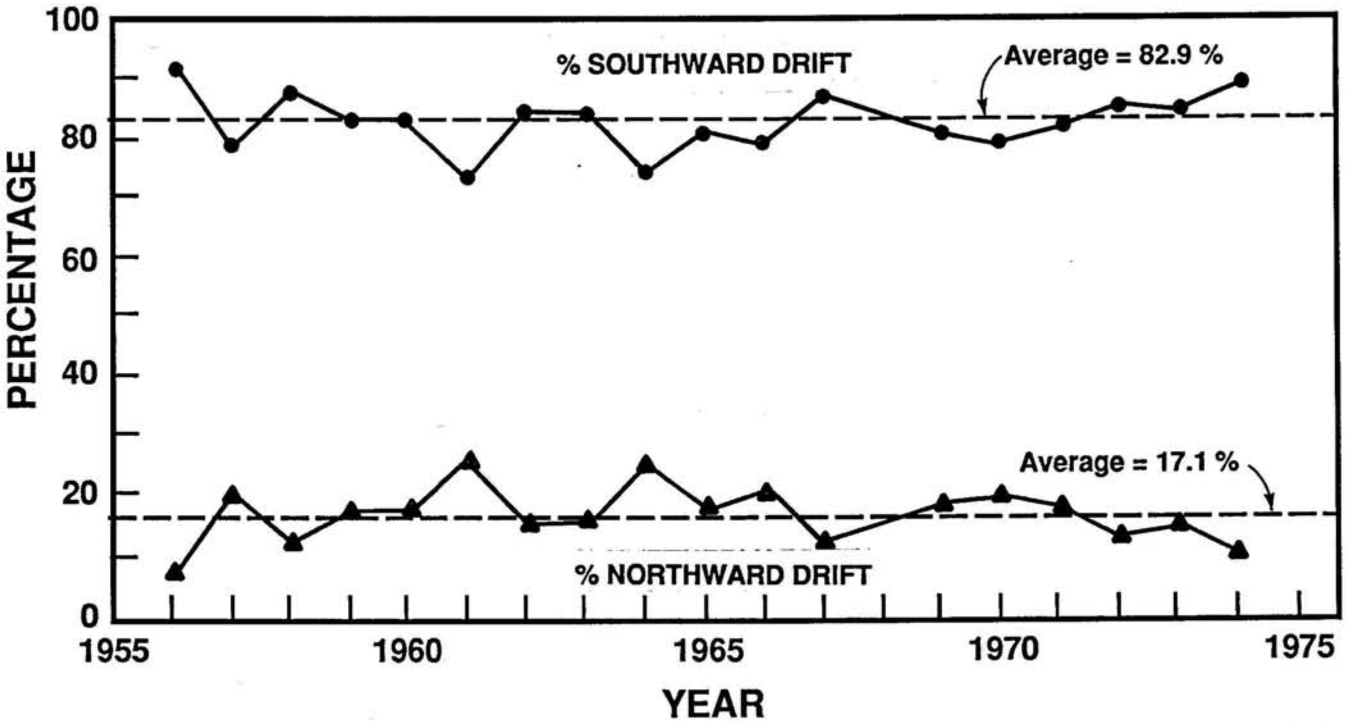


Fig. C.2. Estimated percentages of quantities of southward and northward alongshore sediment transport.

Table C2: JID and Army Corps dredging records for Jupiter Inlet (Dixon and Assoc. Engr., Inc., 1991).

Project Year	J.I.D. Cu.yd. (Continental Shelf Assoc. Inc., 1989a)	Army Corps Cu.yd. (Seymour and Castel, 1985)	Total Cu.yd.
6/52	72,075	-	72,075
		-	
1956	Vol. Unknown	-	-
9/58	42,000	-	42,000
		-	
9/60	45,100	-	45,100
		-	
1961	-	Vol. Unknown	-
8/62	45,000	-	45,000
1963	-	46,000	46,000
	-		
1964	123,000	21,800	144,800
1965	-	24,000	24,000
	-		
6/66	243,000	-	243,000
		-	
1967	-	31,500	31,500
	-		
6/68	131,000	28,000	159,000
1969	-	50,000	50,000
	-		
8/70	77,000	93,500	170,500
9/72	76,500	45,000	121,500
5/75	102,600	154,000	256,600
5/77	93,995	-	93,995
		-	
1979	93,000	118,800	211,800
11/81	75,000	-	75,000
		-	
1983	60,000	110,500	170,500
1985	76,000	-	76,000
		-	
1986	-	130,300	130,300
	-		
1987	65,500	130,300	195,800
1988	69,300	87,000	156,300

Table C3: History of Jupiter Inlet and Intracoastal Waterway dredging and placement of disposal material on the shoreline south of Jupiter Inlet (Continental Shelf Assoc., 1989a).

Year	Volume (cu. yds)
1952	30,000
1954	60,000
1956	70,000
1958	42,000
1960	45,000
1962	56,000
1964	126,000
1966	209,000
1968	120,000
1970	45,000
1972	78,000
1974	50,000
1975	85,000
1977	102,000
1983	172,000
1985	80,000
1987	65,000
1988	175,000
Total	1,610,000

to be far too lower than those for the other years. This is believed to be due to insufficient or erroneous wave data. The average net drift for all the 20 years is 230,778 cubic yards per year, which is close to 230,000 cubic yards per year. In fact this is the rate used in calibrating the Shore Protection Manual relationship between wave conditions and the rate of littoral drift. Therefore the value 230,778 cubic yards per year is not an independent estimate of the net annual mean rate of littoral drift. Percentages of the quantity of southward drift and northward drift with respect to the gross drift are also given in Table C4. It is seen that 17 percent of the gross drift is northward whereas 83 percent is southward. The data given in Table C4 are plotted in Fig. C.3. A log normal probability plot of annual longshore transport magnitudes (northward and southward) is shown in Fig. C.4.

The percentages of duration of occurrence of drift in the southward and northward directions are shown in Table C5 for each year over the period 1956 to 1975. The data are plotted in Fig. C.5. It is noted from Fig. C.5 and Fig. C.4, respectively, that while the average duration of occurrence of drift in the southward and northward directions are 60.7 and 34.8 percent, the corresponding sediment volume rates are 82.9 and 17.1 percent. This indicates that the wave climate inducing northward drift is considerably milder than that producing southward drift.

Table C4: Estimated longshore transport values (Q cubic yards/year) for 20 year period 1956-1975 (calculated from WIS wave hindcast data).

Year	Q_{net}	Q_{south}	Q_{north}	$Q_{south}+Q_{north}$	Percentage of Gross Drift % South	% North
1956	433,633	473,253	−39,621	512,874	92.3	7.7
1957	207,214	278,450	−71,236	349,686	79.6	20.4
1958	381,848	441,072	−59,223	500,295	88.2	11.8
1959	310,889	395,503	−84,614	480,117	82.4	17.6
1960	236,324	302,862	−66,538	369,400	82.0	18.0
1961	147,716	228,766	−81,050	309,816	73.8	26.2
1962	261,973	321,219	−59,245	380,464	84.4	15.6
1963	232,033	286,333	−54,299	340,632	84.0	16.0
1964	146,029	210,080	−72,050	282,130	74.5	25.5
1965	225,910	291,087	−65,177	356,264	81.7	18.3
1966	255,891	346,656	−90,766	437,422	79.2	20.8
1967	270,685	315,307	−44,622	359,929	87.6	12.4
1968[a]	63,430	98,922	−35,492	134,414	73.6	26.4
1969	194,132	253,204	−59,072	312,276	81.1	18.9
1970	203,480	273,624	−70,143	343,767	79.6	20.4
1971	190,001	246,245	−56,244	302,489	81.4	18.6
1972	316,316	375,529	−59,214	434,743	86.4	13.6
1973	316,063	382,845	−66,781	449,626	85.1	14.9
1974	200,821	227,965	−27,144	255,109	89.4	10.6
1975[a]	21,181	78,744	−57,563	136,307	57.8	42.2
Average	251,720				82.9	17.1

[a]These data are excluded from analysis because they do not appear reliable.

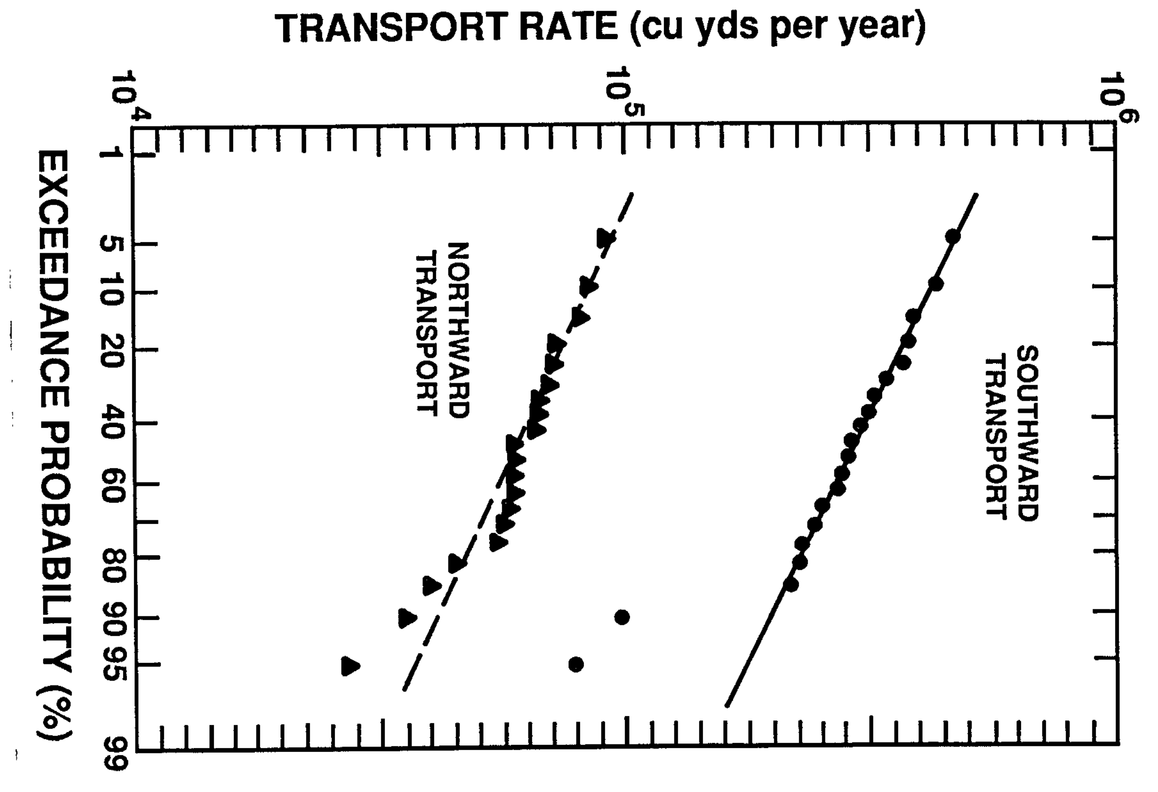


Fig. C.3. Log-normal probability plot of annual longshore transport magnitudes (southward and northward) from WIS hindcasts for the period 1956-1975.

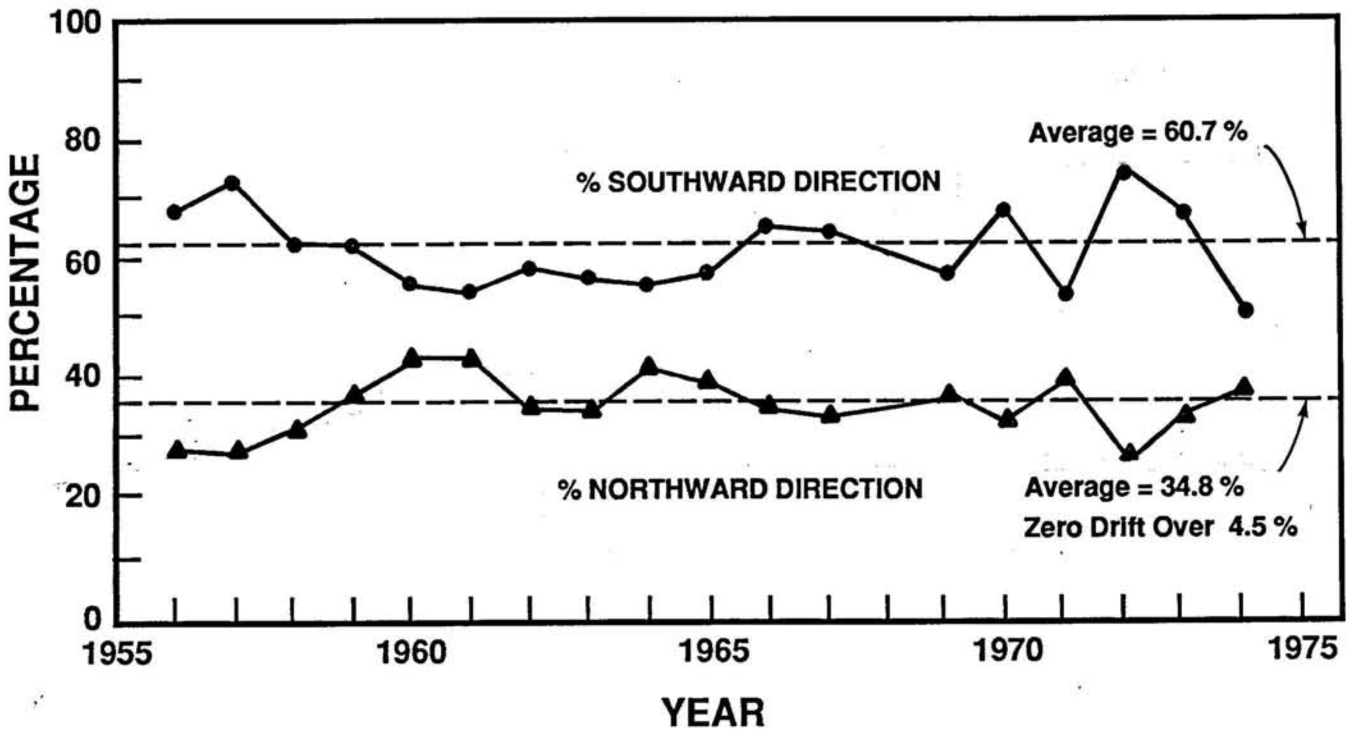


Fig. C.4. Estimated percentages of duration of occurrence of southward and northward alongshore sediment transport.

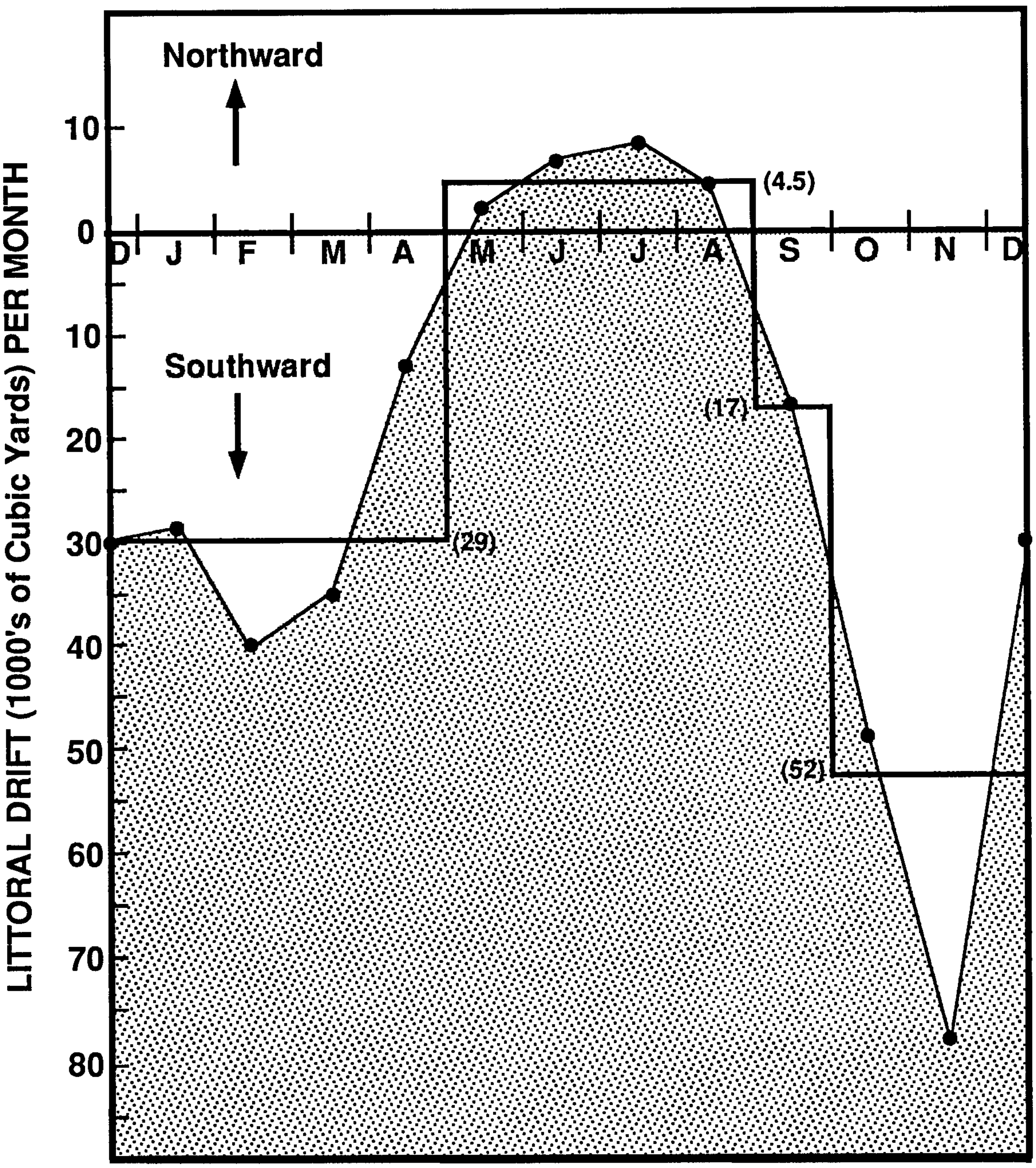


Fig. C.5. Monthly net quantities of littoral drift estimated for the year 1967.

Table C5: Estimated percentage of duration of occurrence of southward and northward drift for 20 year period 1956-1975 (calculated from WIS wave hindcast data).

Year	Percentage Duration of Occurrence % Southward	% Northward	% Zero
1956	67.3	28.2	4.5
1957	72.2	27.6	0.3
1958	61.4	31.4	7.2
1959	60.7	36.8	2.4
1960	55.2	42.4	2.4
1961	53.8	42.2	3.9
1962	58.5	34.0	7.5
1963	56.4	33.7	9.9
1964	55.2	41.0	3.8
1965	56.9	39.1	4.0
1966	64.3	34.6	1.0
1967	64.2	32.6	3.2
1968	53.9	39.7	6.4
1969	56.5	36.1	7.4
1970	67.5	32.1	0.4
1971	52.8	38.8	8.4
1972	74.1	25.5	0.4
1973	66.0	33.5	0.5
1974	49.3	36.7	14.0
1975	31.5	50.4	18.0
Average	60.7	34.8	4.5

C1.3.3 Estimated Monthly Drift

Quantities of monthly littoral drift were estimated using the same procedure as described in the previous section. The results of calculations made for a single year, 1967, are given in Table C6 as an illustration and the same are plotted in Fig. C.6. It is noted that during the four month period May through August, the net drift was northward and in the other eight months it was southward, of which 44 percent occurred during two months, October and November.

Monthly drift was calculated for each of the twenty years and the average of twenty year data for each month was determined. The magnitudes of mean southward, mean northward and gross drift are given in Table C7 along with the percentages of volume with respect to gross drift.

Table C6: Estimated net monthly littoral drift for the year 1967.

Month	Cubic Yards/Month	
	Southward	Northward
January	28,600	
February	39,760	
March	34,420	
April	13,090	
May	-	2,100
June	-	5,660
July	-	7,110
August	-	3,390
September	16,800	
October	48,810	
November	77,400	
December	29,900	
Total for the year	288,780	18,260

Net Southward for the year: 270,520 cu.yd.
Southward and Northward for the year: 307,040 cu.yd.

Table C7: Estimated monthly magnitudes of littoral drift, based on 20 years (1956-1975) WIS wave data.

Month	Mean Southward cu.yd/yr	Mean Northward cu.yd/yr	Southward and Northward cu.yd/yr	% Volume Southward	% Volume Northward
January	55,016	11,256	66,272	83.0	17.0
February	40,870	19,326	60,196	67.9	32.1
March	36,300	18,035	54,335	66.8	33.2
April	23,562	18,410	41,972	56.1	43.9
May	13,957	10,820	24,777	56.3	43.7
June	7,600	9,430	17,030	44.6	55.4
July	1,935	6,258	8,193	23.6	76.4
August	5,450	4,826	10,276	53.0	47.0
September	29,820	9,875	39,695	75.1	24.9
October	62,956	15,213	78,169	80.5	19.5
November	66,616	13,440	80,056	83.2	16.8
December	58,120	18,966	77,086	75.4	24.6
Total	402,202	155,855			

Q_{net} = 246,347 cu.yds/yr.

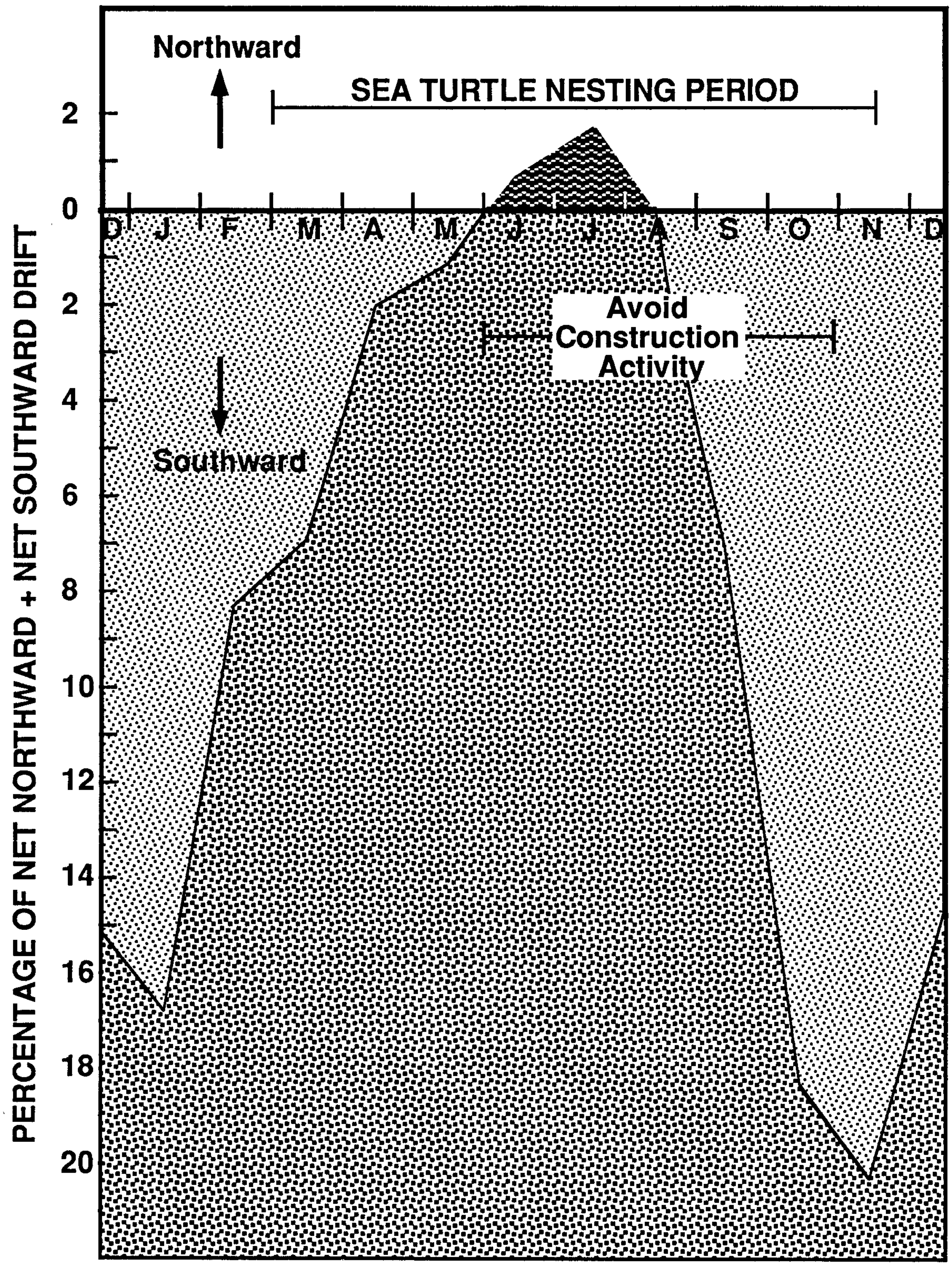


Fig. C.6. Percentage of net littoral drift each month, estimated from 20 years WIS wave data.

Monthly magnitudes of net southward and net northward drift are given in Table C8 based on the 20 year calculations along with the corresponding percentages with respect to the total drift (southward plus northward). The monthly percentages are plotted in Fig. C.7.

The following conclusions are drawn from the above analysis of data:

1. Northward drift takes place mainly during a two-month period of June and July. The quantity of drift being 2.4 percent of the gross drift.
2. Both southward and northward drifts take place during each month. During the four month period October to January, the average southward drift is 80 percent and northward drift is 20 percent of the total volume of gross drift. Hence there is a net southward drift. During June and July the average southward drift is 34 percent and northward drift is 46 percent of the total volume of gross drift. Hence there is a net northward drift.

C1.3.4 Estimated Daily Drift

Results of computations of daily littoral drift are shown in Fig. C.8 for the year 1967. This figure gives the cumulative net southward longshore littoral sand transport for the Jupiter area. Since the net drift during the year 1967 was northward during May through August, Fig. C.8 indicates a decrease in the net southward transport over this period. It may be noted that during the month of November, there is a sharp increase in the cumulative southward transport. It has been estimated that during the two-day period of 7th to 9th November 1967, the net southward transport was 15,840 cubic yards per day, or a total of 31,680 cubic yards during the two days. Since the total northward plus southward sediment transport during this year was 307,040 cubic yards, the two-day volume is equivalent to 10.32 percent of the gross annual sand transport. The average daily transport rate of the gross drift (southward plus northward) over the one year period works out to 841 cubic yards per day. The peak transport rate over the two day period works out to 18.83 times the average daily rate. The occurrence of such high rates of transport over a relatively very short time span is not at all uncommon. In fact, similar observations have been made at other locations along the U.S. coastline and also at other places in the world. Seymour and Castel (1985) have reported that nearly 50 percent of longshore drift occurs during 10 percent of the time associated with storms. Studies related to estimation of beach erosion and effective sand transfer need to take into account such episodic occurrences of high transport rates.

C1.4 Characteristics of Littoral Drift in the Vicinity of Jupiter Inlet

The important characteristics of littoral drift at Jupiter may be summarized as follows:

1. Littoral drift estimates based on WIS wave data over a 20 year period from 1956 to 1975 indicate that southward drift occurs for a total of 60.7 percent of time and northward drift occurs for 34.8 percent of time during a year on an average basis. There is no drift during 4.5 percent of the time, either because there is no significant wave activity or because the waves are normal to the shore.

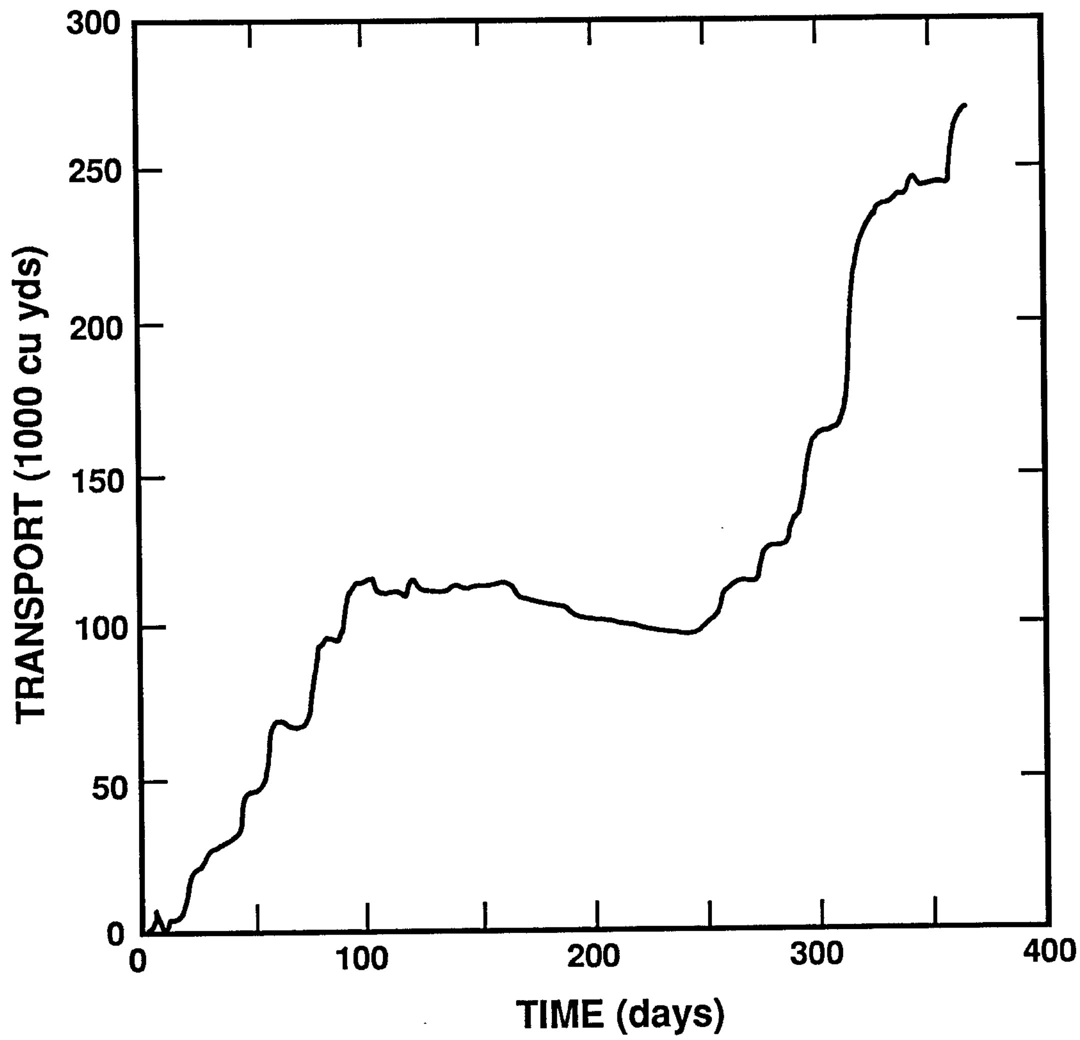


Fig. C.7. Cumulative net southward longshore transport at Jupiter Inlet calculated from WIS hindcast data for the year 1967 (increasing volume implies net southward transport).

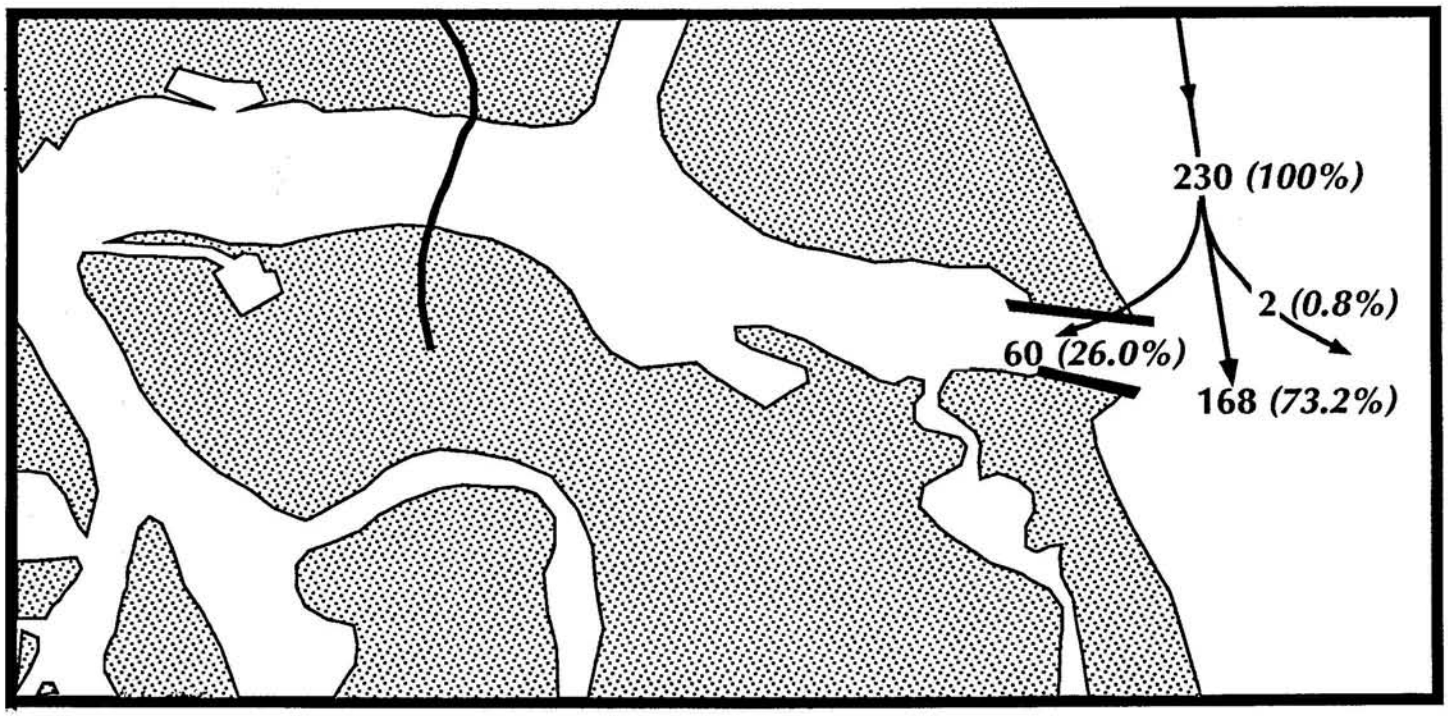


Fig. C.8. Primary littoral drift distribution at Jupiter Inlet.

Table C8: Estimated monthly magnitudes of net southward and northward littoral drift based on 20 years (1956-1975) WIS wave data.

Month	Net Southward cu.yd/yr	Net Northward cu.yd/yr	% of Gross Drift Southward and Northward
January	43,760		16.92
February	21,544		8.33
March	18,265		7.06
April	5,152		2.00
May	3,137		1.21
June	-	1,830	0.71
July	-	4,323	1.67
August	624		0.24
September	19,945		7.71
October	47,743		18.45
November	53,176		20.56
December	39,154		15.14
Total	252,500 (97.6%)	6,153 (2.4%)	100.00

Net Southward = 246,347 cubic yards
Total Southward and Northward = 258,653 cubic yards

2. The wave climate that induces northward drift is milder than the wave climate that induces southward drift. The total volume of southward drift is 82.9 percent of the gross volume whereas the northward drift accounts for 17.1 percent. The volumetric percentages are not proportional to the percentages of duration of occurrence.
3. The net average drift for 20 year period (1956 to 1975) is 230,000 cubic yards. The estimated net minimum drift is 146,000 cubic yards per year whereas the maximum is 434,000 cubic yards per year.
4. It is estimated that under the present site conditions, about 73 percent of the net southward drift bypasses the inlet through natural processes, 26 percent enters the inlet and 1 percent is deposited on the outer shoal.
5. The peak daily transport rate can be as high as 20 times the average daily rate.
6. Field studies conducted by the University of Florida show that some of the sediment from south beach is transported around the tip of the south jetty and enters the inlet. The quantity of such transfer is estimated to be on the order of 10,000 cubic yards per year.
7. Due to variability in the wave climate at Jupiter, considerable variability prevails in the monthly quantity and direction of littoral drift during a year and also from year to year.

C2. Sediment Budget

C2.1 General

A sediment budget is based on sediment erosion, transportation and deposition, and the resulting excesses or deficiencies of material quantities. Usually, the sediment quantities are listed according to the sources, sinks and processes causing the additions and subtractions. For purposes of the present study, the net littoral drift in the study area is taken to be predominantly southward with the rate of transport being 230,000 cubic yards per year. The distribution of this quantity over different areas has been estimated.

C2.2 Primary Distribution

The primary distribution of net southward drift may be considered to be as follows:

i) Sediment transferred southward naturally:

It was concluded from the beach erosion study conducted by the U.S. Army Corps of Engineers (1966) that about 73 percent of the net littoral drift bypasses the inlet through natural processes. Hence this quantity is estimated to be 168,000 cubic yards per year.

ii) Sediment entering Jupiter Inlet:

Most of the sediment entering the inlet probably moves in and out with the flood and ebb currents which are fairly strong. However, the amount of sediment flushing out of the inlet during ebb is smaller than the total sediment entering during flood. It is estimated that the residual sediment deposited inside the inlet is of the order of 60,000 cubic yards per year. Over the past 37 years, sediment dredged from areas inside the inlet and deposited on the south beach has averaged to the rate of 43,500 cubic yards per year. The sediment enters the inlet at the rate of 60,000 cubic yards per year and the dredging accounts for 43,500 cubic yards per year. The differential sediment is mostly deposited inside the inlet in areas other than the sand traps and a small amount of sediment is washed out of the deposited sediment during ebb flow.

iii) Sediment depositing on the outer shoal:

A study of the growth of ebb shoal in terms of its size and change in water depth indicated that the long term mean deposition rate on the shoal is of the order of 7,000 cubic yards per year. Out of this, 2,000 cubic yards per year is believed to be depositing directly out of the sediment bypassing the inlet naturally and 5,000 cubic yards per year depositing out of the sediment-laden ebb jet fanning over the ebb shoal.

Hence, the estimated primary distribution of the net southward drift is as follows:

	Cubic Yards/Year
1. Transferred southward naturally:	168,000
2. Entering Jupiter Inlet:	60,000
3. Deposited on outer shoal:	2,000
Total	230,000

This primary distribution is shown in Fig. C.9.

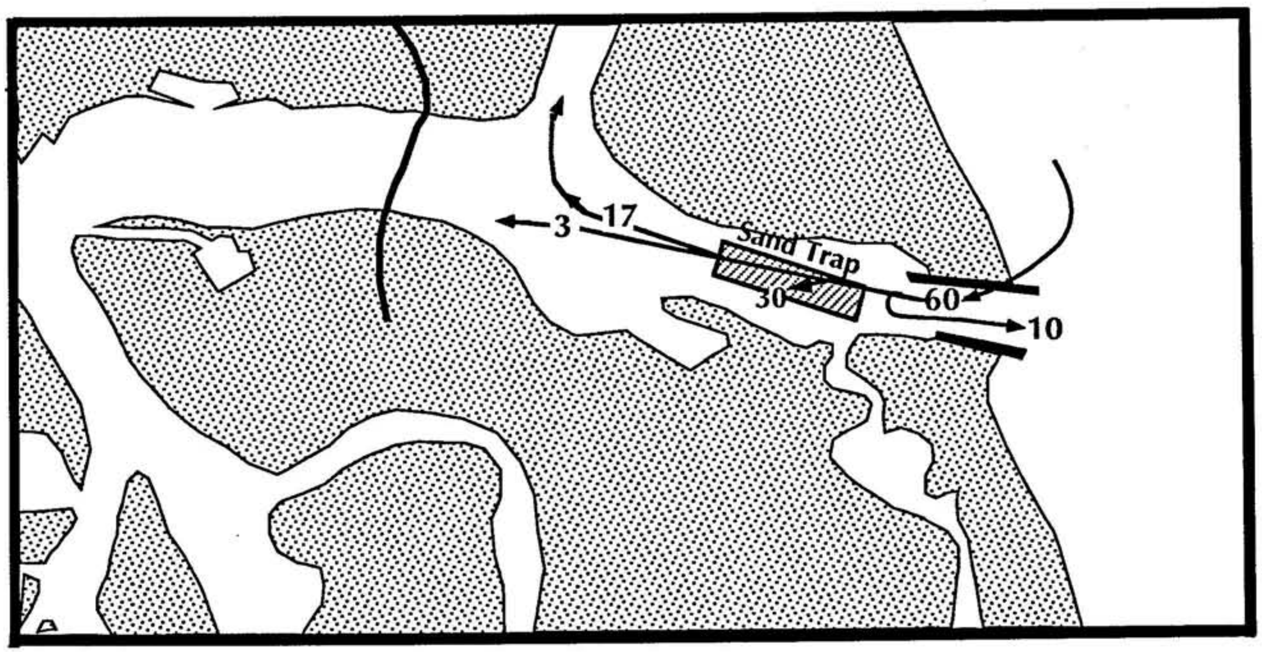


Fig. C.9. Secondary littoral drift distribution at Jupiter Inlet.

C2.3 Secondary Distribution and Return Flows

The secondary distribution consists of the fate of sediment entering Jupiter Inlet and this may be considered to be as follows:

i) Sediment depositing in the sand traps:

Dredging records shown in Table C3 show that sediment is dredged at an average rate of about 43,000 cubic yards per year. In the absence of actual data, it is estimated that out of this total quantity, 30,000 cubic yards are dredged from the channel trap and 13,000 cubic yards from the Intracoastal Waterway's trap.

ii) Sediment deposition inside the inlet:

Sedimentology of the lower Loxahatchee River Estuary and Jupiter Inlet studied by the University of Florida (Mehta et al., 1990b) revealed that the flood tidal delta located at the intersection of the Southwest, Northwest and North Forks of the Loxahatchee River is extending itself into the mouth of Northwest Fork, causing shoaling of the boat channel. Although it is not absolutely clear where the sediment is coming from, both the longshore transport system and the fluvial transport system may be making significant contribution. Bank erosion also contributes to the shoaling process. These conclusions are based on the similarity of textural parameters in different deposits. It is thus evident that a part of the sediment entering Jupiter Inlet is lost from circulation due to deposition in the inner areas of inlet. It is estimated that the average annual quantity of this loss is of the order of 7,000 cubic yards.

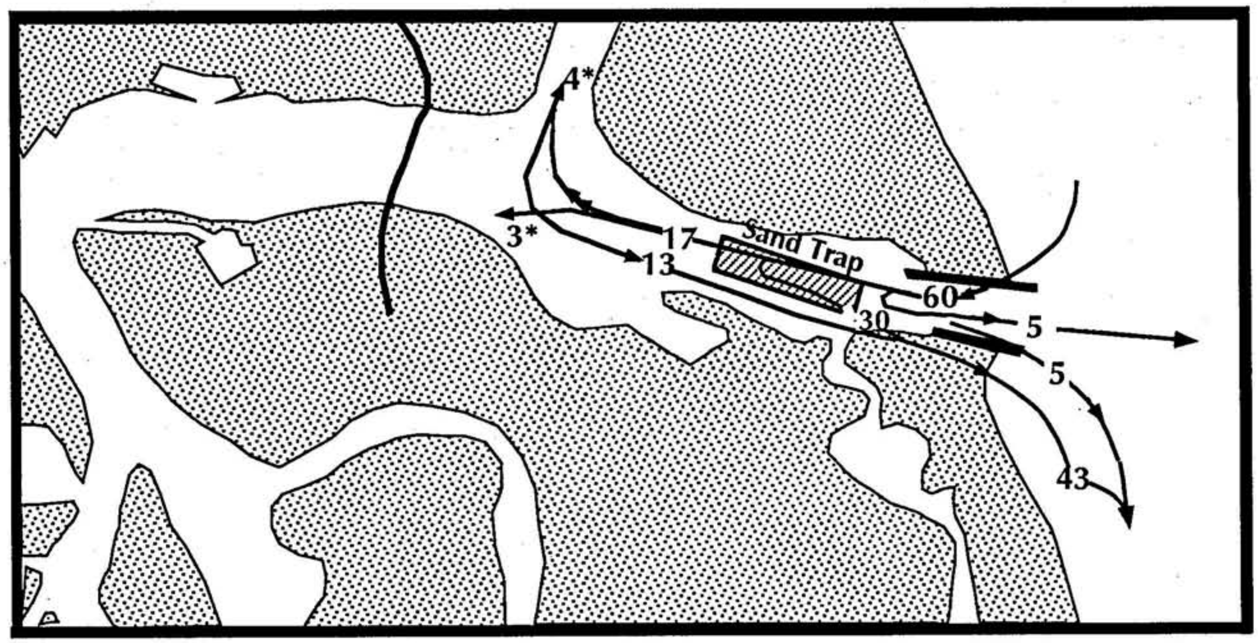
iii) Other factors:

A part of the sediment from the inlet is flushed out during ebb flow. A fraction of this sediment is deposited over the ebb shoal when the sediment-laden ebb flow spreads over a large area outside the inlet. The sediment which does not deposit over the shoal is flushed out in the net southward direction under the combined action of tidal currents, ocean currents and wave-induced currents.

Thus, out of 60,000 cubic yards entering the inlet, the estimated distribution is as follows:

		Cubic Yards/Year
1.	Deposited in channel sand trap:	30,000
2.	Deposited in Intracoastal Waterway and other inside areas:	20,000
3.	Sediment flushed out of the inlet during ebb flow:	10,000
	Total	60,000

The above secondary distribution is shown in Fig. C.10. The return flows consist of the following:



* "Lost" in Transit

Annual Rates in 1,000's of cubic yards

Fig. C.10. Return flows of littoral drift distribution at Jupiter Inlet.

	Cubic Yards/Year
1. Sand dredged from the channel trap and transferred to south beach:	30,000
2. Sand dredged from the Intracoastal Waterway trap and transferred to south beach:	13,000
3. Sediment flushed out of inlet and	
a) deposited on the ebb shoal:	5,000
b) flushed out southwards:	5,000
4. Scattered deposits inside the inlet:	7,000
Total	60,000

The return flows are shown in Fig. C.11.

C2.4 Total Distribution

Taking into account the primary distribution, the secondary distribution and the return flows of sediment, the estimated quantities of total distribution are shown in Fig. C.12. The same distribution in the form of percentages with respect to the net annual southward drift is given in Fig. C.13.

The distribution chart is as follows with quantities given in cubic yards:

Net Annual Southward Drift: 230,000

Transferred Southward: 216,000 (94%)

Lost in Transit: 14,000 (6%)

→ Outer Shoal: 7,000 (3%)

→ Inside Inlet: 7,000 (3%)

Entering Inlet: 60,000 (26%)

Naturally Transferred Southward: 168,000 (73%)

Deposit on Outer Shoal: 2,000 (1%)

→ Deposit in Channel Sand Trap: 30,000 (13.0%)

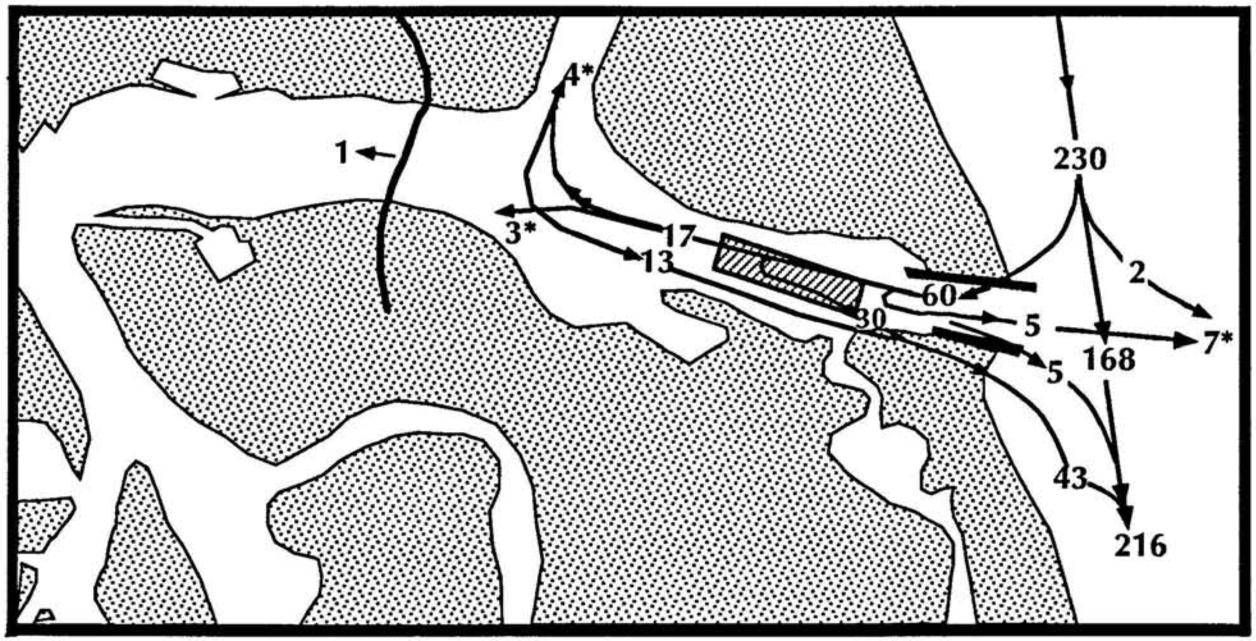
→ Deposit in Intracoastal Waterway: 13,000 (5.6%)

→ Scattered Deposits Inside Inlet: 7,000 (3.0%)

→ Ebb Flow Deposit on Outer Shoal: 5,000 (2.2%)

→ Ebb Flow Sediment Flushed Southward: 5,000 (2.2%)

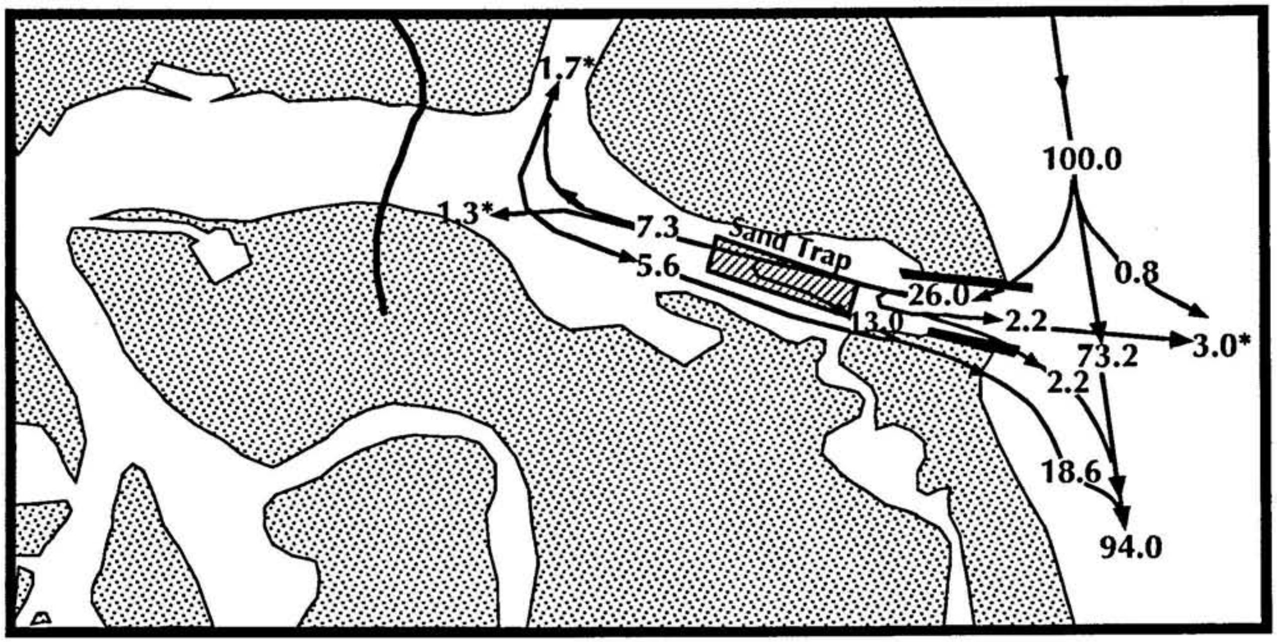
DISTRIBUTION OF ANNUAL NET SOUTHWARD DRIFT



* "Lost" in Transit

Annual Rates in 1,000's of cubic yards

Fig. C.11. Quantities of total distribution of littoral drift at Jupiter Inlet.



* "Lost" in Transit

Annual Rates in 1,000's of cubic yards

Fig. C.12. Percentage of total distribution of littoral drift at Jupiter Inlet.

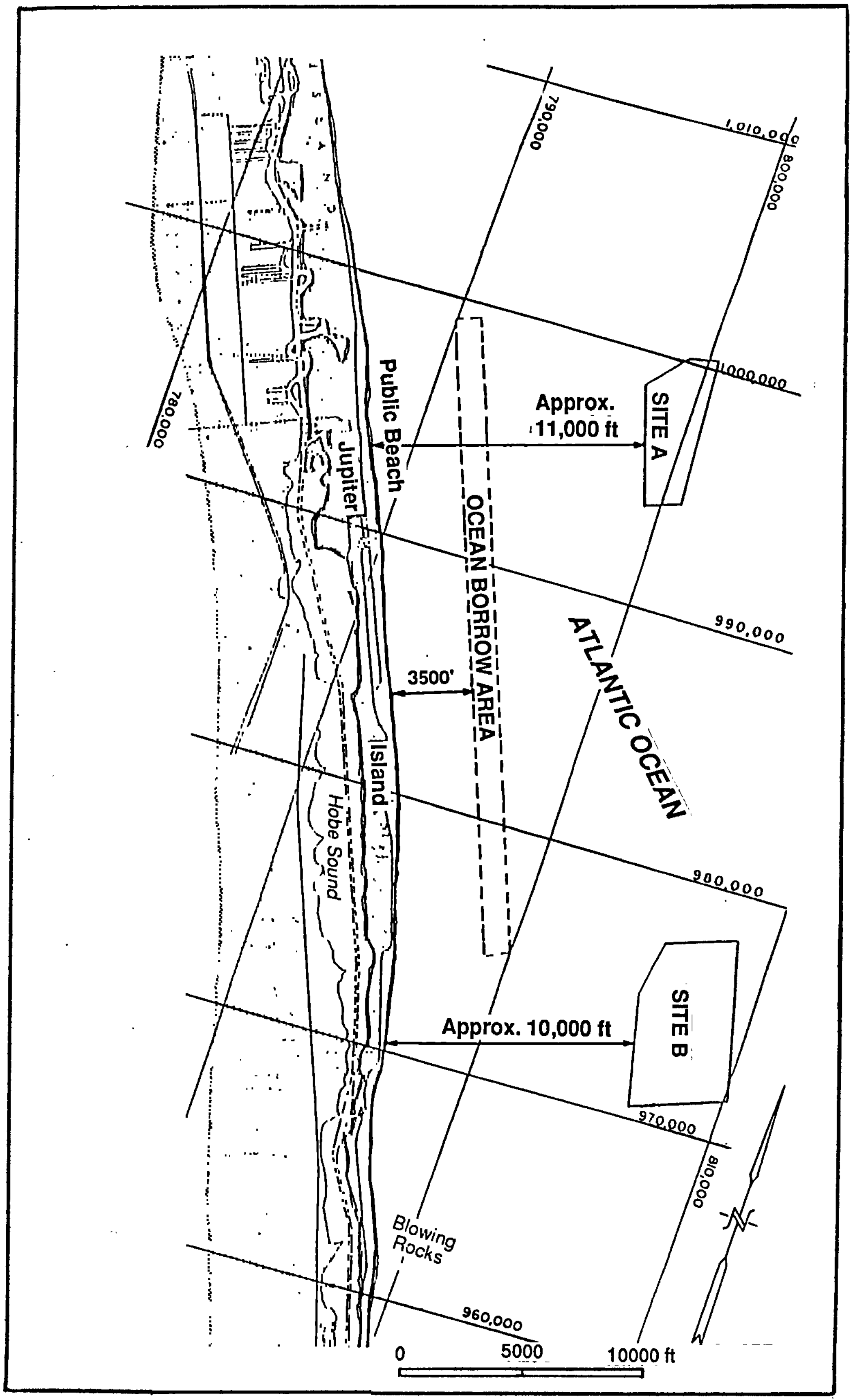


Fig. C.13. Offshore borrow areas for beach nourishment projects at Jupiter (Aubrey and DeKimpe, 1988).

C2.5 Sources of Southward Sand Transfer

The net southward sand transfer at Jupiter Inlet occurs due to natural bypassing as well as due to human efforts consisting of dredging inside the inlet and placing the sediment on the south beach. The distribution appears to be as follows:

		Cubic Yards/Year
Natural bypassing in deep water		168,000
Sediment flushed out of inlet		5,000
	Sub-total	173,000
Dredging and deposition		43,000
	Total	216,000

Thus, out of the estimated 230,000 cubic yards per year, about 14,000 cubic yards per year are not transferred to the south beach. This sediment is "lost" in the form of deposition on the outer shoal and deposition in different areas inside the inlet. This deficit of sediment as well as the deflection of the littoral drift by the inlet jetties is believed to be causing erosion of southern beach and hence the quantity of sediment transferred through human efforts needs to be increased at least by the order of 14,000 cubic yards per year.

APPENDIX D: PHYSICAL MODEL TEST RESULTS RELATED TO POSSIBLE JETTY CONFIGURATIONS AND DREDGING

D1. Introduction

In order to study the flow conditions in the vicinity of Jupiter Inlet, and any changes made to it, a physical model representing the inlet near field was created, as discussed in previous progress reports to JID (Mehta et al., 1991a, and Mehta et al., 1991b), as well as in DelCharco (1992).

D2. Tasks

The tasks of this portion of the study, which have already been documented in Mehta et al. (1991a), and the bases discussed therein, will be restated here:

1. Obtain data on wave heights and wave-induced currents along the shoreline for an assessment of alongshore sediment transport capacity.

2. Obtain data on the changes in flow pattern, current magnitude and eddies caused by implementation of construction and dredging proposals (jetties, offshore shoal mining).

3. Obtain data on the change in wave heights as a result of implementation of construction and dredging proposals.

4. Evaluate relative merits and demerits of different alternatives.

Note that the following development must be viewed only in the strict context of the manner in which the laboratory data were analyzed. In the final choice of modifications recommended, additional factors including the relative "shadow effects" of the two jetties on littoral sand transport, as well as experiences at other inlets, were considered together with these test results. In principle, at least, it should be feasible to "assign numbers" to incorporate the shadow effect as far as its impact is concerned, and to as well translate "experience at other inlets" into quantifiable effects. Such an exercise would enable the reformulation of the quantitative evaluation processes for the laboratory test results. The issue of impacts is particularly relevant to the effect an extension of the south jetty might have on south beach erosion. In that instance it is difficult to quantify impacts, particularly when they are partly based on what is known to have occurred elsewhere under non-identical but comparatively similar circumstances. We will therefore revisit this matter on a qualitative basis in Section D6.1.

D3. Test Criteria

To be able to make an evaluation of the proposed jetty options and offshore dredging, a standard must be set. This standard is the 'normal' conditions at Jupiter Inlet, i.e. the existing conditions that simulate the hydrodynamics at Jupiter without modifications to the system.

The physical model was concerned with improving navigational safety, sheltering the south beach from erosion due to wave action, reducing sediment influx into the inlet mouth, and analyzing the effects of dredging the offshore bottom. When analyzing the effects of jetty improvements, it is also necessary to check the erosion potential of extending the jetty length.

A protocol for studying the above factors due to changes in the inlet system was established. By measuring wave heights, currents, and flow patterns in the model it was possible to achieve the listed objectives. The first three parameters, wave height and current magnitude and direction, were measured at several locations, 4 for each jetty design and 21 for the dredged offshore condition. Flow patterns for the inlet nearfield were also observed for each test. Primarily the tests were done for 'as is' conditions to which the modified tests could be compared. Each jetty configuration was compared to the normal conditions to determine whether or not the changes were beneficial overall.

Criteria for navigational safety were based on wave height measurements, and are discussed in section D5.1. The relationship between wave heights, energy, and sediment transport are discussed here first. Wave energy is a function of the square of wave height; this emphasizes the importance of wave height to wave energy. This relationship is implicit in the equation for predicting longshore sediment transport rates, namely:

$$Q = \frac{k \rho H_b^2 \sqrt{g d_b}}{16 (\rho_s - \rho) Q_s} \sin 2 \alpha_b \qquad \text{(D.1)}$$

where Q = longshore sediment transport rate, k = an empirical coefficient determined by comparing calculated values of Q with measured rates, ρ = density of water, ρ_s = density of sediment, α_b = angle wave crest makes with shoreline at breaking, Q_s = the solids fraction of the in situ sediment deposit (1-porosity), H_b = height of wave at breaking, d_b = depth of water at breaking, and g = acceleration due to gravity (Weggel and Perlin, 1988). By assuming the wave angle to be constant, and combining all other constants, this equation can be reduced to:

$$Q_1 = A H_b^2 \sqrt{g d_b} \qquad \text{(D.2)}$$

This Q_1 value will be considered to represent a longshore sediment transport "factor" as related to wave energy.

Weggel and Perlin (1988) modified Eq. (D.1), and with an expression for longshore current developed by Longuet-Higgins (1970) developed another equation for longshore transport rate:

$$Q_2 = \frac{2 k C_f \rho}{\delta\ 5 \pi (\rho_s - \rho) Q_s} H_b x_b [v] \qquad \text{(D.3)}$$

in which δ = the ratio of mean current velocity to a reference velocity, C_f = friction coefficient, x_b = distance from the shoreline of the breaking waves, and [v] = mean longshore current velocity. This equation has a first order wave height (H_b) term and a longshore velocity term (v). Combining constants yields the simplified equation:

$$Q_2 = B H_b x_b [v] \qquad \text{(D.4)}$$

This equation will be considered to represent longshore sediment transport as related to longshore current velocities. The simplified Eqs. (D.2) and (D.4), are then used to relate the wave and current data taken from the physical model to sediment transport potential factors.

It is well known that the effects of extending jetties on a beach can increase erosion on the down drift side, and accretion on the other. It is therefore necessary to account for these (adverse or beneficial) effects of extending the jetties. A study by Dean and Grant (1989) generated a numerical model which simulated the effects of extending a littoral barrier (such as a jetty) on a coastline. This model was used to simulate end-line beach profiles at Jupiter Inlet for selected cases of extended jetty lengths. The model allows for the historical background erosion and accretion rates to be used in calculating the new (due to jetty modification) profiles. A historical shoreline map of Palm Beach County, generated by the State of Florida Department of Natural Resources, was used to estimate erosion/accretion rates in the Jupiter Inlet vicinity. These rates were then used in the model. The result is a profile, a certain number of years (30 selected here), of the shoreline near Jupiter Inlet. A typical output of the model is shown in Fig. D.1. Note that since the jetties are very close with respect to the scale used in the plot, they are represented by a single line. After several different jetty lengths were tested, a plot relating downdrift erosion distance and jetty length was created; see Fig. D.2. This plot could then be used to relate erosion potential to jetty length, and assign representative integer values. Positive sign implies beneficial impact, while negative sign means an adverse impact. Increasing value of the integer implies increasing impact. A scale of 0 to 3 in steps of one, i.e. 0, 1, 2, 3, was chosen in general for a quantitative evaluation of all impacts considered. Only negative values were assigned with reference to jetty impact on the downdrift beach stability, since extending the jetties would increase erosion of the south beach, as seen from Fig. D.1. Note that the 200 ft jetty length shown in the figure is the existing condition at Jupiter Inlet. So, for example, a 100 ft jetty extension would be a 300 ft jetty. Since the erosion caused by a littoral barrier is due to the cut off of sediment supply, this factor is called the sediment supply factor as related to jetty length. The range of values for this factor, from 0 to -3, were assigned by erosion distances. Erosion distances less than 27,500 ft were assigned a value of zero, between 27,500 and 28,500 ft were assigned -1, between 28,500 and 29,500 ft were assigned -2, erosion distance more than 29,500 ft were given a -3.

The results from this model were selected for a thirty year time period, as noted. From the erosion depth and distance values calculated it was possible to calculate an eroded sand for several jetty length tests. By calculating the area of erosion for distance from a straight shoreline (no erosion) to the erosion line, with a representative slope of 1:10, and multiplying by the distance of erosion, for points every thousand feet, an estimate of beach erosion was made for three jetty lengths. The slope of 1:10 was chosen, from a beach-slope profile south of Jupiter Inlet near the Hilton hotel at Jupiter, obtained on 5/29/91 (Mehta et al., 1991b). The thirty year erosion volumes for the jetties as they exist, for a 100 ft extension (300 ft jetties), and for 200 ft extension (400 ft. jetties) were calculated and shown in Table D1.

Sediment influx into the inlet mouth from the south beach when waves are from the northeast and southeast has been previously established by the sand tracer studies documented in Mehta et al. (1991a) and Mehta et al. (1991b). This sediment influx is an important consideration in jetty modification designs. In order to quantify this influx, the flow patterns around each jetty modification were video-recorded and then sketched (see Fig. D.3 as an illustration). Analysis of these flow patterns allowed determination of the effects each jetty modification had on the sediment influx factor.

The effect of shore structures on the beaches in the proximity of the inlet have been noteworthy at Jupiter Inlet. Fig. D.4 shows the shoreline when the inlet was closed in 1945. Note the effects of the single jetty, which are qualitatively similar to those shown in Fig. D.1. Note also the virtual absence of the ebb shoal. Fig. D.5 shows the shoreline in 1971. Note the sand fillet north of the north jetty, and erosion south of the south jetty. The bulging

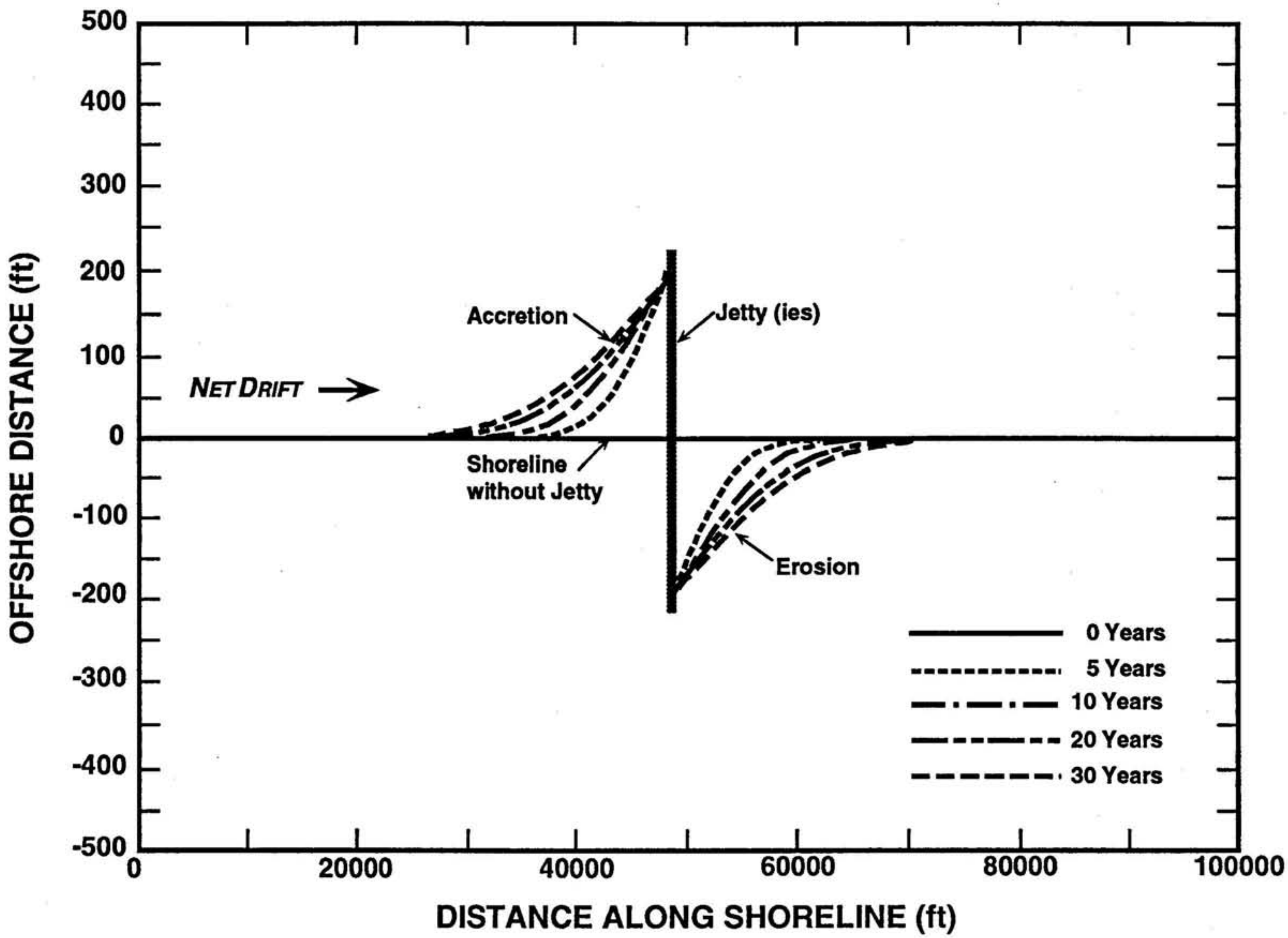


Fig. D.1. Results from numerical simulation of shoreline evolution with a jetty length of 220 ft.

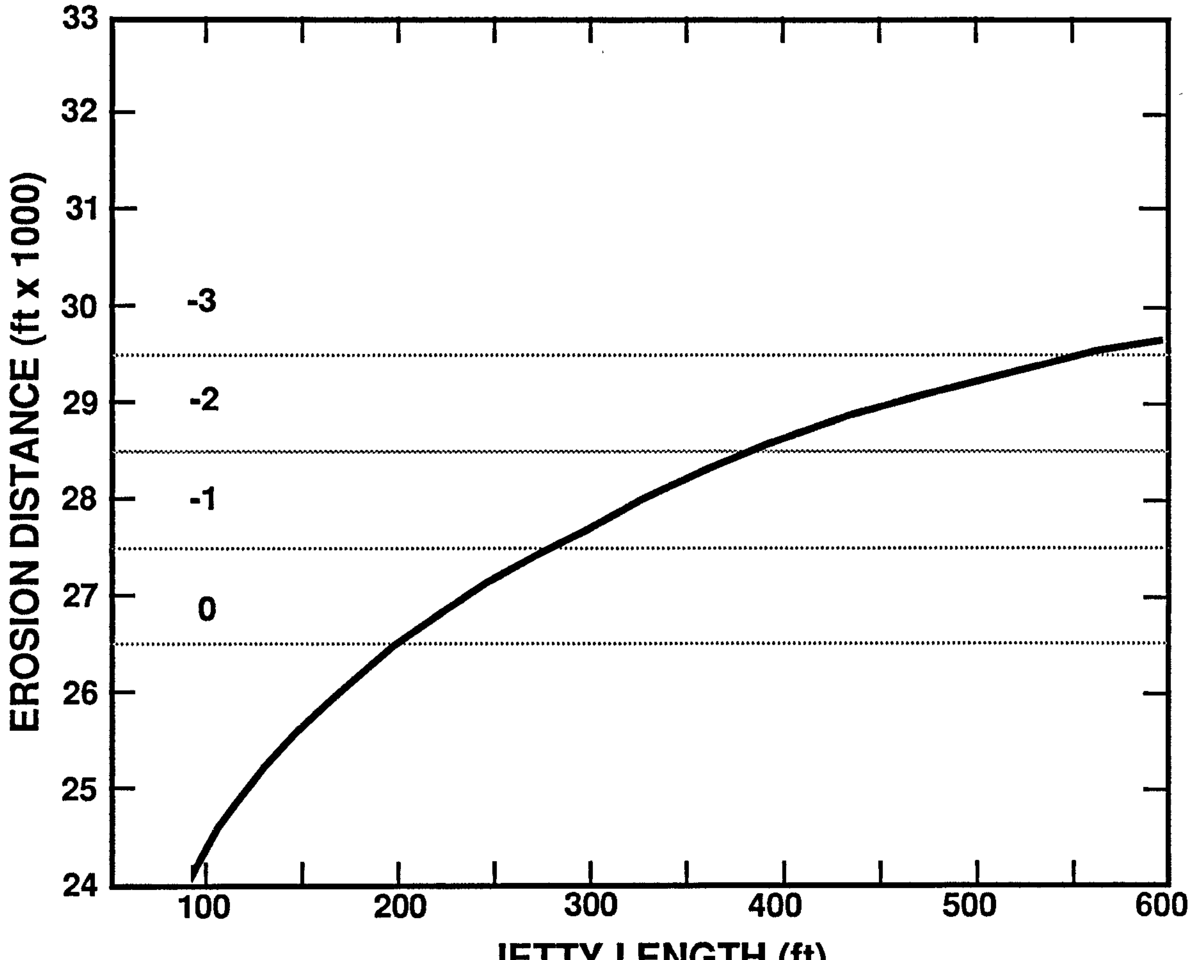


Fig. D.2. Jetty length vs. erosion distance with corresponding scale values (0, -1, -2, -3).

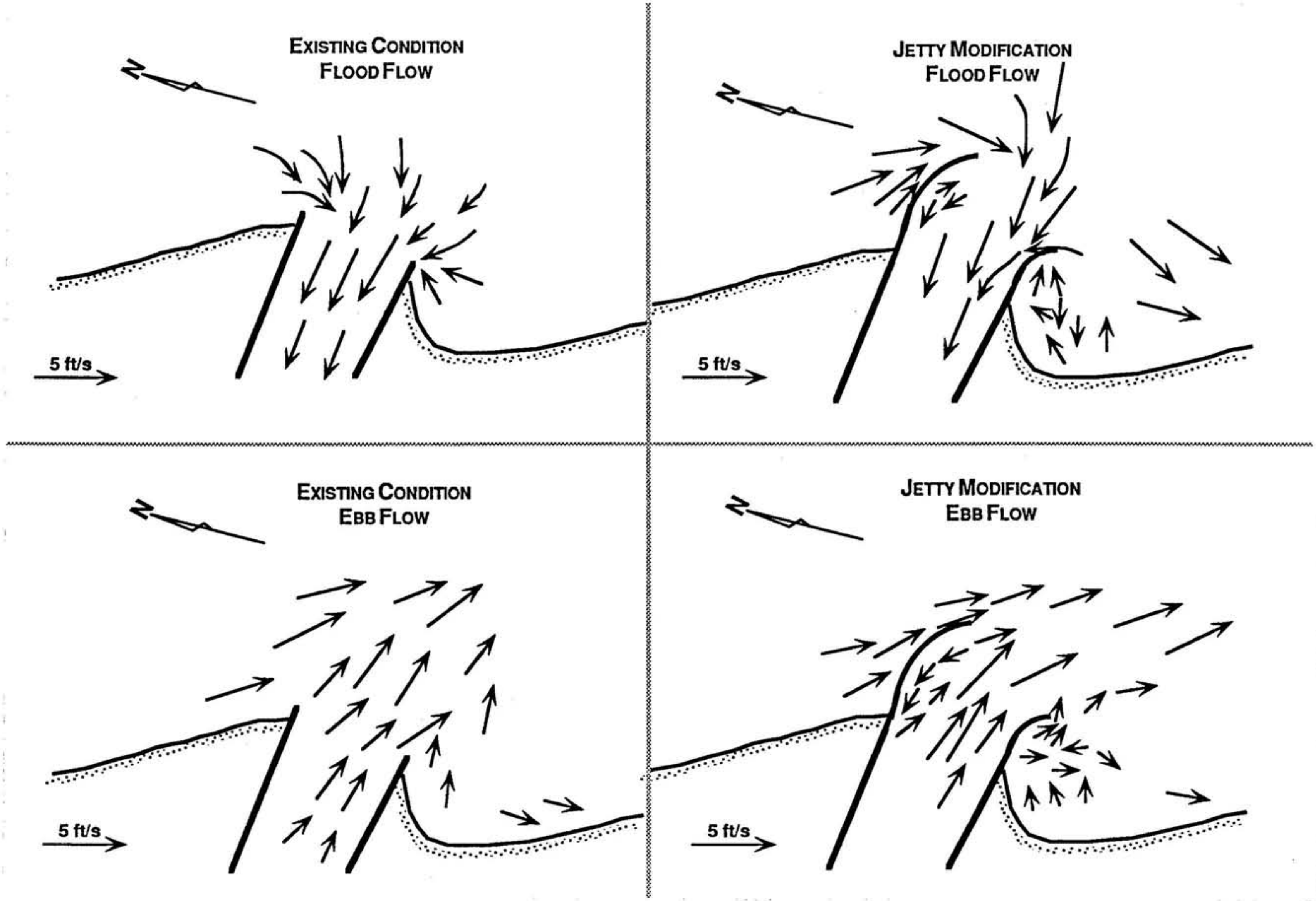


Fig. D.3. Inlet flow patterns for normal condition and modification M: flood and ebb tides.

Fig. D.4. Shoreline in the vicinity of Jupiter Inlet, March 11, 1945.

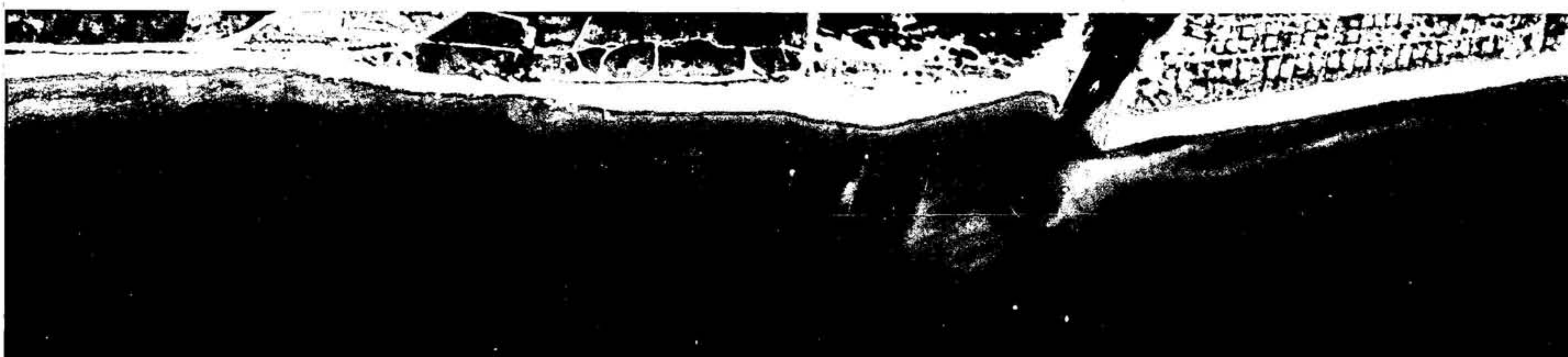


Fig. D.5. Shoreline in the vicinity of Jupiter Inlet, March 8, 1971.

Table D1: Thirty year erosion volume calculations (M indicates million).

200 ft[a] jetty	300 ft jetty	400 ft jetty
6.4 M ft^3	14.0 M ft^3	25.0 M ft^3
(0.24 M yd^3)	(0.5 M yd^3)	(0.9 M yrd^3)

[a]Existing condition

shoreline immediately south of the eroded shoreline appears to reflect the effects of prior nourishment. Note also the characteristic, arcate ebb shoal recognized by the breaking wave pattern, and the natural channel gap through the shoal in the southeastern direction.

The sediment influx factor described above was for conditions at mean sea level (MSL). It has been noted elsewhere (e.g. Mehta et al., 1991b) that significant sediment transport into the inlet takes place during storm events due to increased water levels and wave conditions. In order to study this activity, elevated water levels and increased wave heights were tested in the physical model. These tests, however, did not readily lend themselves to the previously discussed analysis. It was determined that the best analysis for these conditions would be a qualitative discussion of each test. This is done in section D6.2.

D4. Test Conditions

In order to test changes in the hydrodynamic conditions at Jupiter Inlet due to modifications in the system, it is necessary to recreate the dominate wave and current conditions. The dominate wave directions, water levels, wave heights, wave periods, and strength of flood and ebb flows have been discussed in Mehta et al. (1991b).

D4.1 Jetty Modifications

Various jetty designs were tested in order to evaluate their effectiveness at reducing erosion of the south beach, reducing sediment influx, and improving navigational safety. The jetty designs are listed in Table D2 and shown in Figs. D.6 through D.20.

D4.2 Elevated Jetty Modifications

As noted, sediment flux into Jupiter Inlet is found to occur under normal flood tides (Mehta et al., 1991b) but is increased considerably during storm events. A "northeaster" storm typically increases wave height, and therefore sediment transport capability and the water level. Buckingham (1984) has shown that a 1.5 meter storm surge causes the flood tidal flow velocity in Jupiter Inlet to increase to one and one-half times the normal velocity. This velocity rise increases sediment transport into the inlet. Overtopping of the existing jetties, when water and

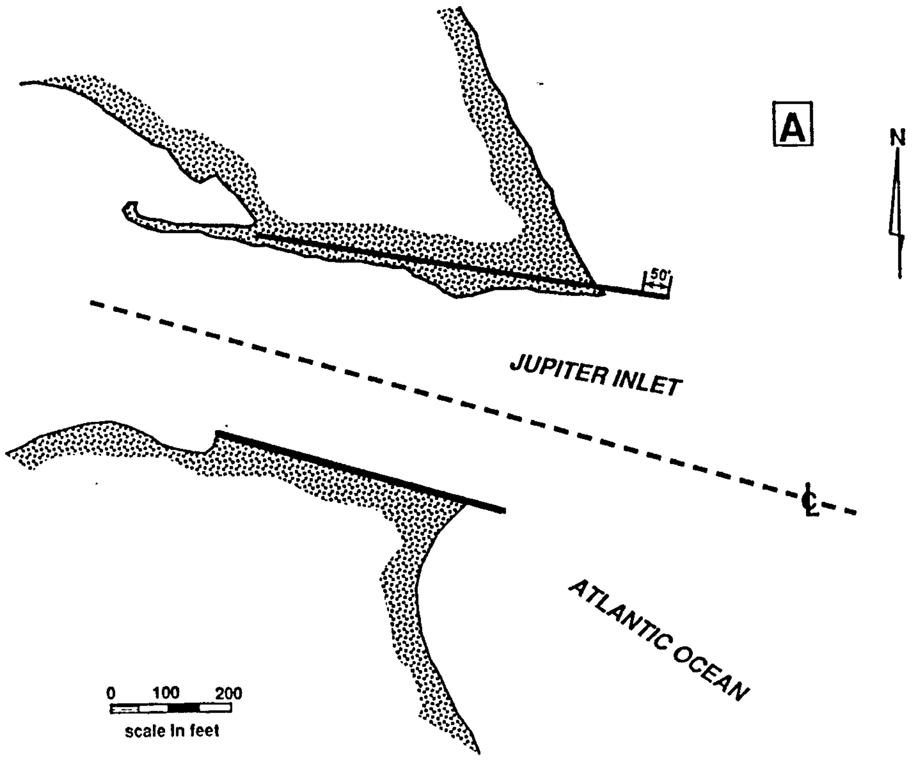


Fig. D.6. Jetty modification A.

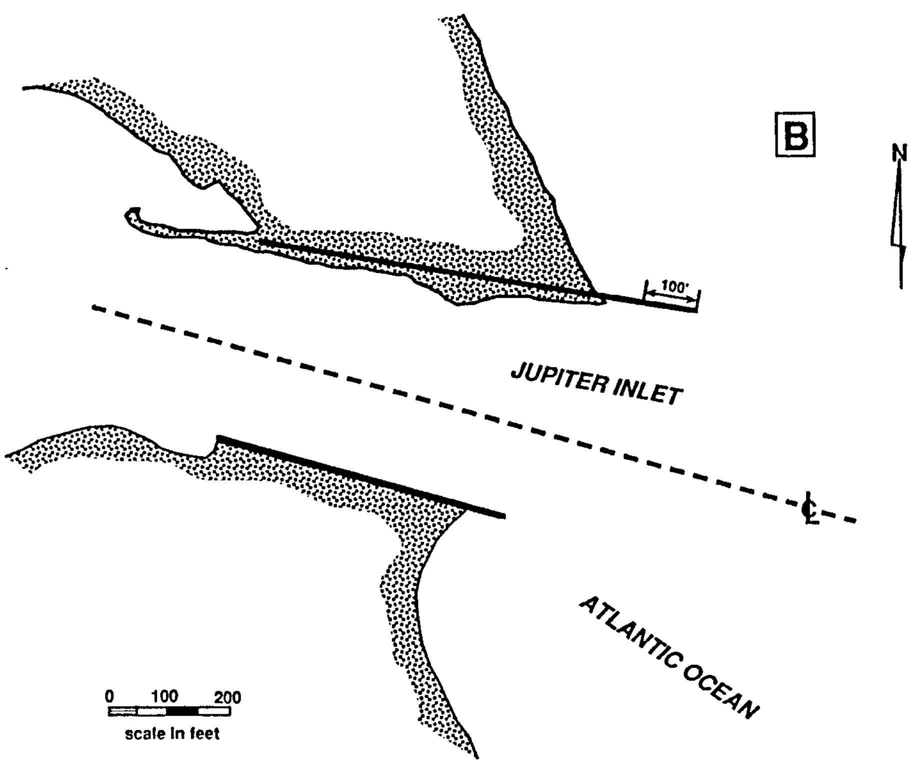


Fig. D.7. Jetty modification B.

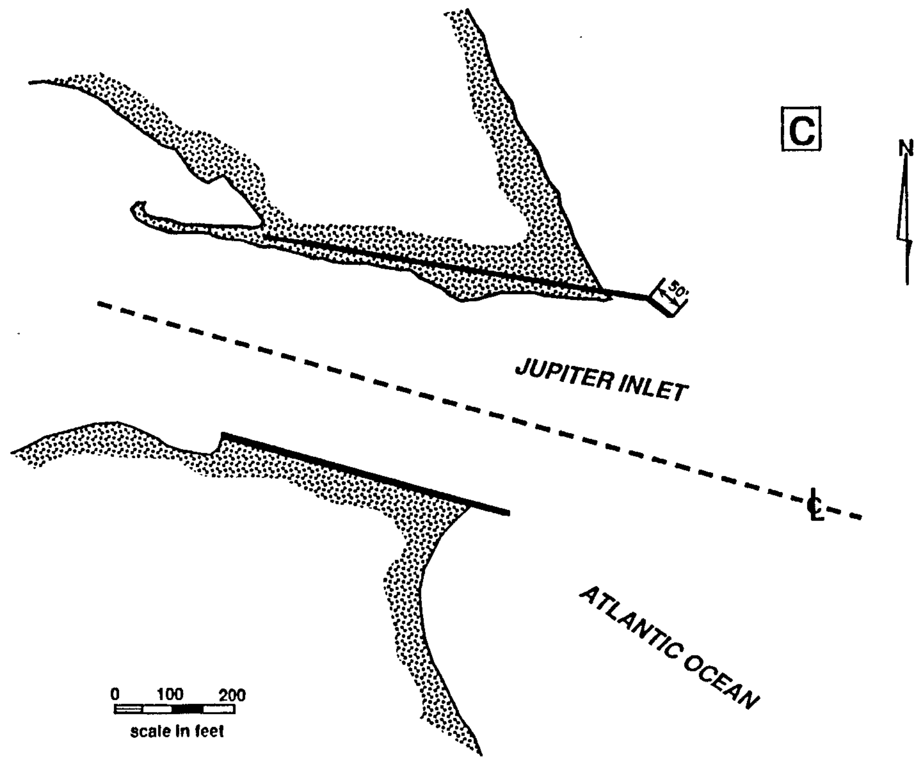


Fig. D.8. Jetty modification C.

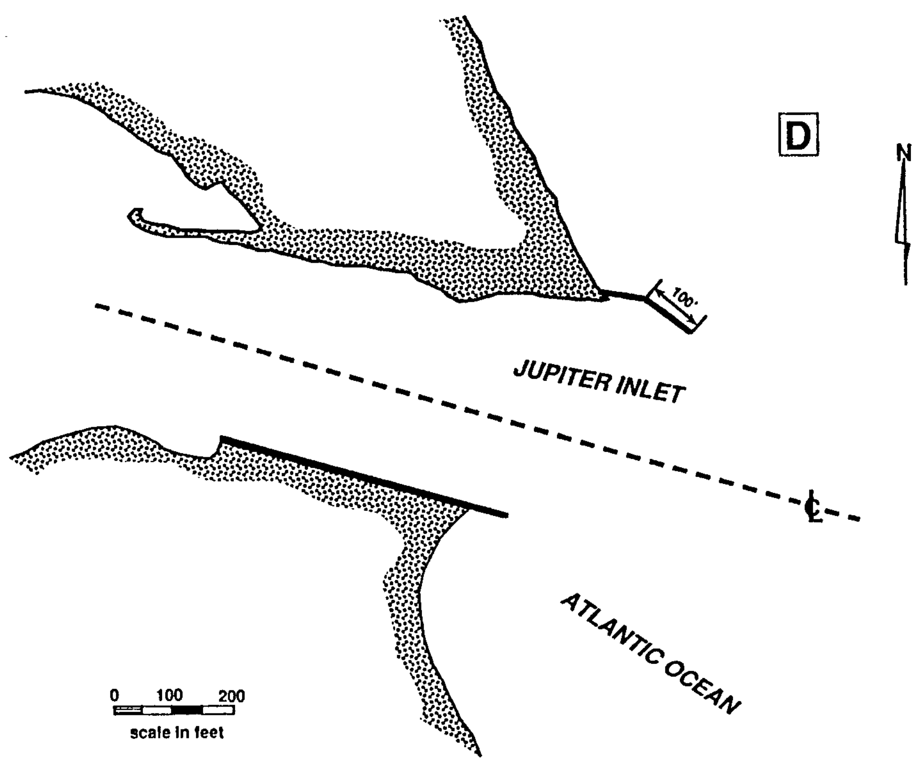


Fig. D.9. Jetty modification D.

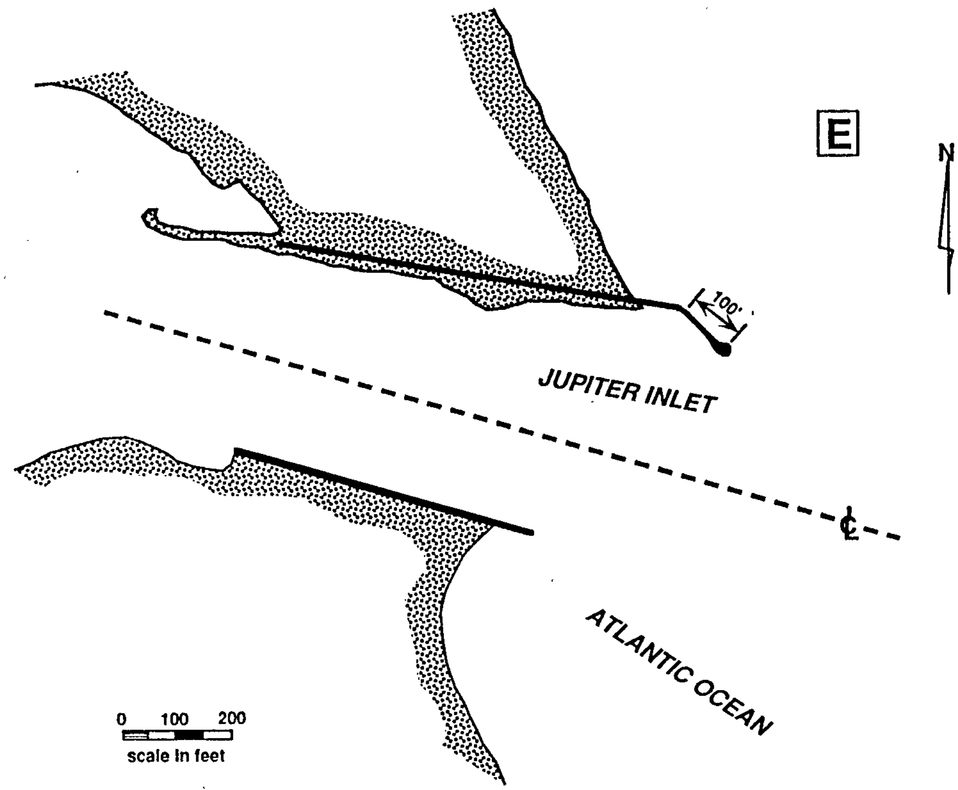


Fig. D.10. Jetty modification E.

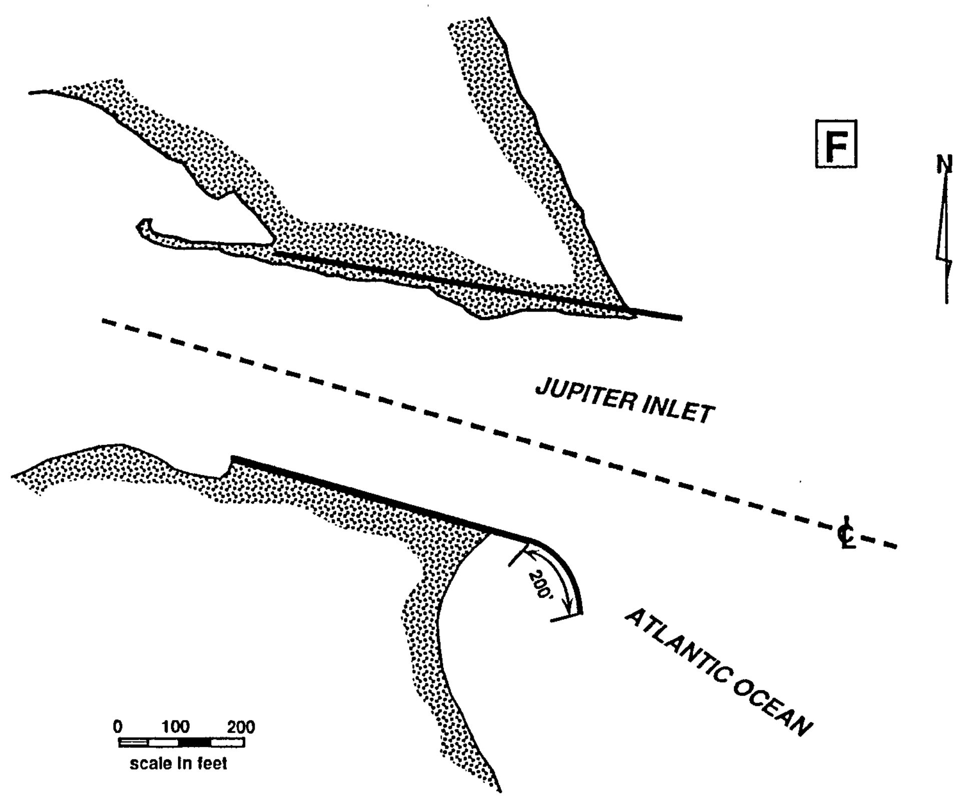


Fig. D.11. Jetty modification F.

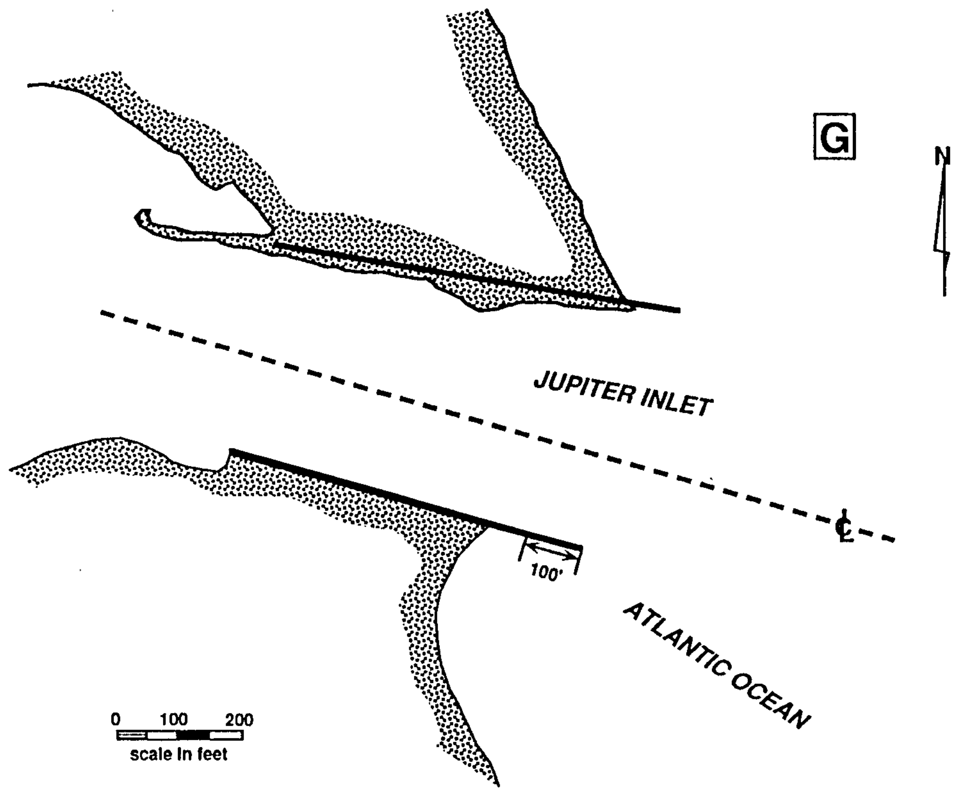


Fig. D.12. Jetty modification G.

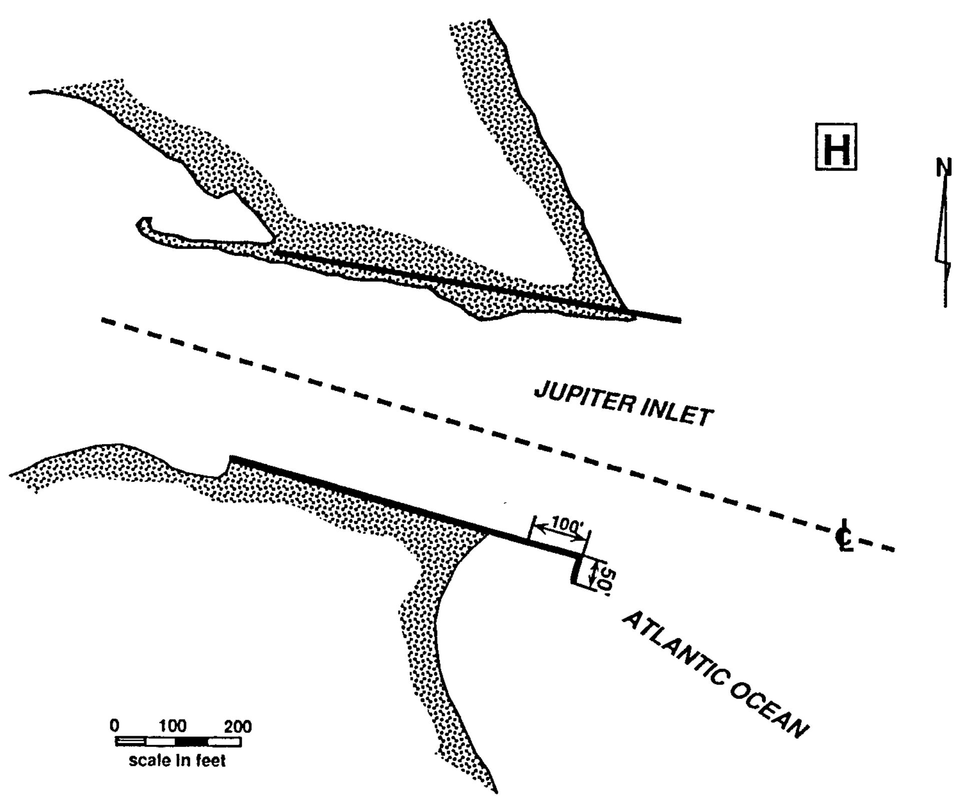


Fig. D.13. Jetty modification H.

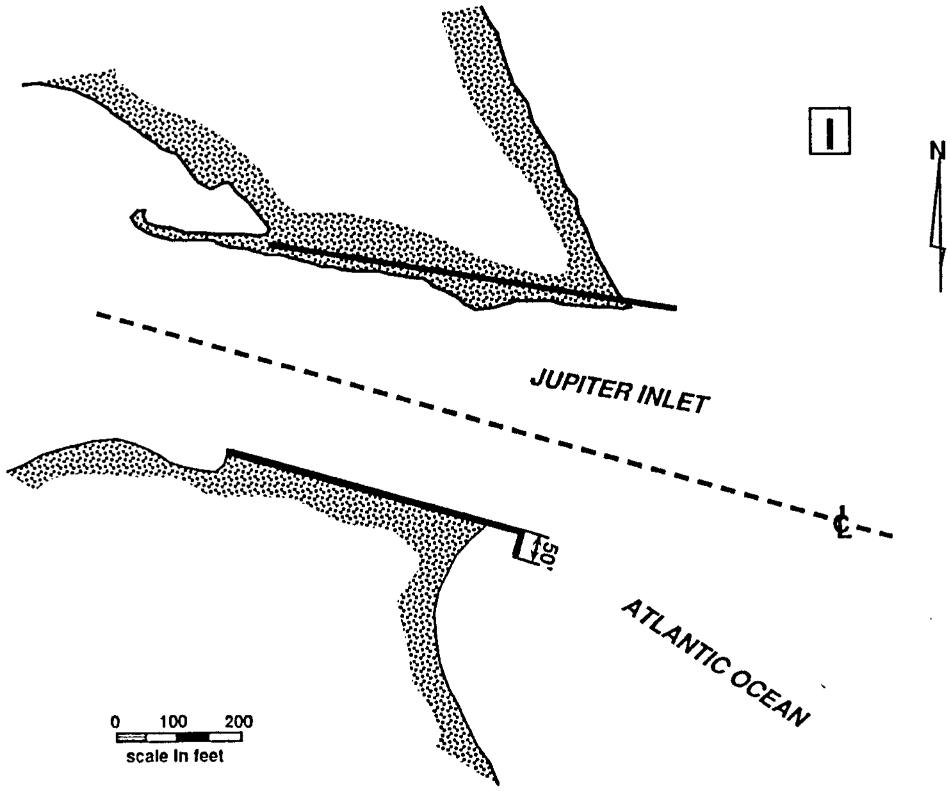


Fig. D.14. Jetty modification I.

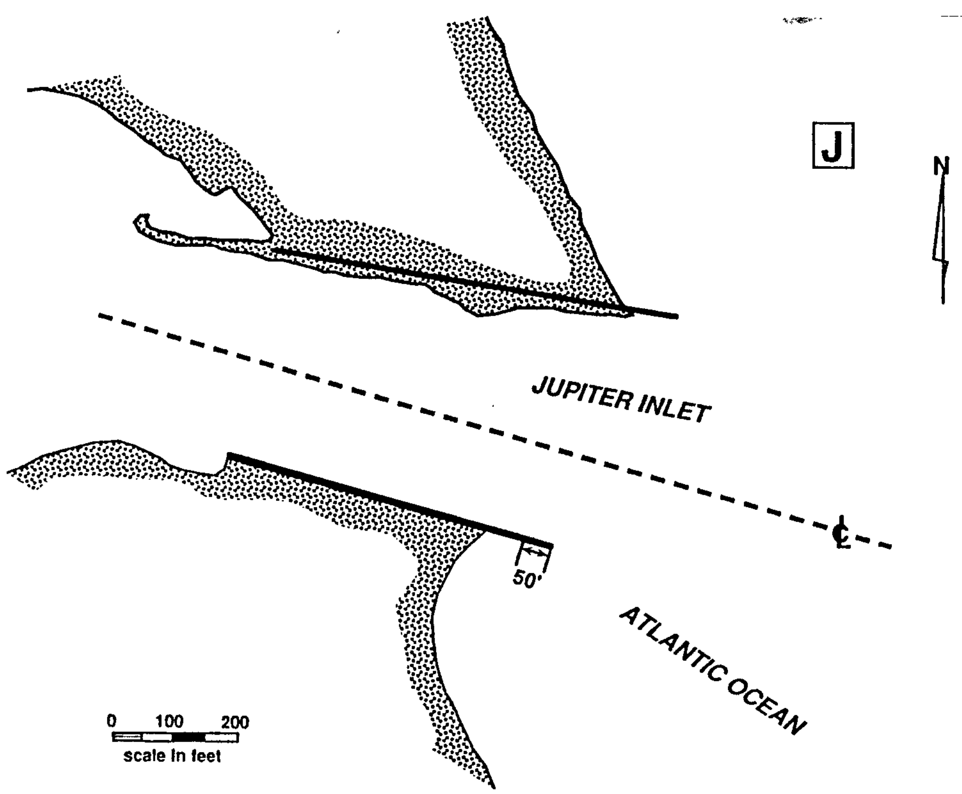


Fig. D.15. Jetty modification J.

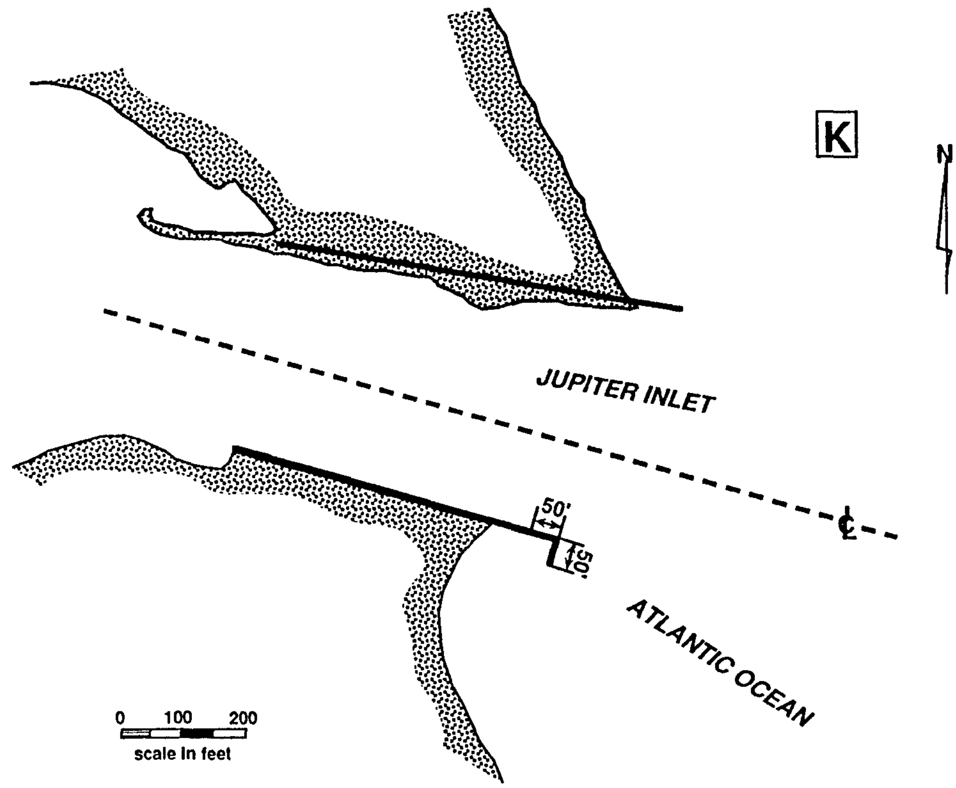


Fig. D.16. Jetty modification K.

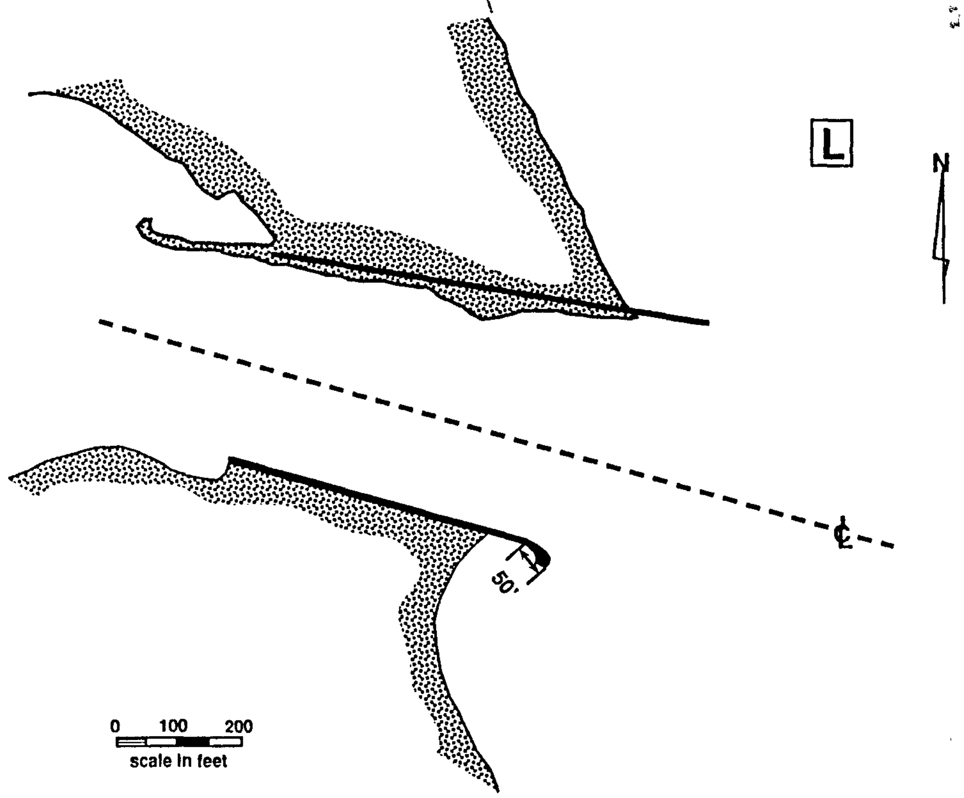


Fig. D.17. Jetty modification L.

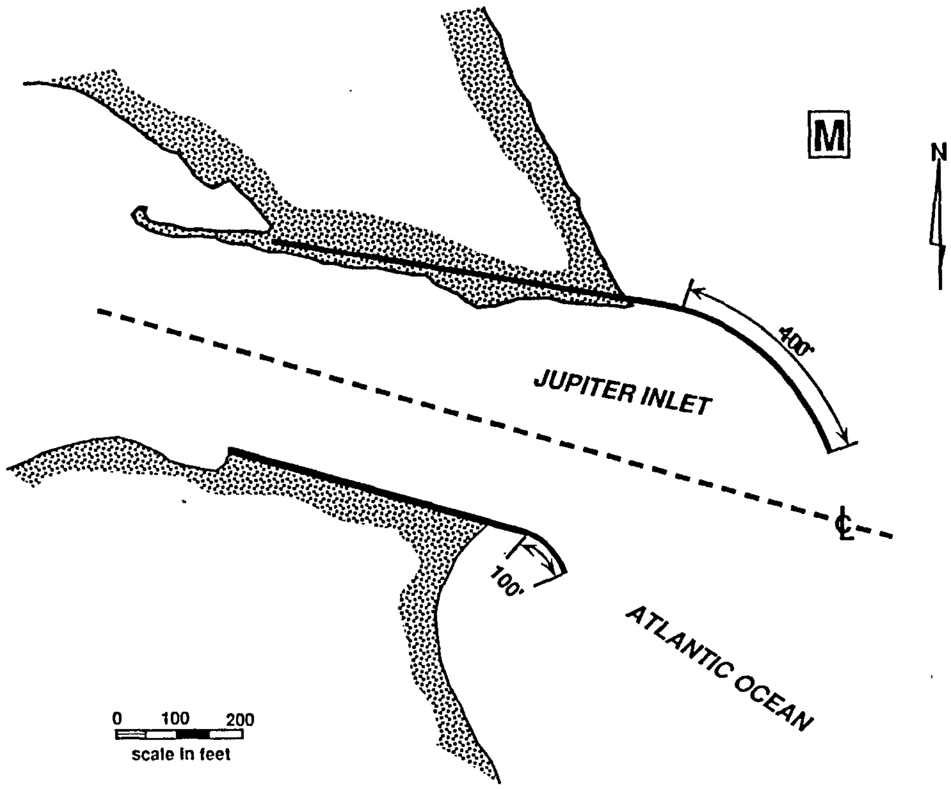


Fig. D.18. Jetty modification M.

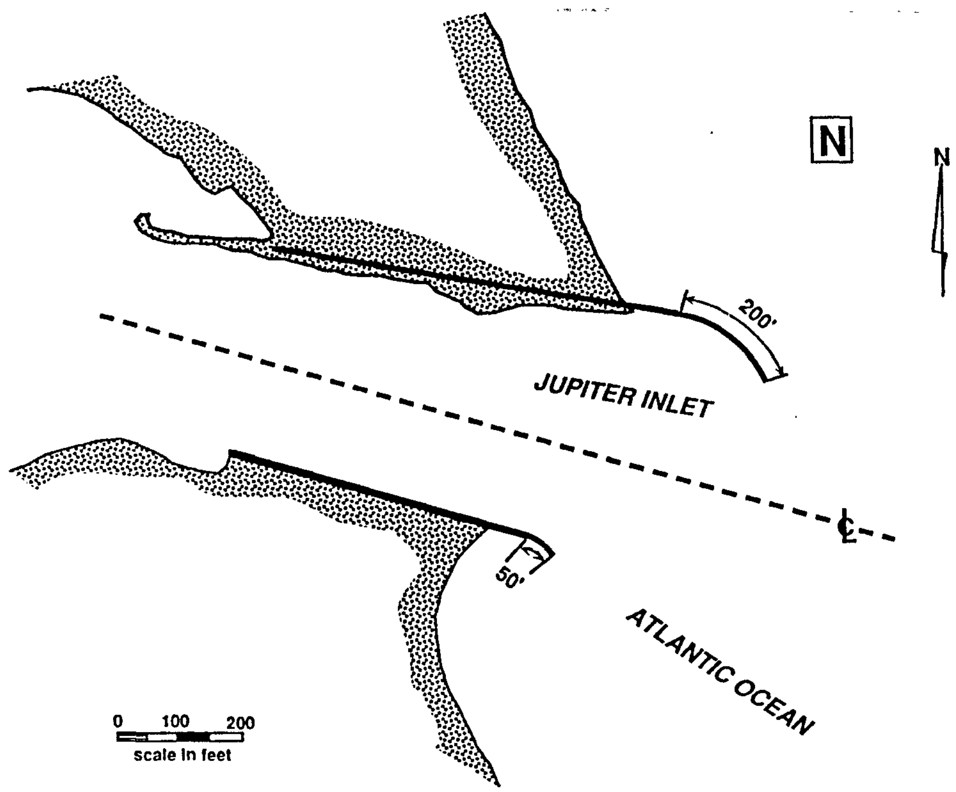


Fig. D.19. Jetty modification N.

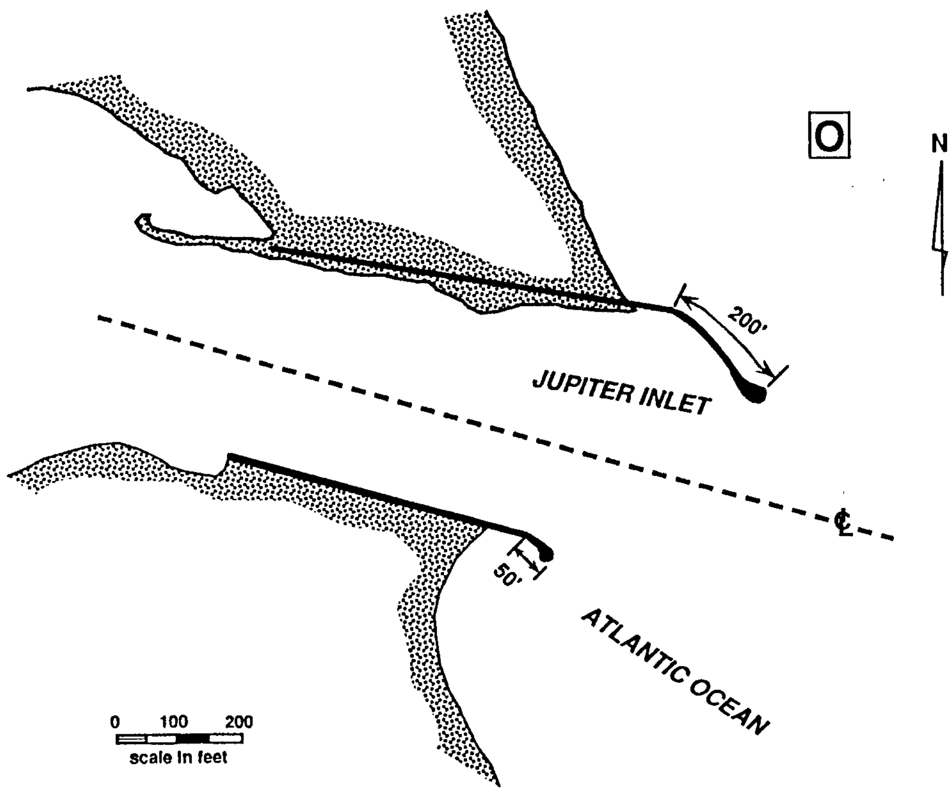


Fig. D.20. Jetty modification O.

Table D2: Jetty modifications.

Modification	North Jetty Extension (ft)	South Jetty Extension (ft)
A	50 straight[a]	0
B	100 straight	0
C	50 diagonal[b]	0
D	100 diagonal	0
E	100 tear drop[c]	0
F	0	200 curved[d]
G	0	100 straight
H	0	100 straight + 50 south[e]
I	0	50 south
J	0	50 straight
K	0	50 straight + 50 south
L	0	50 tear drop
M	400 curved	100 curved
N	200 curved	50 curved
O	200 tear drop	50 tear drop

[a]i.e. along the direction (offshore) of the existing jetty.
[b,c,d,e]See corresponding figures.

waves flow over the jetties, can occur during storm conditions and wash the nearby beach sand into the channel. As one observer put it, "the sand just flows over the (north) jetty" (Reynolds Miller, personal communication, 1991).

A practical approach to decrease this sediment influx during storm events is to increase the height of one or both of the jetties. The north jetty concrete cap is made up of four steps, each at different elevations. The two most seaward steps are the areas of concern. A U.S. Geological Survey marker (Y305) on the third step of the jetty has an elevation of 10.905 ft (NGVD - which is mean sea level in 1929). The steps are approximately 2 ft high so the elevation of the eastern most (seaward) step is 7 ft, and the next step (step 2) is 9 ft above NGVD. The seaward step (step 1) is approximately 100 ft long and step 2 is approximately 200 ft long. The south jetty cap is 525 ft long with the eastern most 100 ft being approximately 5 ft high, the next step being approximately 6.5 ft high.

Four tests were run with different jetty elevations. They are:

1) +2 ft on step 1 of north jetty, NE waves

2) +2 ft on steps 1 and 2 of north jetty, NE waves

3) south jetty raised to + 8 ft, NE waves

4) south jetty raised to +8 ft, SE waves.

Figure D.21 shows the different configurations, including the existing one for the north jetty (a). The test conditions were that of storm condition, discussed in Mehta et al. (1991b), namely, +8 ft storm surge (100 year storm), 8 ft, 10 second waves and increased flood velocity. The reason that the north jetty was raised by 2 ft in each test (b and c in Fig. D.21) was so that the concrete cap steps of 2 ft could just be extended. A 3 ft elevation was used on the first step of the south jetty and a 1.5 ft elevation on the remaining part to bring the overall total jetty height up to that of a predicted 100 year storm surge elevation, 8 ft.

D4.3 Offshore Dredging

Dredging of the offshore bottom shoal is discussed fully in Mehta et al. (1991b). The selected dredged region in the physical model is shown in Fig. D.22.

D5. Test Results

D5.1 Jetty Modifications

The jetties were modified to better protect the channel from wave action and/or reduce wave action on the south beach. These are the reasons for modifications to the north jetty (to protect the channel), and to the south jetty (to protect the south beach), and combinations of both.

The application of the test criteria given in section D3 is illustrated here. As stated previously, the equations selected for analysis relate the data to factors such as navigational improvement and sediment transport potential. The result of employing these equations is shown in Table D3, but it is difficult to interpret each number without

Table D3: Raw data from the physical model, Test #41: NE waves, MSL, ebb flow, "normal" conditions.

Position	Wave Height Model (cm)	Wave Height Prototype (ft)	Current Magnitude (ft/s)	Current Direction (deg. North)	Longshore Velocity (ft/s)	Q_1 (ft^3/s)	Q_2 (ft^3/s)
S2	1.0	1.7	2.8	81	2.1	33	542
J1	0.7	1.1	2.1	90	1.8	14	291
J2	0.9	1.6	2.9	110	2.8	29	687
C1	0.6	1.0	3.7	106	3.6	11	536
C2	1.5	2.5	3.6	115	3.5	71	1324
J3	1.1	1.9	2.4	94	2.2	41	615
J4	1.0	1.6	0.6	100	0.5	29	127
J5	0.9	1.4	1.0	76	0.7	22	148

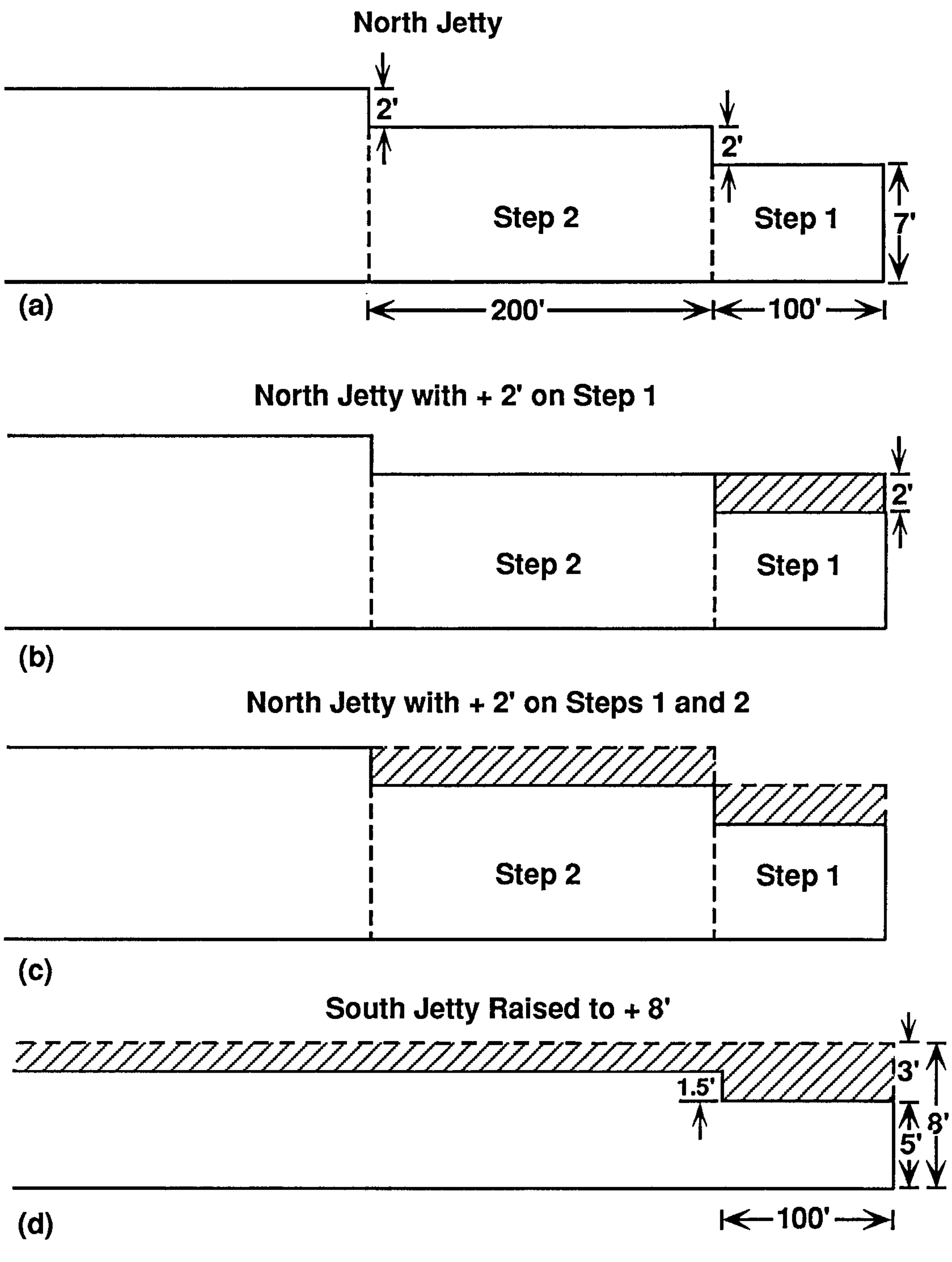


Fig. D.21. North jetty and south jetty elevation views and height modifications.

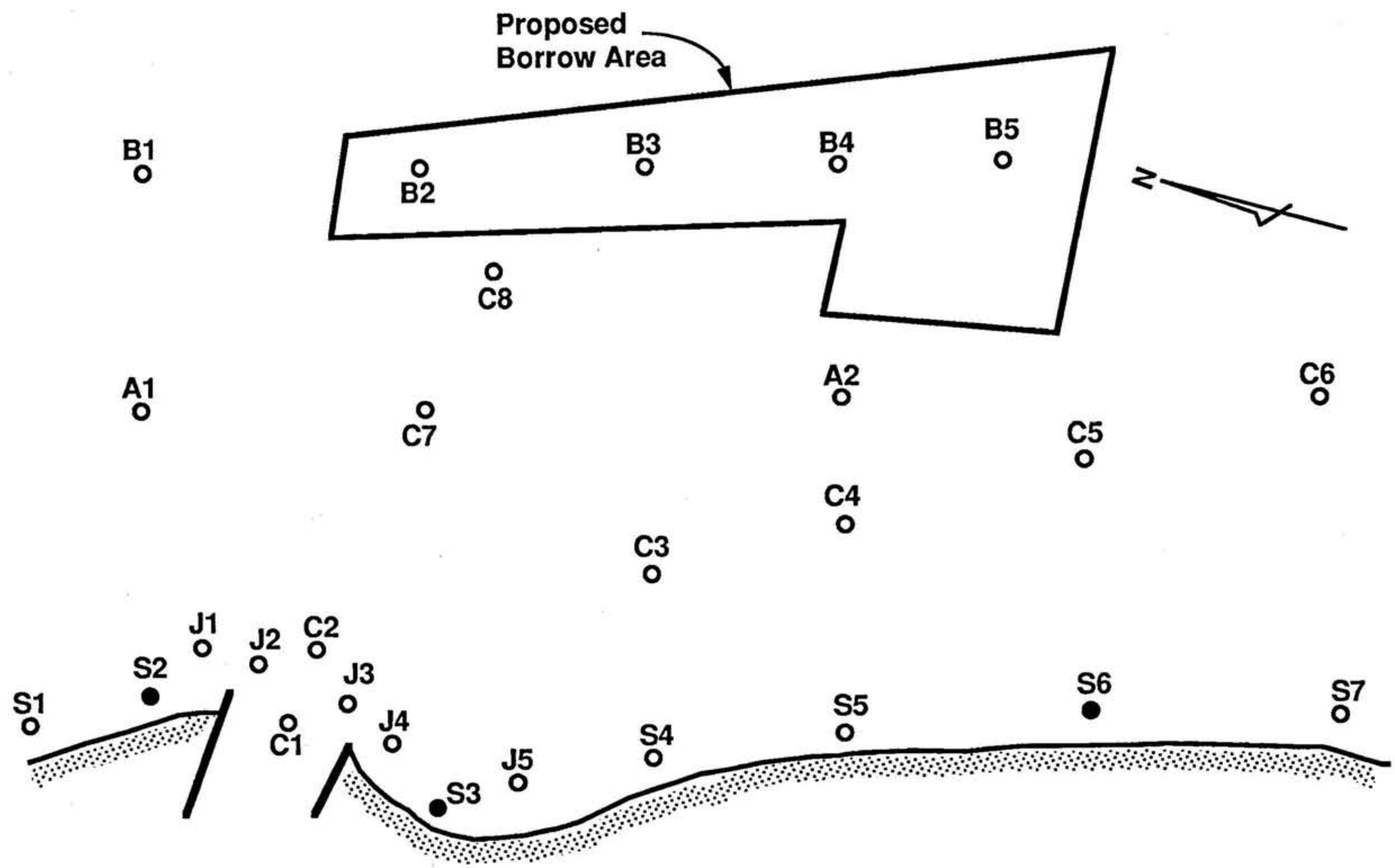


Fig. D.22. Physical model data collection points and dredged ebb shoal area.

carrying out further analysis. By dividing each modified test by the "normal" test, for the corresponding tide and wave conditions, a percentage relative to the normal condition was calculated. This would show, for example, if wave heights were reduced at certain locations or not. If the wave height ratio was greater than 100% then the wave height of the modified test were obviously higher than the normal conditions. As noted previously, a scale was developed that would allow these percentages to be converted to a positive or negative number to represent a desired or undesired effect, respectively. In this case the numbers assigned show whether an effect is strongly positive or negative by using a + or - 2, while + or - 1 represents a slightly positive or negative effect. A zero is assigned if the effect is minimal. Two scales were developed, one for wave height ratios and one for the sediment transport rates and are shown in Table D4. The scales were employed to generate a table that reveals the positive or negative effects of wave height (for navigation safety) or sediment transport (erosion potential) ratios at four locations for flood and ebb tides, and the other effects noted in section D3. An example of the table is shown in Table D5. Since four data points (locations) were used, their average values were calculated and stated at the bottom of each column. This allows the assigned numbers to be seen as overall effects of the modification, instead of the effects at certain locations.

The next step in the analysis is to weigh each of the columns shown in Table D3 according to their relative importance. Two of the five columns are for sediment transport values, two are for sediment supply factors, and one is for navigation. In order to weigh navigation safety evenly with the other factors its weighting must be doubled. Since the northeast and southeast wave directions were tested separately they had to be combined. Since the predominant wave direction at Jupiter is from the northeast, approximately 8 months of the year, and southeast wave action is the remaining 4 months, factors of 8/12 and 4/12, respectively, were multiplied to the wave height ratios. The same "monthly" ratios were multiplied to the sediment supply influx factor. When wave action from the southeast is dominant, erosion potential need not be considered. This is because southeast dominant waves usually occur in the summer, a time when beaches are naturally accreting due to moderate to light wave action and south to north longshore sediment transport. For this reason the Q_1 and Q_2 factors were omitted for the southeast waves. The result is a formula which combines the assigned positive and negative values for the southeast and northeast wave directions:

$$\begin{aligned} &\left(\frac{H_{mod}}{H_{exist}}\right)_{NE}(2)\left(\frac{8}{12}\right)+\left(\frac{Q_{1mod}}{Q_{1exist}}\right)+\left(\frac{Q_{2mod}}{Q_{2exist}}\right)+\text{(S.S. jetty length)} \\ &+\text{(S.S. influx)}\left(\frac{8}{12}\right)+\left(\frac{H_{mod}}{H_{exist}}\right)_{SE}(2)\left(\frac{4}{12}\right)+\text{(S.S. jetty length)} \\ &+\text{(S.S. influx)}\left(\frac{4}{12}\right)=V \end{aligned} \tag{D.5}$$

where V is the resulting value assigned to the jetty modification, and S.S. denotes sediment supply factor with respect to jetty length or influx into the inlet mouth. This equation was used for each modification for both the ebb and flood tides; the results are shown in Table D6 along with the total value, V. The letters represent the jetty

Table D4: Scales for navigational safety and erosion potential ratio calculations.

Wave Height Ratios:

Value Assigned	Ratio of Wave Heights (in %)
-2	> 150
-1	125 - 149
0	75 - 124
+1	50 - 74
+2	< 49

Q_1 and Q_2 Transport Ratios:

Value Assigned	Ratio of Q_1's or Q_2's (in %)
-2	> 200
-1	125 - 199
0	75 - 124
+1	25 - 74
+2	< 25

Table D5: Example of data for NE wave testing of Modification D.

Tidal Condition	Position	Nav. Factor (H_{mod}/H_{exist})	Erosion Potential (Q_{1mod}/Q_{1exist})	Erosion Potential (Q_{2mod}/Q_{2exist})	Sand Supply (Jetty	Sand Supply (Influx) Length)
Flood	C1	0	+1	0		
Tide	J3	+2	+2	+1	-2	+2
	J4	+2	+2	+2		
	J5	0	0	0		
	(Average)	(1.0)	(1.25)	(0.75)		
Ebb	C1	+1	+1	+2		
Tide	J3	-2	-2	0	-2	a
	J4	0	-1	+2		
	J5	0	+1	+1		
	(Average)	(-0.25)	(-0.25)	(1.25)		

[a] Sand supply influx not a factor during ebb tide

Table D6: Results of jetty modification tests.

Modification	Flood	Ebb	Total
B	2.6	-3.8	-1.2
C	2.5	-2.1	0.4
E	2.8	-2.7	0.1
G	2.2	-3.8	-1.6
I	3.0	-2.3	0.7
J	2.7	-2.5	0.2
K	3.0	-1.3	1.7
L	2.4	-1.9	0.5
M	0.9	0.3	1.2
N	1.1	-3.1	-2.0
O	0.7	-4.2	-3.5

modifications listed in Table D2. In Table D6 it is noted that several letters of the alphabet are missing (i.e. A, D, F, and H; see, however, Section D6.1). This is because when these tests were initially run, with waves from the northeast, their analysis showed predominantly negative effects; therefore further testing was not merited.

The sand supply factor due to jetty length has been included for both the northeast and southeast directions in the above calculations. It can be argued that this factor may be negligible during the summer months when wave action is from the southeast. Because southeast dominant waves occur for a shorter period, 4 months, with considerably lighter wave action, and because the north beach does not initially have an eroded profile, erosion of the north beach can be considered to be minimal. As a test of sensitivity of weighting to the final results, the data in Table D6 were recalculated so that the sand supply factor related to jetty length was only used for the northeast tests, and put in Table D7.

D.5.2 Example Calculation

In order to understand how the values in Tables D6 and D7 were calculated, it would be instructive to go through the steps and analysis it took to determine them. The values for modification "L", a 50 ft tear drop on the south jetty will be calculated. The first step is to list all the test experiments with the L configuration, and then the corresponding "normal" tests.

1) Test 58 NE,MSL,ebb tide, L
2) Test 60 NE,MSL,flood tide, L
3) Test 87 SE,MSL,ebb tide, L
4) Test 98 SE,MSL,flood tide, L
5) Test 41 NE,MSL,ebb tide, normal

Table D7: Results of jetty modification tests without SE sand supply factor related to jetty length.

Modification	Flood	Ebb	Total
B	3.7	-2.8	0.9
C	2.5	-2.1	0.4
E	3.8	-1.7	2.1
G	3.2	-2.8	0.3
I	3.0	-2.3	0.7
J	2.7	-2.5	0.2
K	3.0	-1.3	1.7
L	2.4	-1.9	0.5
M	2.9	2.3	5.2
N	3.2	-1.2	2.0
O	2.7	-2.2	0.5

6) Test 45 NE,MSL,flood tide, normal

7) Test 80 SE,MSL,ebb tide, normal

8) Test 92 SE,MSL,flood tide, normal

These data were obtained from the data recorded in the physical model tests and using Eqs. (D.2) and (D.4), so that tables such as Table D3 were generated for each test. As an example, the data for position J3 (see Fig. D.22) in test #87 will be carried out. The wave height found in the model was 1.2 cm. To convert this to prototype feet:

$$1.2cm \times \frac{50}{1} \times \frac{1ft}{30.48cm} = 2.1ft$$

The sediment transport factors are:

$$Q_1 = A\ H_b^2 \sqrt{g\ d_b} = (1)(2.1\ ft)^2 \sqrt{(32.2\ ft/s^2)\ (4ft)} = 48\ \frac{ft^3}{\sec}$$

where 4 is used as the approximate breaking depth of 4 ft waves, and A, the sediment characteristic constants, are set to 1, and

$$Q_2 = B\ H_b\ x_b\ [v] = (1)(2.1\ ft)(150\ ft)(1.39\ \frac{ft}{\sec}) = 432\ \frac{ft^3}{\sec}$$

Now we divide the Q_1 and Q_2 values found in this test (#87) by the normal conditions found in test #80, which has the corresponding conditions of MSL, southeast waves, and ebb tide. Therefore at J3:

$$\frac{H_{mod}}{H_{exist}} = 2.1 \frac{ft}{2}.6\ ft \times 100 = 81\%$$

$$\frac{Q_{1mod}}{Q_{1exist}} = \frac{48 \frac{ft^3}{sec}}{75 \frac{ft^3}{sec}} \times 100 = 64\%$$

$$\frac{Q_{2mod}}{Q_{2exist}} = \frac{432 \frac{ft^3}{sec}}{652 \frac{ft^3}{sec}} \times 100 = 66\%$$

$$\frac{Q_{2mod}}{Q_{2exist}} = \frac{432 \frac{ft^3}{sec}}{652 \frac{ft^3}{sec}} \times 100 = 66\%$$

Thus by using the scales given in Table D4 the corresponding values for the ratios at J3 are: $H_{mod}/H_{exist} = 0$, $Q_{1mod}/Q_{1exist} = +1$, $Q_{2mod}/Q_{2exist} = +1$. The sand supply factor related to jetty length is found by using Fig. D.2. Since the modified jetty length is 50 ft, the corresponding factor is zero. On an ebb tide no sediment will pass into the inlet, so a value of zero is assigned to the sand supply factor related to influx.

This same procedure is used for each of the data collection points on both ebb and flood tides. The assigned numerical values, such as those generated above, for H_{mod}/H_{exist}, Q_{1mod}/Q_{1exist}, and Q_{2mod}/Q_{2exist} are averaged together. The sand supply factors in the last two columns remain constant for each data point (J2, J3 etc.) so that no averaging is necessary.

The complete set of calculated values is presented in Table D5. The weighing factors have already been discussed, and will now be used to combine northeast and southeast wave directions. The flood tide values for modification L will be considered first. The formula is given as Eq. (D.5). Using this equation for modification L gives:

$$(0.5)(2)(0.667) + (0.5) + (0.25) + (0) + (2)(0.667)$$
$$+ (-0.5)(2)(0.333) + (0) + (0)(0.333) = 2.4$$

The same method is employed for the ebb tide data and gives a value of -1.9. Combining these two gives 0.5 (2.4 - 1.9 = 0.5). This number shows an overall positive impact of jetty modification "L".

D5.3 Offshore Dredging

The offshore dredge area and data station locations are shown in Fig. D.22. To be consistent with the numerical model results shown in Mehta et al. (1991b), the wave ratios were calculated with respect to an offshore reference wave height and are presented in Table D8. Note that for northeast waves station B1 was used for the

Table D8: Comparison of wave heights (from NE and SE at MSL) with dredged and normal conditions.

	Northeast Waves				Southeast Waves			
	Normal		Dredge		Normal		Dredge	
Position	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb
A1	93	75	97	125	42	44	42	55
A2	60	48	34	38	75	51	30	62
B1	100	100	100	100	14	25	33	10
B2	86	91	116	107	57	58	94	42
B3	38	32	47	69	95	84	132	114
B4	14	16	26	14	81	84	75	66
B5	12	11	22	23	86	76	77	72
C1	19	27	31	57	16	40	14	14
C2	52	70	40	106	42	45	24	50
C3	38	43	101	35	61	59	23	40
C4	43	36	57	56	64	49	75	35
C5	24	9	31	16	93	77	60	65
C6	51	14	15	21	100	100	100	100
C7	31	84	105	94	42	27	37	40
C8	93	70	94	99	83	84	97	53
S1	40	23	23	18	9	8	9	8
S2	43	25	33	35	61	23	39	27
S3	40	34	58	53	27	14	18	20
S4	19	30	34	33	29	27	24	23
S5	31	25	49	52	27	16	27	32
S6	26	25	33	41	26	24	31	24
S7	10	23	21	12	41	42	38	33

Table D9: Dredged ebb shoal condition wave height ratios at several points from numerical and physical models.

Model	Wave Height Ratios, H_{mod}/H_{exist}					
	A2	C4	S2	S3	S4	S6
Computer	1.7	1.4	0.8	0.4	1.1	1.3
Physical	0.4	1.3	0.7	0.8	0.9	1.3

reference wave height, and for southeast waves station C6 was used. The normal and dredged condition wave heights are shown as percentages of the reference wave height for both northeast and southeast waves. The results of the offshore dredge physical model study are compared to the results of the numerical model study given in Mehta et al. (1991b). These results are shown in Table D9. Both tests were preformed with 4 ft 8 second waves, but the water level in the physical model was at MSL while the numerical model used +8 ft storm surge. The flood tidal velocities were also slightly different; 3.6 fps for the numerical model and 5.4 fps for the physical model. Even with these differences in test conditions, because the wave heights were similar, the results compare favorably, with the exception of station A2, and S3. These results are shown as ratios of H_{mod}/H_{exist} for each station shown.

D6. Evaluation of Test Results

The presented test results will now be discussed. The first section will discuss the modifications to jetty lengths, the next raised jetties, and lastly the dredged offshore bottom.

D6.1 Jetty Length Modifications

The initial jetty modification tests are listed in Table D2, which includes 15 tests with modifications to the jetties. Table D6 shows the results of the tests and gives a "total" for each test. This total shows the overall performance of the jetty, based on the evaluation process described. All of the tests were initially run for northeast waves. For reason cited, the results of these tests were analyzed and 4 tests were omitted from further testing. The remaining 11 test modifications were carried out for southeast wave directions. Table D6 can be further narrowed by eliminating modifications with negative values, which are test modifications B, G, N, and, O. These tests were negative due to the ebb tide results. The reason for ebb tide conditions giving such strongly negative numbers was two-fold. First, the elimination of the sediment supply factor related to influx lowered the total result by removing this, primarily positive, number from analysis. Second, the wave conditions during ebb tide can be increased by increasing the flow velocity out of the inlet, which can happen if a jetty modification constricts the inlet width. So if a jetty modification increases the exit velocity of the water, or channels it in another direction, the effect can be wave heights higher than normal conditions. The remaining positive modifications range from 0.1 to 1.7, with five of the seven being less than 1.0. These five modifications should not be ruled out as possible solutions because combinations or derivations of these options could prove very beneficial, but only the two modifications which are greater than 1.0, K and M, will be further discussed for illustration.

Modification K is a 50 ft straight with 50 south extension on the south jetty (Fig. D.16). This modification greatly sheltered the south beach when wave action was from the northeast, and also cut off sediment influx into the channel, as measured by tests using floats. This modification also had a high rating because it was a short extension, and would not greatly alter the littoral drift pattern. Because it did not seem to change the flow conditions very much in the ebb tide situation, the ebb tide value was not very low when compared to other modifications. Again, the best advantage of modification K was its relatively short length.

The next highest modification, M, is a 400 ft curved extension on the north jetty and 100 ft curved extension on the south jetty (Fig. D.18). This modification greatly sheltered the inlet channel and the south beach, and therefore the analysis showed it to be a very favorable result related to navigational safety. However, the effect of modifying the jetties by such great distances must be approached carefully. The time scale used for the sand supply factor was 30 years; perhaps a longer time scale would show more detrimental long range effects. It is possible that the extended jetties may only increase the erosion problems at Jupiter Inlet by offsetting the coastline even more than predicted, and as well alter the position of the ebb shoal by shifting it southwards. Therefore, although this modification came up with very positive results for reasons of navigational safety, careful thought should be given to the long term affects.

Table D7 shows the results for jetty modifications with the jetty length factor only being included once, for northeast waves, as noted. The results shown in this table reveal the sensitivity of the weighing factors in analyzing the present data. Notice that there are now no negative numbers, showing that the jetty length factor can greatly influence the outcome of the results. In this table modification M is significantly the highest number, with E and N being the next best results. This table is a useful way to visualize the effects that the jetty length factor played in calculating the results. Note too that these modifications could be considered if somehow sediment supply to the south beach were not a problem, i.e. if a pumping station were installed or if the dredged material was continually placed on the south beach.

Figure D.23 shows Baker's Haulover Inlet in Dade County, in 1966, while Fig. D.24 shows the same inlet in 1981, after a south jetty extension was installed. For comparative purposes note that the inlet width is 800 ft (244 m). Arrow in Fig. D.23 shows a seawall, which is also the shoreline at that location. The corresponding arrow in Fig. D.24 illustrates the degree of sand accumulation south of the modified south jetty. Note the new shoreline position (dashed line).

The south jetty at Baker's Haulover Inlet is now substantially more "intrusive" than the north jetty, yet accumulation on the south side has been achieved successfully, inspite of the fact that the dominant direction of littoral drift is due south. Figure 4.8 shows that at Jupiter Inlet the north jetty would continue to be more "intrusive" than the south jetty, even after a 175 ft (53 m) extension. At this inlet, the littoral drift is substantially higher than that at Baker's Haulover, so that the situation with respect to the magnitude of the littoral drift is not comparable. Nonetheless at both inlets the net drift is southward, and at Jupiter the north jetty should continue to act as a "shadow", as far as littoral sand transport is concerned. Modification H in Table D2 is qualitatively amenable to this experience, and in our opinion it represents not only a viable but a desirable alternative as far as sand retention on the south beach is concerned. The rationale for a 175 ft (53 m) south jetty extension, as proposed under action P2, is thus based on: 1) experience at Baker's Haulover Inlet, 2) the fact that the north jetty would continue to determine the sand transport regime south of the south jetty, and 3) any shorter extension would probably not yield adequate cost benefits with respect to sand retention.

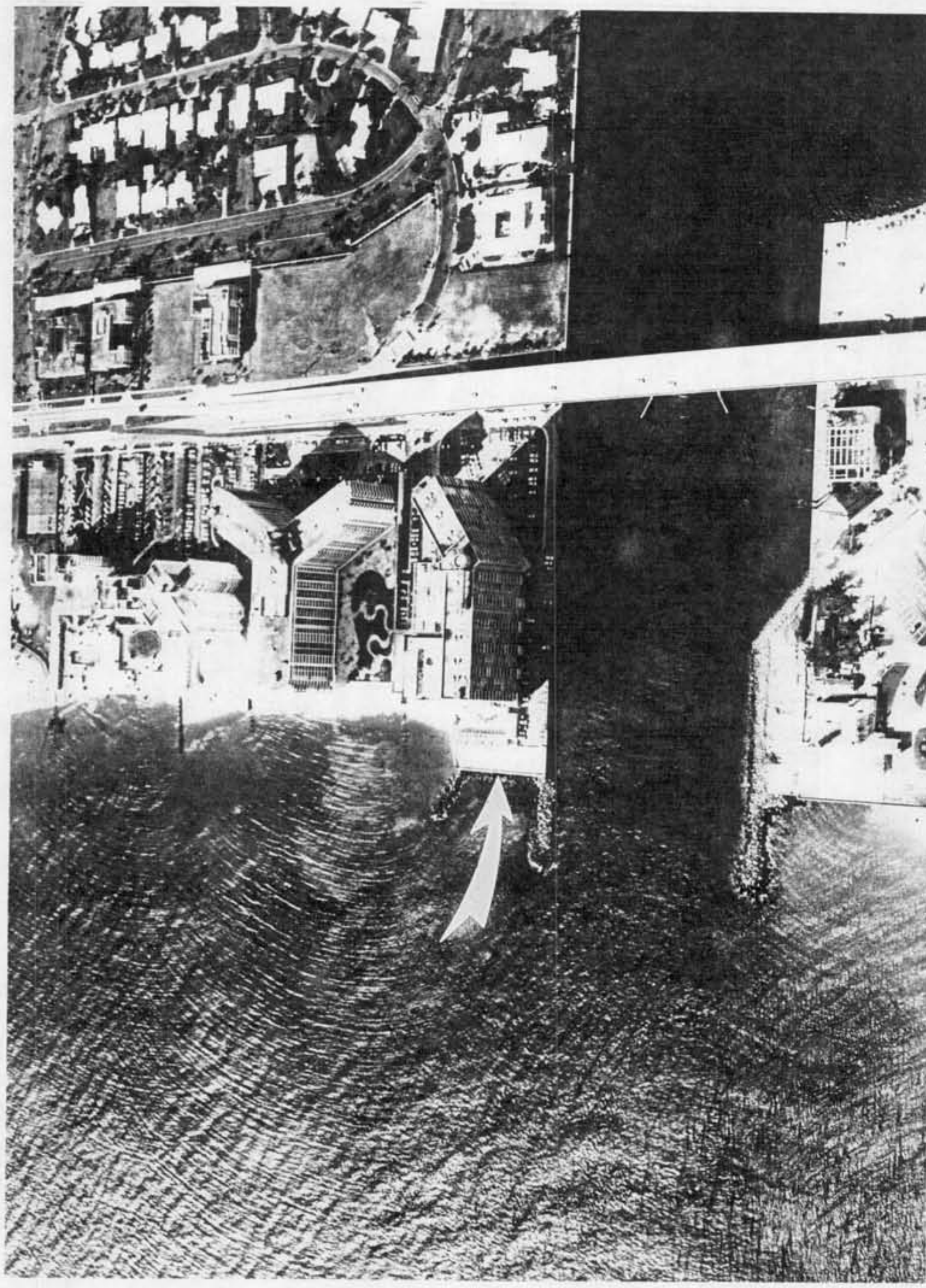


Fig. D.23. Baker's Haulover Inlet in 1966.

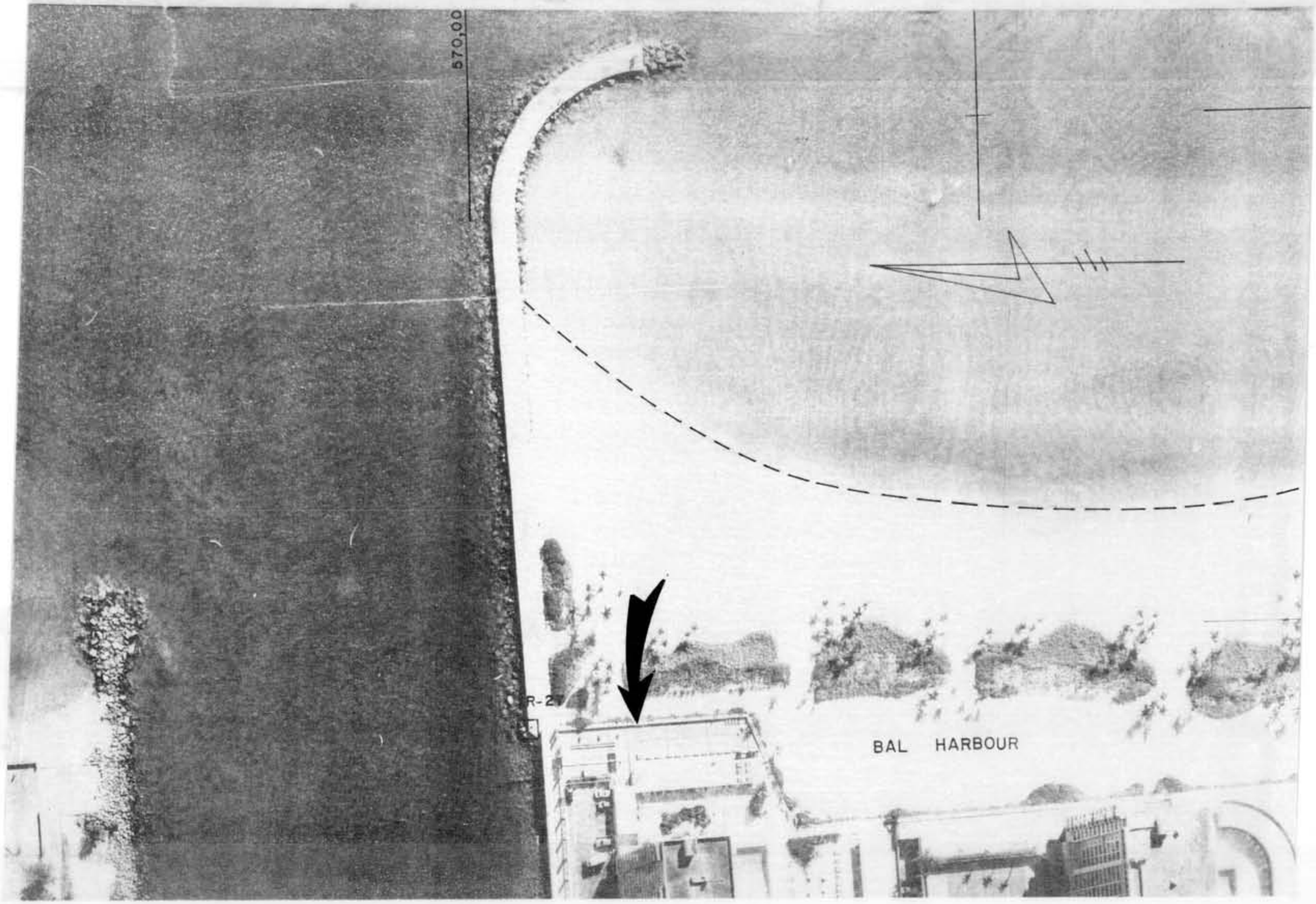


Fig. D.24. Baker's Haulover Inlet in 1981.

D6.2 Elevated Jetties

The desired result of raising the jetties is so that the sediment influx into the inlet would be reduced during storm events. A qualitative description is given below as an evaluation of the tests results.

When a normal (i.e. no modifications to the existing system) storm condition was tested, the flood tidal velocity increased, and seemingly everything (bits of styrofoam, wooden balls, dye, etc.) was transported into the inlet if placed on the north beach. The severe wave action caused a strong littoral drift which "pushed" material down the coast. When the jetties were, for the most part, submerged under the +8 ft storm surge, they could not block the entrance of material into the inlet. Although most of the transport was due to wave action, the increased flood velocity had a strong effect on pulling material into the inlet as well. It was noticed during the experiments that when wave action was from the northeast, most of the material set on the south beach did not enter the inlet, but rather got pushed down the coast by the wave action, and vice versa.

The first test was a +2 ft elevation on the first step of the north jetty with northeast waves (Fig. D.21b). Even with the added height the first step was still only 9 ft above MSL, so with a +8 ft storm surge and 8 ft waves, the effect was negligible. This +2 ft rise might be beneficial for other storm surge elevations, such as a 50 year (+7 ft) storm or less.

The second test raised the first and second steps of the north jetty by 2 ft (Fig. D.21c). The second step was then 11 ft above MSL. This test certainly showed the beneficial effects of raising the jetty to an elevation substantially above the 100 year storm elevation. Even though large waves overtopped the second step, material did not "flow" over it. Wooden balls that were placed on the north beach rapidly moved down the coast to the inlet, but did not pass over the second step of the jetty. In fact most of the floats, and even dye, would flow around the second step to the (submerged) first step, and then into the inlet.

The third test raised the south jetty to an overall height of +8 ft (NGVD) (Fig. D.21d). When the wave action was from the northeast, the modification had almost no effect on influx into the inlet, because as previously noted, material placed on the south beach did not enter the inlet even with normal storm surge conditions. This test did show that wave heights on the immediate south beach were reduced, since the waves broke on the jetty. From this test it was seen that testing modifications to the north jetty with southeast waves was not necessary, since virtually no effect would be seen.

The last test was the raised south jetty with waves from the southeast. The longshore current that was generated by the waves was so strong that it seemed to wash any material placed on the south beach into the inlet. The angle of the waves, combined with the topography of the area just south of the jetties, seemed to enhance the effect of overwash into the inlet. Although it would take the wooden balls and dye a few seconds longer to pass into the inlet than they did without modifications, the effects of raising the south jetty only 3 ft were minimal.

The second test run, with 2 ft added on both the first and second steps, showed that raising the north jetty height would reduce sediment from flowing over it, but it also revealed the possibility that sediment may flow around the jetty and still enter the inlet mouth. Since all the tests done with raised jetty heights showed that the materials continued to enter the inlet, flow of sediment around the jetty and into the inlet during storm events should be taken into account for any jetty modification. The effects of raising the jetty height and that of any length modification could be combined to, perhaps, reduce the sediment influx over and around the jetties.

D6.3 Offshore Dredged Bottom

Mehta et al. (1991b) discuss offshore dredging in detail, so the results shown here are meant merely to support all observations already made. The results in Table D8 show that, as stated in Mehta et al. (1991b), "wave heights will decrease or increase depending upon wave refocussing due to bottom modification."

In Table D9 most of the positions show almost the same wave height ratio between the numerical and the physical models. The strong similarities between these two models gives confidence in the results of both. Position A2 does not seem to match very well, probably because this location was at the shallowest part of the ebb shoal in the physical model, and the waves broke before they reached the wave height gage.

APPENDIX E: TIDES, CURRENTS AND SEDIMENTATION - EFFECTS OF POTENTIAL MODIFICATIONS ON FLOW AND SAND TRANSPORT IN THE LOXAHATCHEE RIVER

E1. Introduction

This appendix presents the results from the sediment transport modeling (using a two-dimensional depth-averaged finite element model) of the Loxahatchee River estuary. The sediment transport model used in this study, described in Mehta et al. (1990b), predicts the two-dimensional (depth-averaged) velocity and salinity fields, and the change in bottom elevation due to scour or deposition resulting from sand transport at the nodes comprising the finite element grid.

The objectives of the modeling effort described herein were to analyze the effects of eight potential modifications to the Jupiter Inlet-Loxahatchee River estuarine system on the sedimentary and hydrodynamic regimes. The purposes of the potential modifications were to (a) reduce the flux of sediment into Jupiter Inlet and hence into the Loxahatchee River and Intracoastal Waterway (Modifications 1 - 5), and (b) reduce the flux of sediment west of the Florida East Coast Railroad bridge (Modifications 6 - 8). The eight modifications analyzed are:

(1) Extension of both the north and south jetties by 15.2 m (50 ft).

(2) Extension of the north jetty by 122 m (400 ft) and the south jetty by 30 m (100 ft).

(3) Increase the dredged depth of the JID sand trap, located in the inlet channel, to 5.8 m (19 ft).

(4) Enlargement of the JID sand trap to the dimensions shown in Fig. 6.27 in Mehta et al. (1991b). Two dredged depths were considered: 5.8 m (19 ft) and 4.1 m (13.5 ft).

(5) Increase the length (but not the width) of the JID sand trap to the dimensions shown in Fig. 6.27 in Mehta et al. (1991b) and increase the dredged depth to 5.8 m (19 ft).

(6) Dredging of a new sand trap to -3.7 m (-12 ft) immediately west of the Florida East Coast Railroad bridge (see figure on page 39 in Mehta et al. (1991c)). The areal dimensions of the trap are 175 m (575 ft) wide (centered laterally across the Loxahatchee River) and 46 m (150 ft) long (along the longitudinal axis of the river).

(7) Dredging of a 2.4 m (8 ft) deep, 22.9 m (75 ft) wide navigation channel starting at the center of the railroad bridge and running 390 m (1280 ft) westward along the longitudinal axis of the river (see figure on page 39 in Mehta et al. (1991c)). Two cases were considered: one with the navigation channel and new sand trap described in Modification 6 above, and one with only the navigation channel.

(8) Dredging of a new sand trap to -3.7 m (-12 ft) immediately east of the Florida East Coast Railroad bridge (Fig. E.1). The areal dimensions of the trap are 152 m (500 ft) wide (centered laterally across the Loxahatchee River) and 61 m (200 ft) long (along the longitudinal axis of the river). Two different median sediment sizes (0.20 mm and 0.50 mm) were used with this modification, whereas only a 0.50 mm sand size was used with the previous seven modifications.

These modifications were made to the original finite element grid of the Loxahatchee River estuary shown in Fig. E.2, and then the sediment transport model was run for a period of one month for each of the cases

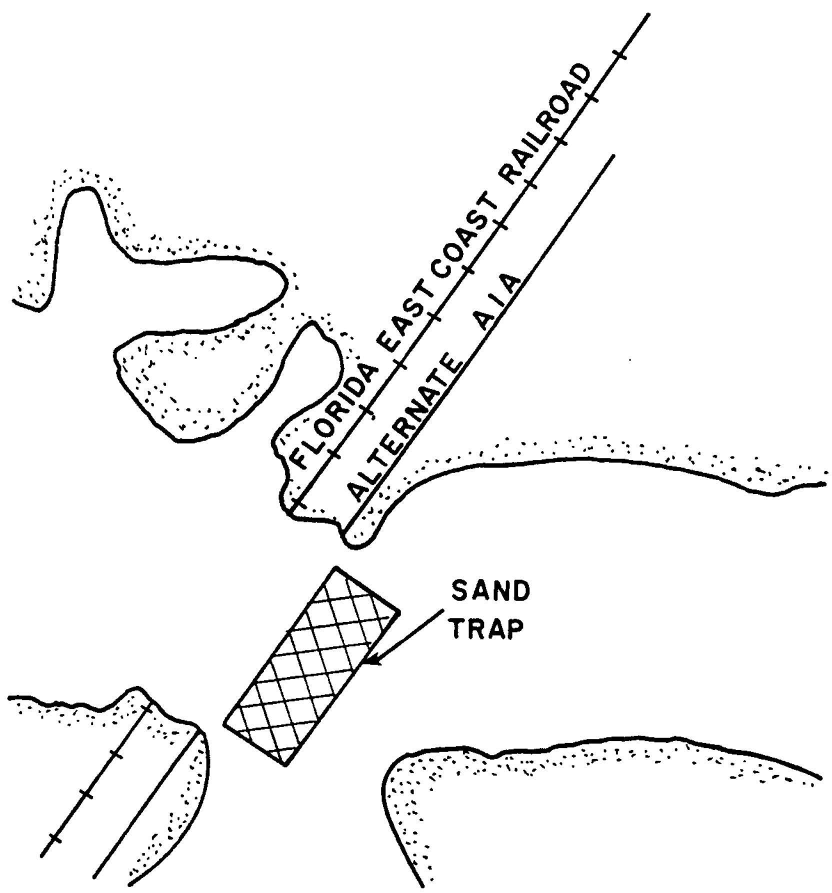


Fig. E.1. Proposed sand trap east of Florida East Coast Railroad bridge.

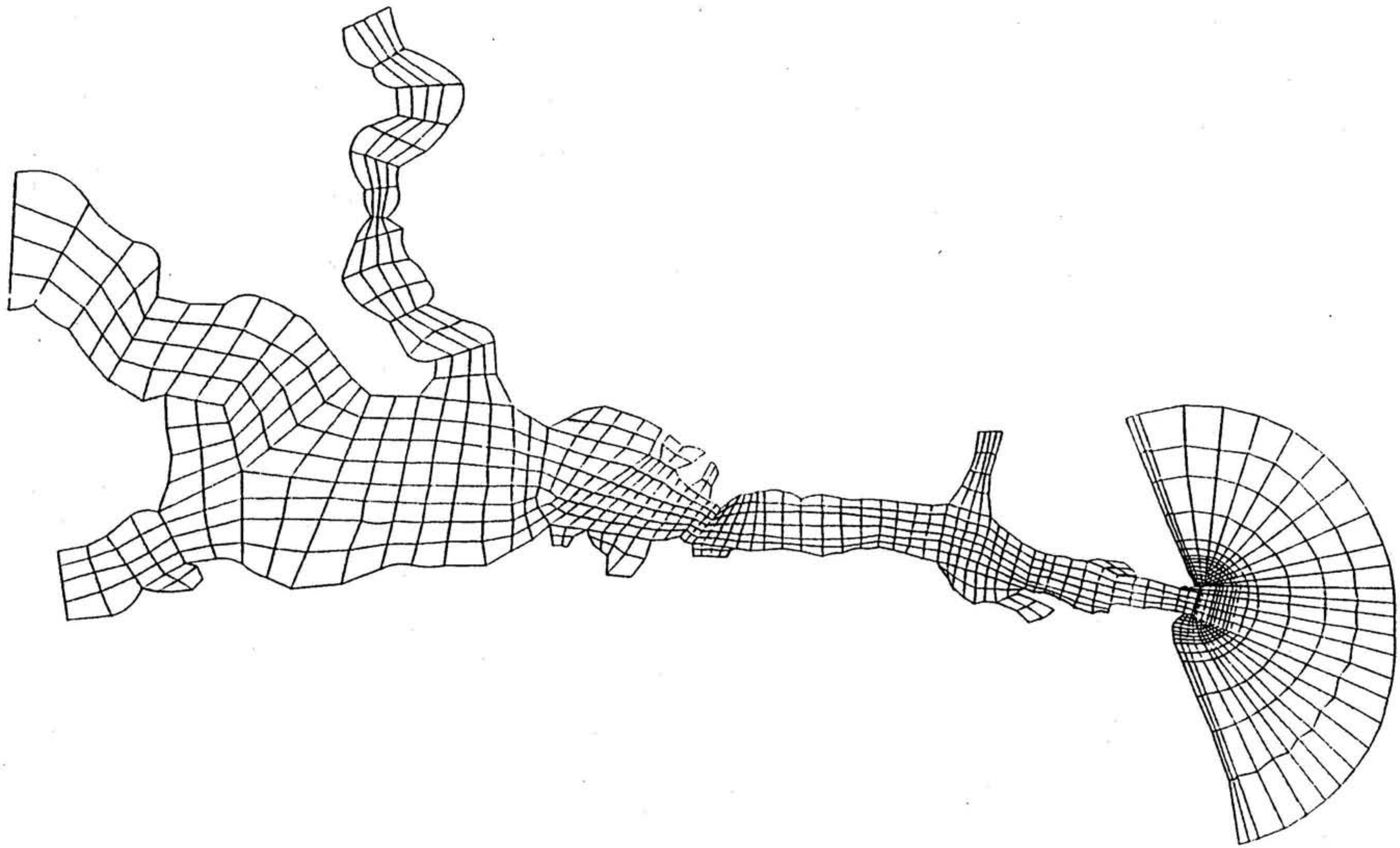


Fig. E.2. Original finite element grid for the Loxahatchee River estuary.

described above. The results from each model run were compared with the sediment transport modeling results reported in Mehta et al. (1991b). A description of how the model was applied to each of these cases, followed by a discussion of the results obtained from the modeling effort, is given later in this chapter. A review of a study performed by Environmental Consulting & Technology, Inc. (ECT) on the longitudinal salinity distribution in the Loxahatchee River is given next.

E2. Salinity Distribution

One of the management issues to be included in the Loxahatchee River estuary comprehensive management plan is improvement of the navigation channel "to meet the recreation demand of the area and to improve boating safety" (ECT, 1991). Using the results of a study by Applied Technology and Management, Inc. (ATM) to determine "the optimal locations and configuration of the proposed channel modification of main channels as well as access channels" (ECT, 1991), the computer model RECEIV-II was used to estimate the changes in salinity intrusion caused by the recommended channel improvements. The recommended channel improvements, which would be implemented by dredging, proposed by ATM are given in the Task 6.1, Access Channel Assessment, and Task 6.2, Main Channel Assessment, reports, and are shown in Fig. 4-2 in ECT (1991).

ECT used four bathymetric conditions for the salinity modeling, each for two flow conditions, average low flow and extreme low flow. The four bathymetric conditions used were (1) existing bathymetry, (2) channel improvements recommended by ATM, (3) dredging of a shallow segment of the Northwest Fork near Tequesta (shown in Fig. 4-3 in ECT (1991)) to -4 ft NGVD in addition to the channel improvements recommended by ATM, and (4) dredging of a segment in the lower reach of the Northwest Fork to a depth of -6 ft NGVD and filling a deeper segment to -6 ft NGVD (see Fig. 4-4 in ECT (1991)) in addition to the channel improvements recommended by ATM (ECT, 1991). The results from the salinity modeling using the RECEIV-II model showed that the maximum salinity increase due to the proposed channel modifications was approximately 0.5 ppt, a conclusion that is in complete agreement with that reached in the present study when considering jetty and sand trap modifications (see Mehta et al., 1991c). ETC concluded that the impact on the salinity intrusion caused by the dredging alternatives contained in the second, third, and fourth bathymetric conditions listed above would be insignificant. Figures 4-5 through 4-7 in ECT (1991) show the predicted longitudinal salinity distributions for both average and extreme low flow conditions for the second, third, and fourth bathymetric conditions.

E3. Model Application

The original finite element grid (see Fig. E.2) was composed of 963 quadrilateral elements and 3193 nodes. The size of the elements was varied such that the highest density of nodes occurred in the areas of expected high spatial velocity gradients (e.g., in the proximity of the jetties). The same water boundaries in the Loxahatchee River indicated in Fig. 6.6 in Mehta et al. (1990) were used in the original grid. The ocean boundary consists of the outer semi-circular arc. These water boundaries were chosen because of their proximity to tide gage stations used during a study in 1976 by the University of Florida (Chiu, 1975) and because of their proximity to NOS secondary tide stations.

Calibration of the hydrodynamic module in the sediment transport model, described in Mehta et al. (1991a), was performed by matching predicted and measured (Chiu, 1975) water surface elevations and velocities at several locations throughout the estuary. Calibration of the sediment transport module, described in Mehta et al. (1991b), was performed by matching predicted sedimentation rates in the JID trap and the U.S. Army Corps of Engineer (USACOE) trap with the available dredging records.

For Modification 1, the original finite element grid was altered to extend both jetties at Jupiter Inlet by approximately 15.2 m (50 ft). The altered portion of the original grid is shown in Fig. E.3. To extend the jetties, four additional elements and 18 additional nodes were used.

For Modification 2, the lengths of the north and south jetties shown in Fig. E.3 were increased to approximately 122 m (400 ft) and 30 m (100 ft), respectively. The modified portion of the original grid is shown in Fig. E.4. The modified grid is composed of 988 quadrilateral elements and 3286 nodes.

For Modification 3, the dredged depth of the existing JID sand trap was increased to 5.8 m (19 ft) in the original gird.

For Modification 4, the enlarged JID sand trap shown in Fig. 6.27 in Mehta et al. (1991b) was scaled onto the original finite element grid. Then the bottom elevations of the nodes inside the enlarged trap were set equal to first -4.1 m (-13.5 ft), and then -5.8 m (-19 ft). The side slopes of the enlarged sand trap were taken to be 1V:3H. This slope was used to calculate the bottom elevations of the nodes immediately surrounding the trap.

For Modification 5, the increased JID trap length used in Modification 4 and the original width were used. The grid used for Modification 3 was modified to account for the increased trap length and 5.8 m (19 ft) dredged depth.

For Modification 6, the new sand trap immediately west of the railroad bridge was scaled onto the original finite element grid. Then the bottom elevations of the nodes inside the new trap were set equal to -3.7 m (-12 ft). The side slopes of the new sand trap were again assumed to be 1V:3H. This slope was used to calculate the bottom elevations of the nodes immediately surrounding the trap. The same procedure was used to modify the original grid and the grid for Modification 6, respectively, for the navigation channel only case and the navigation channel and new sand trap case contained in Modification 7.

For Modification 8, a new sand trap immediately east of the railroad bridge was scaled onto the original finite element grid. Then the bottom elevations of the nodes inside the new trap were set equal to -3.7 m (-12 ft). The side slopes of the new sand trap were again assumed to be 1V:3H.

Initial conditions used in the hydrodynamic module for all model runs reported herein were zero velocity and constant water surface elevation at all nodes. The initial nodal salinity values of the 1970 nodes inside the inlet were set equal to the average of the high water slack and low water slack salinity distributions measured in the Loxahatchee River from Station 1 to Station 15 on February 26, 1975 (Chiu, 1975) (station numbers refer to those used in the 1975 study). That is, the initial salinities at the 1970 interior nodes were taken to decrease approximately

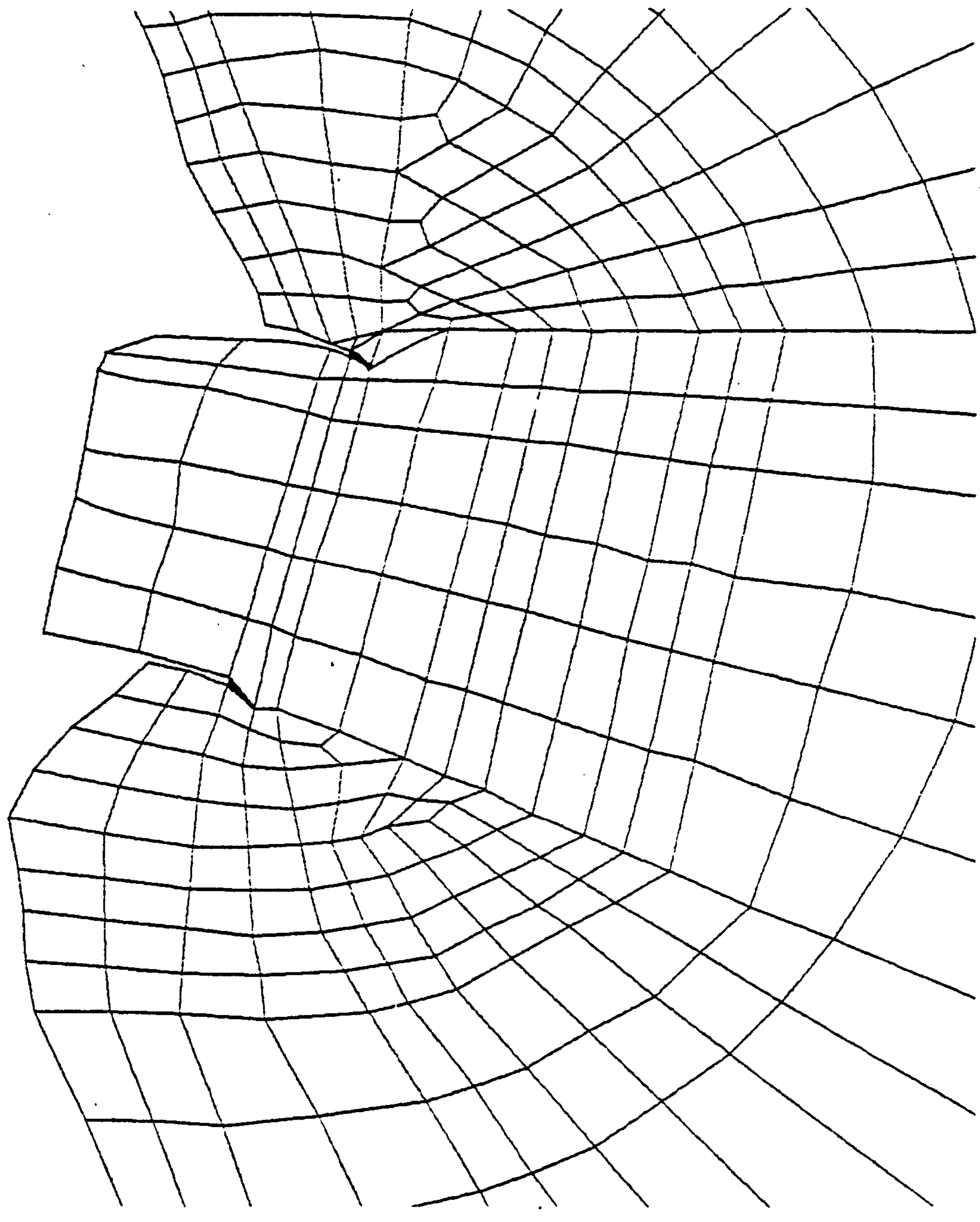


Fig. E.3. Finite element grid for Modification 1 - extension of the jetties. Only the ocean part of the grid is shown.

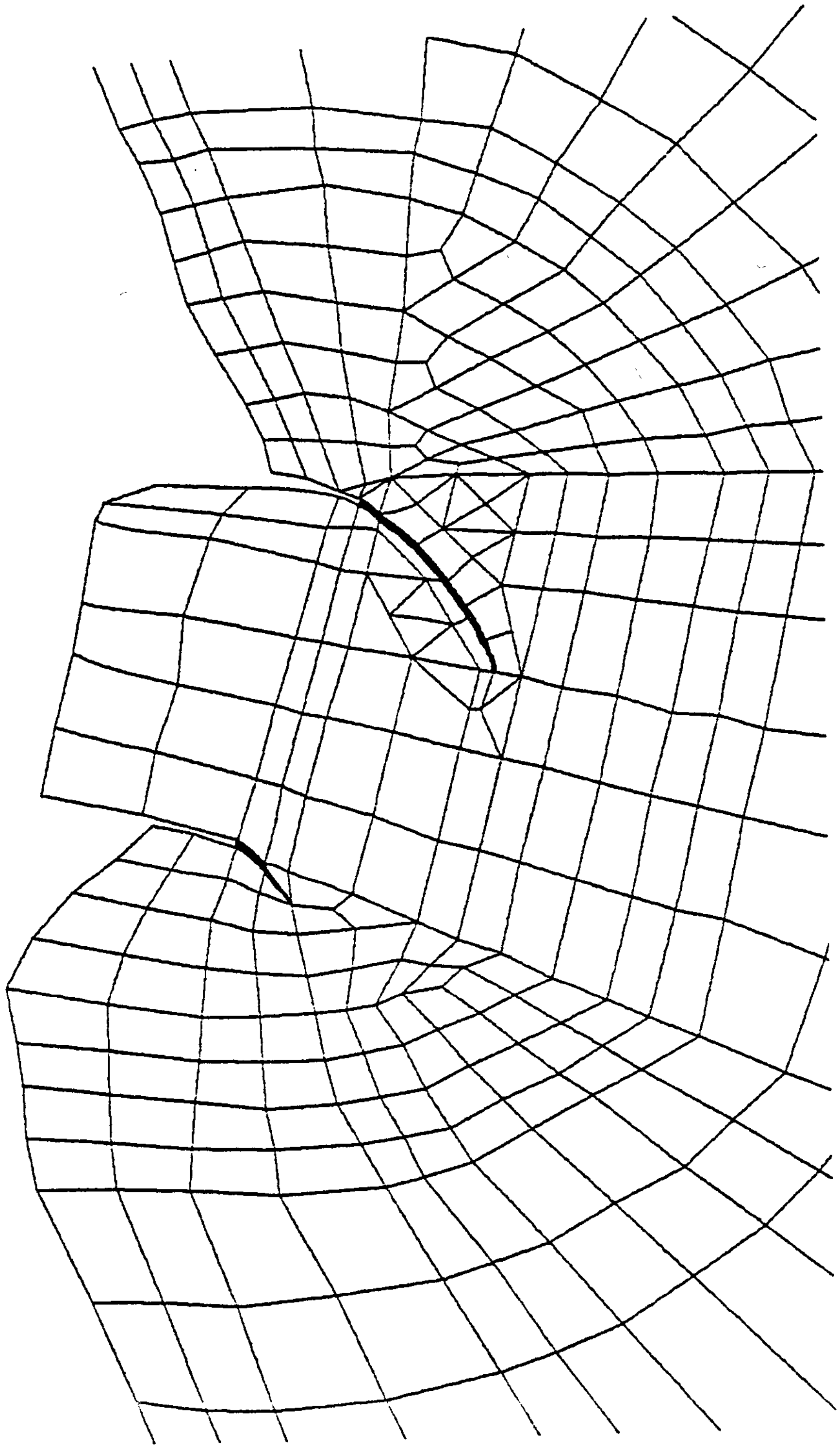


Fig. E.4. Finite element grid for Modification 2. Only the ocean part of the grid is shown.

linearly (with distance upstream from the inlet) from 34.5 ppt at the inlet mouth to 31.5 ppt at the grid boundary in the northwest fork. The initial nodal salinity values in the ocean part of the grid were set equal to 35 ppt.

Boundary conditions used for the hydrodynamic module for all model runs consisted of the NOS predicted water surface elevations at the specified water boundaries for the period March 1 - 30, 1991. The predicted tide for the ocean boundary nodes for this period is shown in Fig. E.5. Salinity boundary conditions for the ocean boundary nodes were taken to be a constant 35 ppt, while those at the five interior open water boundaries were assumed to vary sinusoidally between the low water salinity and high water salinity measured during the 1975 study at the longitudinal positions in the estuary corresponding to the locations of the boundaries. For all the model runs, except for Modification 8 as noted previously, a single grain size of 0.50 mm was used for sediment transport calculations.

E4. Model Results

The estimated net sediment transport rates, repeated from Mehta et al. (1991b), into Jupiter Inlet, west of the railroad bridge, and west of the US 1 bridge, and the gross transport rate at the inlet mouth for D_{50} = 0.50 mm, predicted using the existing (unmodified) finite element grid are given in Tables E1 and E2, respectively. These are included here for comparative purposes.

Table E1:: Estimated net sediment transport rates for existing system.

Location	D_{50} (mm)	Net Sediment Flux (m^3/yr)
Jupiter Inlet	0.50	60,000
US 1 Bridge	0.50	1,400
Railroad Bridge	0.50	800

Table E2: Estimated gross sediment transport rates for existing system.

Location	D_{50} (mm)	Gross Sediment Flux (m^3/yr)
Jupiter Inlet	0.50	94,000

A discussion of the effects of each of the modifications on the hydrodynamic and sedimentary regime in the Loxahatchee River estuary is given next. The one general conclusion that applies to all eight modifications analyzed is that, as noted, negligible effects (less than 0.5 ppt difference) on salt intrusion was noted between the salinity field obtained with the original grid and the modified grids. This result was found by comparing the

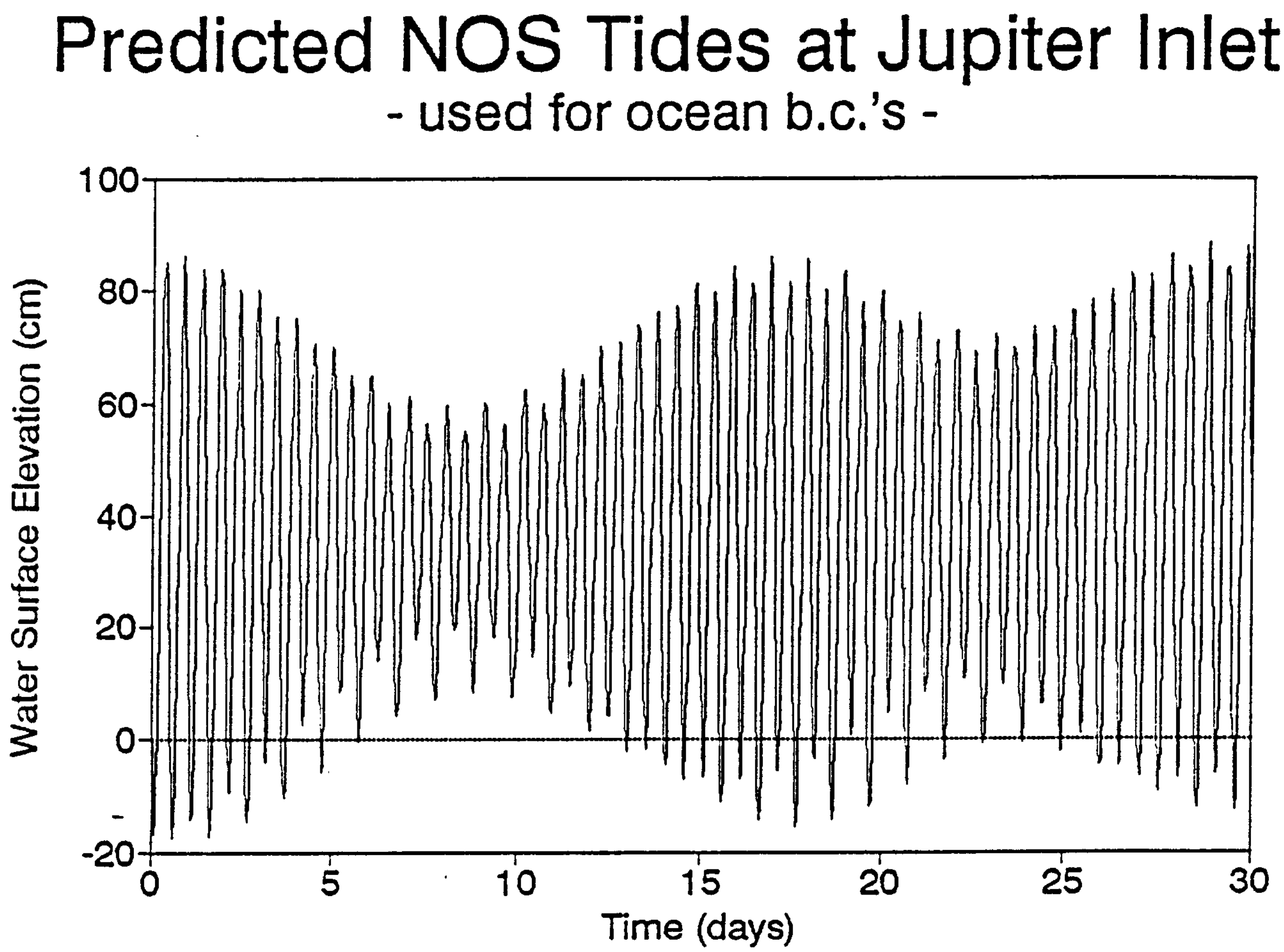


Fig. E.5. Predicted tides at Jupiter Inlet for March 1-30, 1991, used for ocean boundary conditions.

predicted salinity fields from the original and modified grids at critical locations, e.g., at locations where changes in bottom elevation were made, at the grid boundaries in the northwest and southwest forks. The reason for this finding is that the use of sinusoidally varying salinity boundary conditions at the five interior open water grid boundaries, as discussed in Mehta et al. (1991b), controlled the salinity variation in the grid interior to such an extent that the relatively small changes made in the four grid modifications did not cause any differences in the predicted salinity fields. The artificial sinusoidally varying salinity boundary conditions were used because no measured salinities were available.

E4.1 Modification 1

Comparisons discussed in this section are between the original grid configuration and Modification 1. The predicted current pattern in proximity of the extended jetties varies, as would be expected, from that with the original grid. The biggest change occurs in the current direction, as it is strongly controlled by the configuration of the jetties. However, the current speed at nodes around the jetties which did not change location between the original grid and Modification 1 did not differ by more than five per cent at any node. In the inlet channel, the predicted velocities at six nodes were compared. The difference in current speed was never more than four percent at any of the six nodes. Negligible differences were noted in current directions at the six nodes. The net sediment flux into Jupiter Inlet was predicted to be seven per cent less than the value given in Table E1. Considering the margin of error typically associated with sediment transport calculations, the seven per cent difference is definitely not significant.

E4.2 Modification 2

Comparisons discussed in this section are between the original grid configuration and Modification 2. The predicted current pattern in proximity of the extended jetties varies significantly from that with the original grid. The biggest change occurs in proximity of the north jetty due to the major modification in jetty length and configuration. In the inlet channel, the predicted velocities at six nodes were compared. The difference in current speed was never more than eight percent at any of the six nodes. Negligible differences were noted in current directions at the six nodes. The net sediment flux into Jupiter Inlet was predicted to be 27% less than the value given in Table E1. Even considering the margin of error typically associated with sediment transport calculations, the 27% difference is significant, and indicates that less sediment would be transported into the inlet with this jetty modification. The last statement is true in the short run after initial jetty modification, but once sediment built up along the north side of the north jetty, it is thought that more sediment would be transported into the inlet, thus possibly increasing the net sediment flux into the inlet.

E4.3 Modification 3

Comparisons discussed in this section are between the original grid configuration and the two cases considered with Modification 3. The predicted current pattern in the proximity of the deepened JID sand trap varies very little from that with the original grid. The biggest difference occurs with current speed within the trap. The decrease in the predicted current speed over the deepened trap causes the increase in the sand trap filling rate given in Table E3 for Modification 3. The percentage changes in net sediment flux and trap filling rates are with respect to those values calculated using the original grid. The percentage increase in net sediment flux into the inlet shown in Table E3 is primarily the result of less sediment being transported out of the inlet on an ebb tide due to the presence of the deeper trap, which traps more sand during both flood and ebb tides than the existing trap.

Table E3: Results from model runs for Modifications 3, 4, and 5.

Mod. No.	Case Identification	Change in Net Sediment Flux into Inlet	Change in Trap Filling Rate	Change in Net Sediment Flux past RR Bridge
3	-5.8 m (-19 ft)	+ 5%	+ 12%	- 9%
4a	-4.1 m (-13.5 ft)	+ 3%	+ 5%	- 4%
4b	-5.8 m (-19 ft)	+ 11%	+ 28%	- 23%
5	-5.8 m (-19 ft)	+ 8%	+ 21%	- 16%

E4.4 Modification 4

Comparisons discussed in this section are between the original grid configuration and the two cases considered with Modification 4. The predicted current pattern in the proximity of the enlarged JID sand trap varies somewhat from that with the original grid. The biggest difference occurs with current speed within the trap (as would be expected) between the two depths considered in conjunction with enlargement of the trap. The difference in predicted current speed in proximity of the trap results in the rather substantial differences noted in the sand trap filling rates given in Table E3. The percentage changes in net sediment flux and trap filling rates are with respect to those values calculated using the original grid. The percentage increase in net sediment flux into the inlet shown in Table E3 is insignificant. However, the percentage change in the net sediment flux to the west of the Railroad Bridge with Case 4b (see Table E3) is significant. This result is obviously tied to the percentage increase in the trap filling rate predicted to occur for Case 4b.

E4.5 Modification 5

Comparisons discussed in this section are between the original grid configuration and the two cases considered with Modification 5. The predicted current pattern in the proximity of the deepened and lengthened JID sand trap varies little from that with the original grid. The biggest difference occurs with current speed within the trap. The decrease in the predicted current speed over the deepened and lengthened trap causes the increase in the sand trap filling rate given in Table E3 for Modification 5, as compared with that given for Modification 3. The predicted increase in net sediment flux into the inlet for Modification 5 compared with Modification 3 is obviously due to the increased length of the trap used in Modification 5.

Comparison of the results given in Table E3 for Modifications 3 - 5 shows the expected conclusion that the largest change in net sediment flux into the inlet, change in trap filling rate, and change in net sediment flux past the RailRoad bridge occurs for Modification 4b, which used the deepest and largest trap. Comparison of the results for Modifications 3 and 5 with 4b show that deepening and lengthening the trap had more affect than widening the trap on the predicted sediment transport rate. This finding was expected since the predicted increase in trap filling rate would be more or less linear with increase in trap width, whereas the increase in trap filling rate caused by trap deepening would be expected to be greater than a linear increase. The justification for this statement is that sediment transport capacity is proportional to the cube of the velocity; thus as the depth-averaged velocity over the trap decreases more or less linearly with increase in the trap depth, the sediment transport rate will decrease at a much higher rate.

E4.6 Modification 6

Comparisons discussed in this section are between the original grid configuration and Modification 6. The original JID sand trap was used with this modification. The new sand trap simulated in the modified grid did not cause any noticeable effects on the tides upstream of the trap. This is not surprising considering the relatively small size of the trap. However, the trap reduced the predicted net upstream (past the trap) sediment flux by 55 per cent. Thus, a sand trap at the proposed location would be very effective at reducing the movement of sand further upstream, i.e., westward.

E4.7 Modification 7

Comparisons discussed in this section are between the original grid configuration and the two cases considered with Modification 7. The effects of dredging a navigation channel to the west of the Railroad Bridge, both in conjunction with the new sand trap considered with Modification 6 and without the new sand trap are summarized in Table E4. The significant difference in the predicted filling rate for the two cases again emphasizes the effectiveness of the proposed new sand trap in reducing the movement of sand further westward. The addition of the navigation channel and new sand trap (Case 7b) resulted in an additional (with respect to Modification 6) 8 per cent decrease in the net movement of sand further upstream. The navigation channel by itself (Case 7a) caused a 15 per cent decrease in the net upstream movement of sand. Neither case considered with Modification 7 caused any noticeable effects on the predicted tides upstream of the trap/navigation channel. Again, this is not surprising considering the relatively small size of the trap and navigation channel.

E4.8 Modification 8

Comparisons discussed in this section are between the original grid configuration and the two cases considered with Modification 8. The effect of dredging a new sand trap east of the Railroad Bridge are summarized

Table E4: Results from model runs for Modifications 6, 7, and 8.

Mod. No.	Case Identification	Filling Rate of Navigation Channel (Mod 7) (m^3/yr)	Change in Net Sediment Flux West (upstream) of Railroad Bridge
6		-	- 55%
7a	without new trap	147	- 15%
7b	with new sand trap	56	- 63%
8a	d_{50} = 0.20 mm	-	- 29%
8b	d_{50} = 0.50 mm	-	- 51%

in Table E4. The significant difference in the predicted net sediment flux upstream of the Railroad bridge for Cases 8a and 8b is caused by the different sediment sizes. Less sediment is transported past the trap with the 0.50 mm sand than with the 0.20 mm sand, because the lower velocities which occur when a trap is present are not able to transport as large a quantity of 0.50 mm sand as 0.20 mm sand. Thus, one can conclude that the trap is more "efficient" with larger sediment sizes. Neither case considered with Modification 8 caused any noticeable effects on the predicted tides upstream of the trap/navigation channel.

E5. Conclusions

The main conclusions reached from the sediment transport modeling effort described in this report are summarized below.

Modification 1: No significant change occurred in either the hydrodynamic or sedimentary regimes as a result of extending both jetties 15.2 m (50 ft).

Modification 2: The net sediment flux into Jupiter Inlet was rather significantly reduced (27%) as a result of extending the north jetty by 122 m (400 ft) and the south jetty by 30 m (100 ft).

Modification 3: Deepening the existing JID sand trap to - 19 ft resulted in an increase in the net sediment flux into the inlet caused by a predicted decrease in the sediment transport rate out of the inlet during ebb tides. The latter is attributable to the predicted increase in the trap filling rate.

Modification 4: Case 4b (-19 ft bottom elevation in the enlarged sand trap) resulted in a significant increase in the predicted trap filling rate and decrease in the net flux of sediment to the west of the Railroad bridge.

Modification 5: Deepening and lengthening the JID sand trap again resulted in an even greater (compared with Modification 3) increase in the net sediment flux into the inlet. The longer length of the trap compared with that used in Modification 3 caused the increase in trap filling rate, and therefore in the net sediment flux into the inlet.

Modification 6: The new sand trap located immediately to the west of the Railroad bridge results in a predicted decrease in the net movement of sand further to the west of 55 per cent.

Modification 7: The addition of the navigation channel and new sand trap resulted in an additional 8 per cent decrease in the net movement of sand further upstream. The navigation channel by itself caused a 15 per cent decrease in the net upstream movement of sand.

Modification 8: The new sand trap east of the Railroad bridge results in a predicted decrease in the net movement of sand upstream of the bridge of 51 per cent for the 0.50 mm sand and 29 per cent for the 0.20 mm sand.

APPENDIX F: AN ECOLOGICAL ASSESSMENT

F1. Preamble

An assessment of sea turtle nesting, offshore rocky outcroppings, mangroves and seagrasses relevant to the Jupiter Inlet area is presented briefly in what follows.

F2. Sea Turtle Nesting

Nesting sea turtles require 1) access to a nesting site 2) excavatable sand, and 3) a stable beach for incubating eggs (see Nelson, 1985; Nelson and Dickerson, 1988; Ross, 1982; Witham, 1989).

Although many variables affect the selection of a nest site by a turtle, one which is most relevant to beach nourishment is beach-profile slope. Profiles of beaches that are used by turtles near Jupiter Inlet have a slope of roughly 1 ft of rise per 10 to 20 ft of run in the zone from mean sea level to about 100 ft toward land. A photograph of such a beach is given in Fig. F.1 and the elevation profile for this beach is given in Fig. F.2. Beaches with steep scarps between means sea level and 100 ft toward land are unlikely to be chosen by turtles for nesting. The beach just south of Jupiter Inlet sometimes has such a profile, as illustrated in the photograph given in Fig. F.3.

Sand coming from traps and the ebb shoal is of a grain size suitable for nest excavation by turtles. It is similar to the sand now on the beach in areas frequently used by turtles. Finer sand, perhaps such as that found in the flood shoals west of the railroad bridge, may become too compact for turtles to excavate.

The heavily eroded beach immediately (ca. 0.33 km) south of the south jetty is problematical. Restoration of the beach is desirable, yet the presence of the south jetty reflects waves. Hence, added sand can suddenly disappear during a wind storm, resulting in a radically changing beach profile, as illustrated in Fig. F.4. The restored beach becomes an "attractive nuisance" to nesting turtles. Eggs laid in this stretch of restored beach are at much greater risk of being washed out before hatching than eggs laid on a more stable beach. To solve this problem, either the south jetty must be removed (with an increase in sand pumping or dredging required), all nests must be relocated (perhaps 60 or 70 nests per year), turtles must be prevented from nesting in this area 0.33 km stretch (perhaps with a fence), or a certain amount of nest loss must be tolerated (perhaps 5 to 20 nests per year).

Continuous sand pumping (with a fluidizer), as opposed to intermittent dredging, is a desirable option with respect to sea turtle nesting and general beach ecology. Unlike intermittent dredging, continuous pumping does not cause sudden alteration of beach profiles and burial of existing organisms. Sudden perturbation of the beach requires a period of ecological recovery and may discourage nesting turtles.

F3. Offshore Rocky Outcroppings

A map of submerged offshore rocky outcroppings in the vicinity of Jupiter Inlet is provided (Fig. F.5). Rocky outcroppings exist 1 km to the north and 1.2 km to the south of the inlet and a possible rocky outcropping

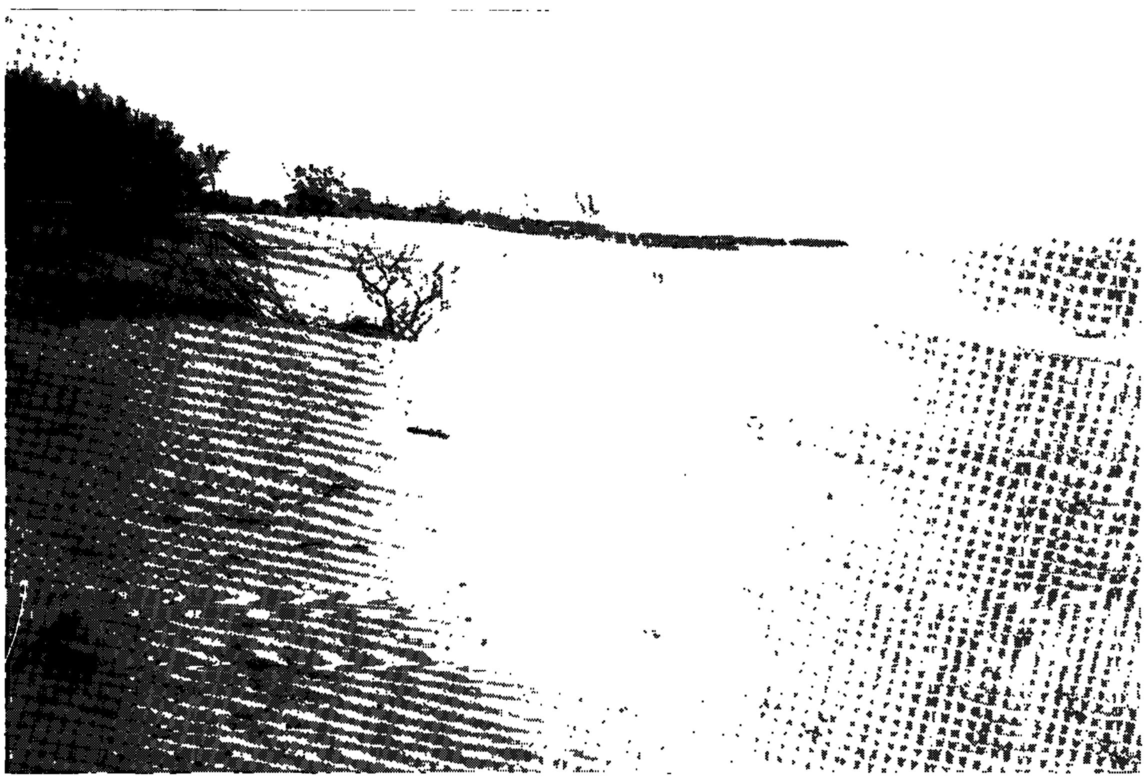


Fig. F.1. Good sea turtle nesting beach near the Hilton Inn at Jupiter, Florida, looking north toward Jupiter Inlet.

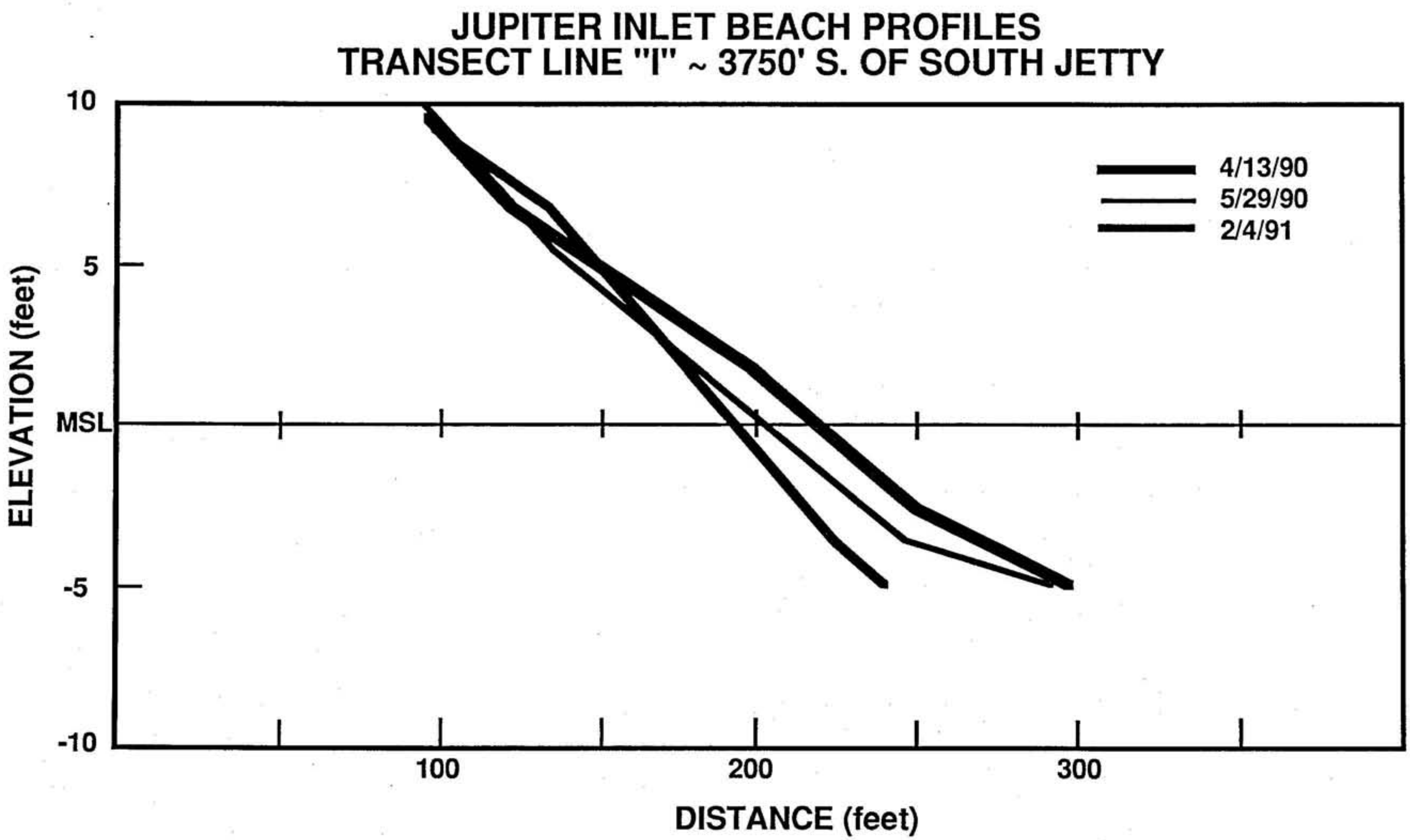


Fig. F.2. Beach-slope profile south of Jupiter Inlet near the Hilton hotel at Jupiter, Florida on three occasions in 1990 - 1991.

Fig. F.3. Steep scarp discouraging to nesting sea turtles just south of the south jetty at Jupiter Inlet, Florida, looking south toward the Hilton hotel.

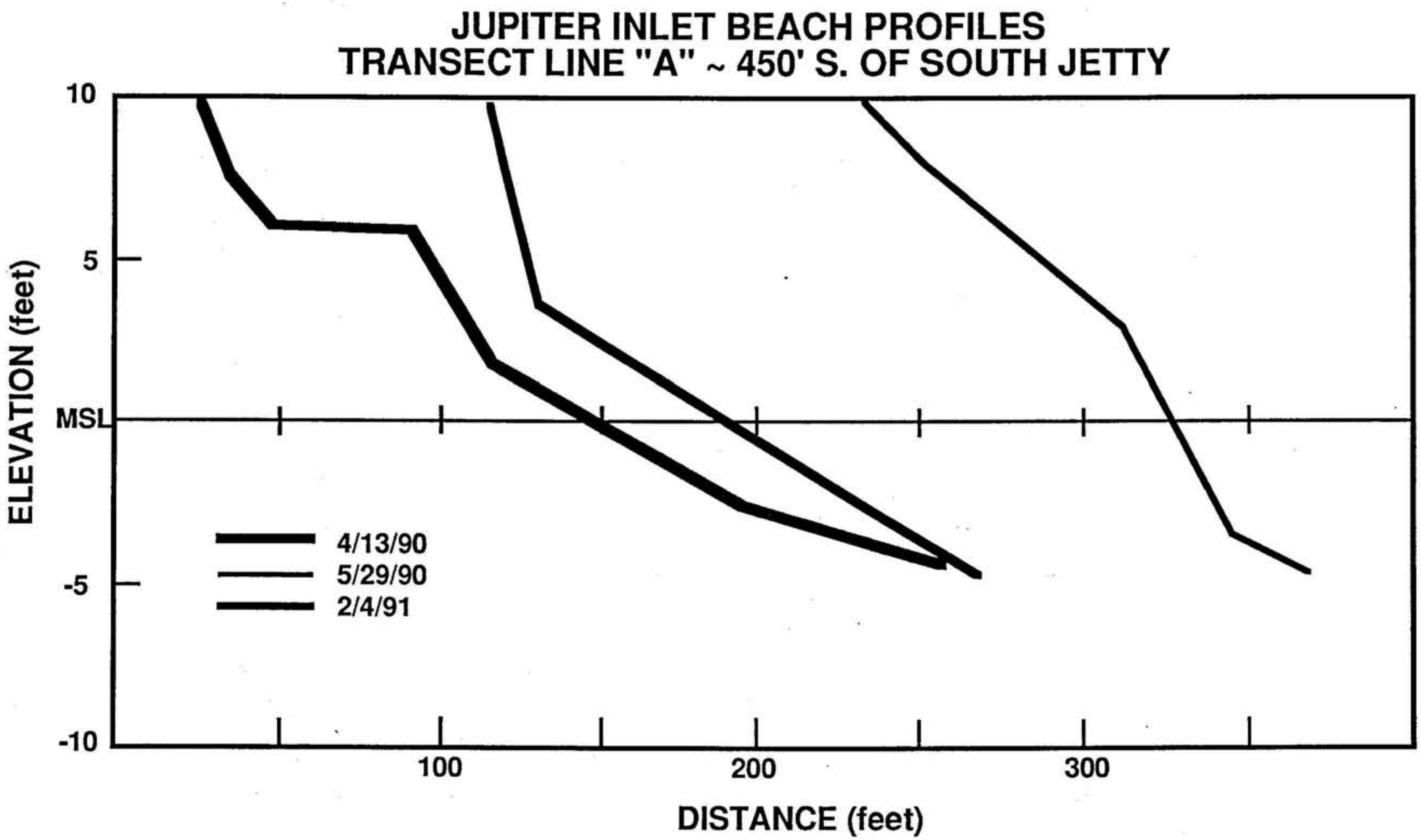


Fig. F.4. Beach-slope profile just south of the south jetty at Jupiter Inlet, Florida on three occasions in 1990 - 1991.

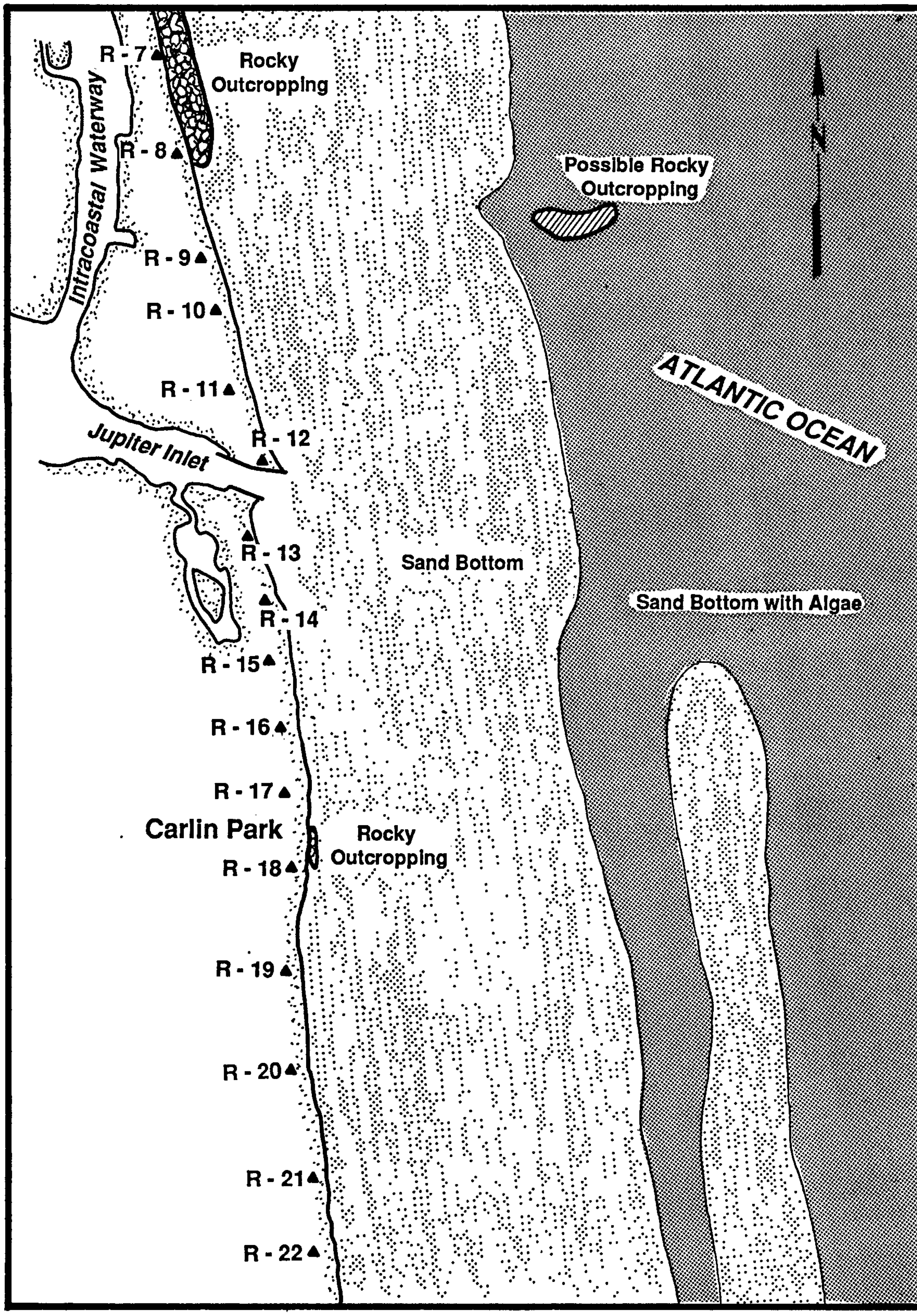


Fig. F.5. Location of rocky outcroppings in the vicinity of Jupiter Inlet, Florida (adapted from Continental Shelf Associates, 1985; 1987; 1989b; 1989c).

exists about 1.4 km northwest of the inlet (Continental Shelf Associates, 1985; 1987; 1989b; 1989c). The "X" on the map 2 km due east of Jupiter Inlet marks the approximate location of a popular fishing and diving site called "Grouper Hole".

Although rocky outcroppings appear and disappear throughout the bare-sand area surrounding the inlet, the only major group of presently exposed outcroppings that lie within the probable impact area of inlet management operations are those 1.2 km to the south along the beach at Carlin Park. Like all rocky outcroppings these are habitat for nearshore fishes (see Nelson, 1989). Those at Carlin Park are shallow, very near shore, and hence also have recreational value to snorkelers. Although natural sand transport may occasionally bury these outcroppings (and re-expose others) in the absence of any human activity, it is recommended that beach nourishment activities avoid burying these rocky outcroppings.

The jetty consists of rocks that provide fish and invertebrate habitat similar in many ways to that of natural submerged rock in the area (Van Dolah et al., 1984; 1987; Hay and Sutherland, 1988). In addition, exposed natural rocks occur both intertidally and subtidally around the jetty, as well as subtidally right in the inlet. A diagram from Captain Miller (Fig. F.6) illustrates the location of five submerged rocks between the north jetty and the inlet centerline. It is likely that these rocks are used as habitat for fishes and invertebrates as well. Furthermore, we observed several fishes and a long-spined sea urchin (*Diadema antillarum*) on a small rocky outcropping in the Dubois Park lagoon.

F4. Mangroves

As illustrated in Fig. F.7, fifty-five percent of the mangroves in the area east of the railroad bridge are in the intertidal zone of the Dubois Park lagoon. The Dubois Park lagoon is also very close to the inlet. Another 40% are in the south arm of the intracoastal waterway (the portion considered part of the study region ended at Burt Reynolds Park).

Mangroves occupy the intertidal zone, the extent of which is determined by the slope of intertidal lands and the range of the tides. Changes in mean water level, tidal range, or sediment loading can change the extent of area occupied by mangroves. Because of the values of mangroves as fish habitat, sediment stabilizers, and water quality and food-supply buffers (see Odum et al., 1982; Odum and McIvor, 1990), changes in inlet management that could create these effects are not recommended. Changes in inlet cross-sectional area, or in the cross-sectional area of the "bottle-neck" to flow at the railroad bridge may cause subtle changes in water-level and tidal range inside the inlet.

Perhaps the main area of concern should be the tiny inlet of the Dubois Park lagoon. Alterations in this small inlet may create dramatic changes in the intertidal and subtidal parts of the lagoon. Such alterations are not recommended and do not seem necessary to achieve inlet management objectives.

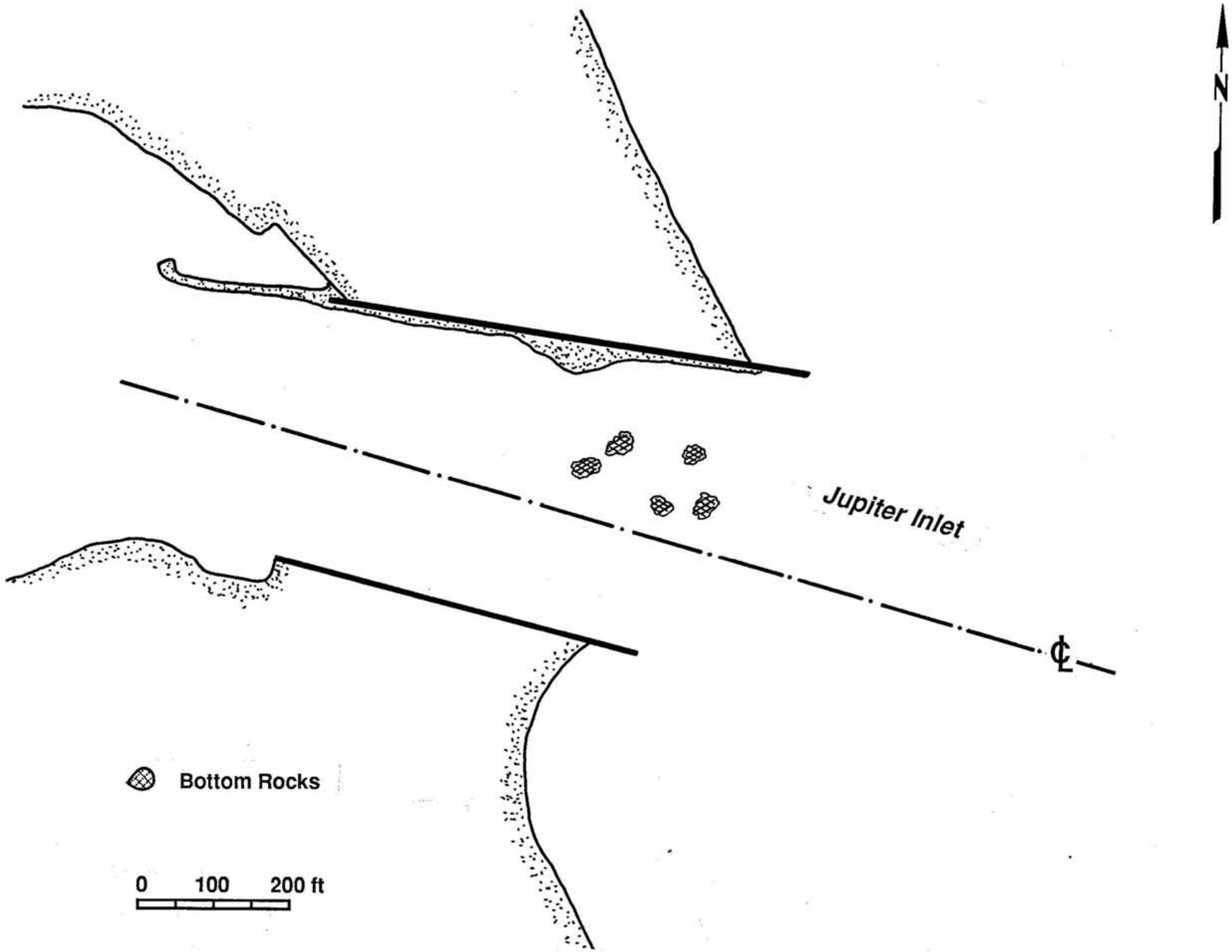


Fig. F.6. Drawing of Jupiter Inlet, Florida from Captain Miller, showing location of bottom rocks just inside the inlet.

JUPITER INLET AREA MANGROVE ASSESSMENT

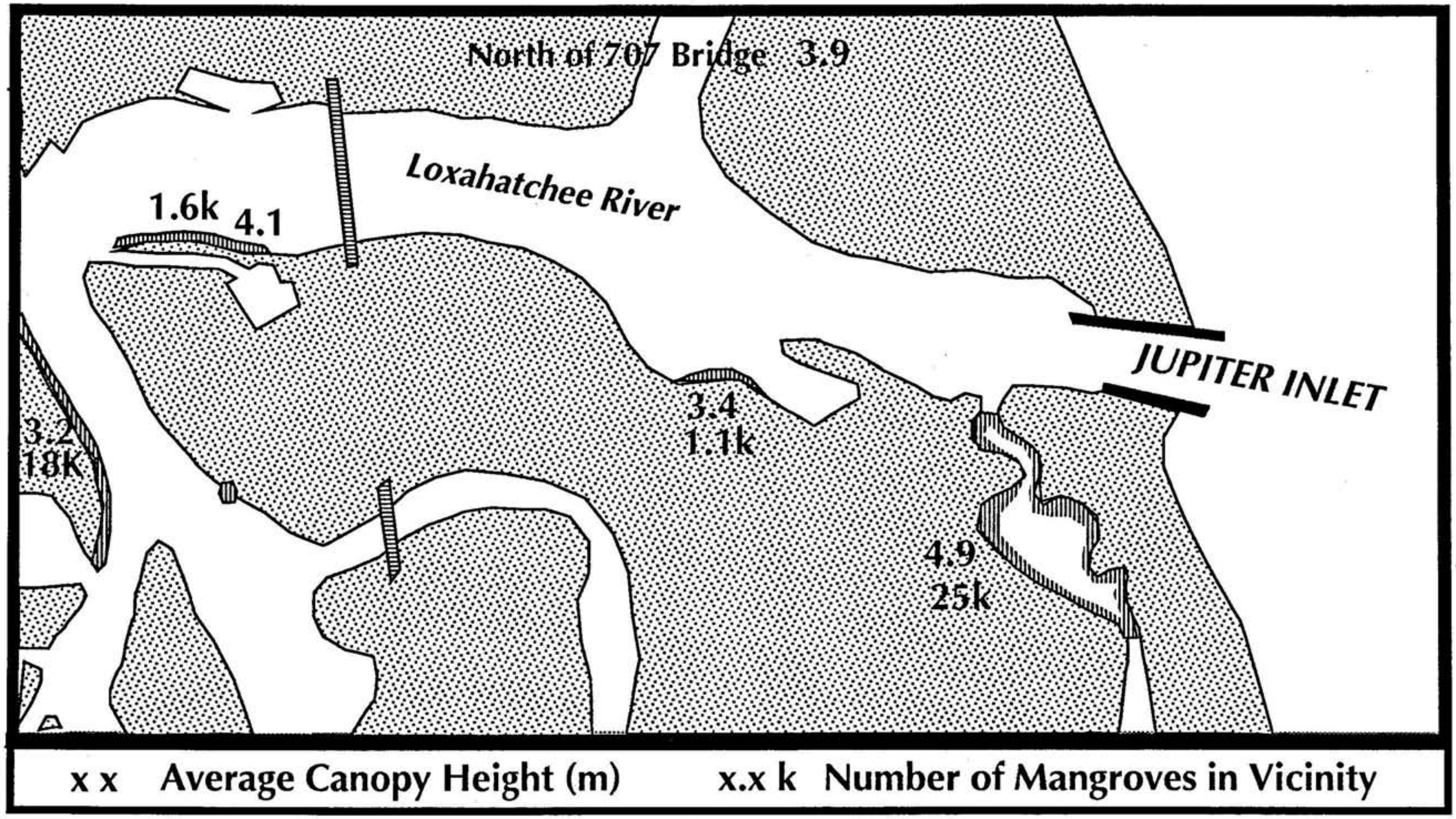


Fig. F.7. Location, canopy height, and number of mangroves in mangrove forests in the Loxahatchee River estuary east of the railroad bridge.

F5. Seagrasses

As illustrated in Fig. F.8, almost half of the seagrasses in the study region east of the railroad bridge are found in one bed along the south shore just opposite the entrance to the north arm of the Intracoastal Waterway. Another smaller but densely populated bed is just west of that one, on the eastern edge of the marina area. Other less dense beds occur in Dubois Park lagoon, in the north arm of the intracoastal waterway and along most of the edges of the estuary west of the north arm of the intracoastal waterway. Seagrass density decreases in the more western beds in the study region.

Seagrass bed success is dependent on many factors (see Zieman, 1982; 1987), but good light penetration, moderate tidal range, stable sediments, low fluctuation in salinity, and gentle bed slope are very important east of the railroad bridge. Seagrasses here occur in shallow water where light can penetrate sufficiently but where frequent exposure to air, scour, or high temperature does not occur. Where bed slopes are gentle, the suitable area for growth is large. Changes in water level, tidal range, turbidity, and fluctuation in salinity will influence seagrass beds. These types of change are not expected unless management options involve the cross-sectional area at either the inlet, the "bottle-neck" at the railroad bridge, or the tiny inlet of the Dubois Park lagoon.

Perhaps the greatest threat to seagrass beds, however, is changing bathymetry, especially by dredging, but also perhaps by the movement of flood-tidal shoals. Broad, shallow zones that support seagrasses are unsuitable for navigation and marinas. These zones must either be avoided by boats, or else the loss of seagrasses must be tolerated. Although seagrasses can stabilize shoals, the shoals must first be stable enough to allow the initial growth of the grasses. Existing seagrass beds may be buried by rapid shoaling or eroded by altered flow patterns. Any inlet modification that buries, destabilizes, or dredges existing seagrass beds should be avoided, or damaged beds should be appropriately mitigated.

F6. Seagrass Mitigation

To address the possibility of mitigating any unavoidable destruction of seagrass beds that might occur in future inlet-management activities, we have examined the bathymetry of the seagrass beds and searched bathymetric maps for similar sites in the study region that are not presently occupied by seagrasses. Seagrass beds east of the railroad bridge are found at depths less than 2 ft below mean low water. East of the railroad bridge, all sites that could be occupied by seagrasses appear to be occupied now. West of the railroad bridge, the flood shoal contains some shallow areas that may not now be occupied by seagrasses. Whether these sites would support planted seagrasses is not clear. A study should be done to identify why no seagrasses are now there (if indeed none are). If it is because sediment is slightly too unstable, planting may help stabilize the sediment, so mitigation might be successful, though risky (Fonseca and Fisher, 1986). If, however, it is because the aquatic environment will not support seagrasses (because, for example, salinity fluctuation is too extreme or light is insufficient), mitigation will not be successful without major changes in estuarine management.

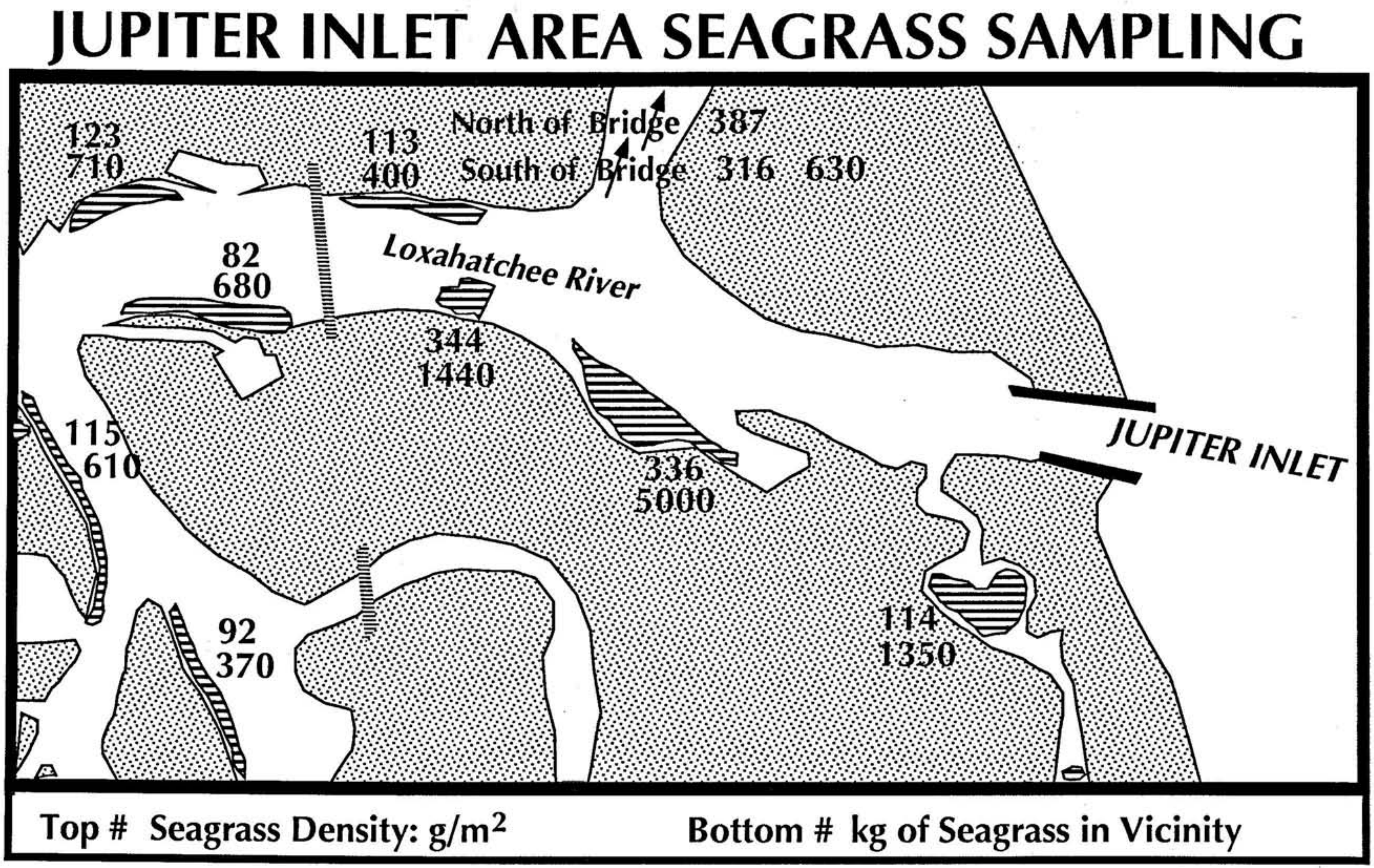


Fig. F.8. Location, density, and total weight of seagrasses in seagrass beds in the Loxahatchee River estuary east of the railroad bridge.

APPENDIX G: DESIGN CRITERIA FOR SEA TURTLE NESTING BEACHES

Table G1: Needs of nesting sea turtles and habitat design considerations.

Need of Sea Turtles	Design Consideration
1. Access:	Uniform, moderate beach slope rising to a soft sand berm.
2. Nest excavation:	Excavatable sand of sufficient depth.
3. Nest incubation:	Stable beach.
4. Hatchling emergence:	Sand excavatable by hatchlings.

Table G2: Summary of design criteria for sea-turtle nesting beaches.

I. Sufficient quantity of sand.
- A. Balanced sand budget.
- B. Uniform, moderate beach slope (1:10), without steep scarps.
- C. Soft sand berm.
- D. Sand layer > 1.5 m thick under berm.

II. Adequate type of sand (excavatable by both adults and hatchlings).
- A. Compaction < 35 kg/cm^2.
- B. Not prone to form crustal concretions (no marls or clays).
- C. Sand not too fine (compaction), but no large rubble.

III. Appropriate frequency of nourishment.
- A. Annual or continuous.

IV. Effective timing of nourishment.
- A. More than 30 d before nesting season to allow profile equilibration.

V. Constructive placement of nourishment.
- A. Away from hard structures that reflect wave energy (to avoid nest washout).

BIBLIOGRAPHY

Aubrey D.H. and DeKimpe N.M. (1988). Performance of beach nourishment at Jupiter Inlet, Florida. *Proc. Beach Preservation Technology '88*, FSBPA, Tallahassee, FL, 409-420.

Bowles J.E. (1970). *Engineering properties of soils and their measurement.* McGraw-Hill, Inc., New York.

Bruun P. (1990). Bypassing plants or arrangements. Prices on transfers. *Journal of Coastal Research*, Special Issue No. 9, 936-950.

Buckingham W.T. (1984). Coastal engineering investigation at Jupiter Inlet, Florida. *UFL/COEL-84/004*, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Chiu T.Y. (1975). Evaluation of salt intrusion in the Loxahatchee River, Florida. *UFL/COEL-75/013*, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Coastal Engineering Laboratory (1969). Coastal engineering study at Jupiter Inlet, Palm Beach County, Florida. *UFL/COEL-69/009*, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Continental Shelf Associates (1985). Ecological assessment of the nearshore rock outcrops off Jupiter Island. *Final Report*, Jupiter, Florida. Jupiter, FL.

Continental Shelf Associates (1987). Environmental assessment of the Palm Beach County erosion control program. Phase III: Jupiter/Tequesta. *Final Report*, Jupiter, FL.

Continental Shelf Associates Inc. (1989a). Background environmental assessment, Jupiter Inlet, ten year maintenance dredging permit application, Jupiter, FL.

Continental Shelf Associates (1989b). *Draft Environmental Statement*, Carlin Park, Palm Beach County, Florida, 17 August 1989. Jupiter, FL.

Continental Shelf Associates (1989c). *Field Survey at Jupiter/Carlin Park and Coral Cove.* A letter report to the Palm Beach County Department of Environmental Resources Management, 3 October 1989.

Davies B.E. (1974). Loss-on-ignition as an estimate of soil organic matter. *Soil Sci. Soc. Amer. Proc. 38*, p. 150.

Dean R.G. (1988). Sediment interaction at modified inlets. In: *Hydrodynamics and Sediment Dynamics of Tidal Inlets*, D.G. Aubrey and L. Weishar eds., Springer-Verlag, New York, 412-439.

Dean R.G. and Grant J. (1989). Development of methodology for thirty-year shoreline projections in the vicinity of beach nourishment projects. *UFL/COEL-89/026.* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

DelCharco M.J. (1992). Tidal flood water withdrawal, with special reference to Jupiter Inlet, Florida. *M.S. Thesis*, University of Florida, Gainesville, FL.

Dewall A.E. and Richter J.J. (1978). Beach and nearshore processes in southeastern Florida. *Proc. Coastal Sediments '77*, ASCE, New York, 425-443.

Dixon and Associates Engineering Inc. (1991). Personal Communication, West Palm Beach, FL.

Dolan R., Inman D.L. and Hayden B. (1990). The Atlantic coast storm of March 1989. *Jour. Coast. Res.*, 3, 721-725.

Dubois B.W. (1981). Jupiter Inlet. *Gateway Magazine of the Port of Palm Beach,* Jan-Feb., Palm Beach, FL.

Fonseca M.S. and Fisher J.S. (1986). A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Mar. Ecol. Prog. Ser.*, 29, 15-22.

Fonseca M.S. and Kenworthy W.J. (1987). Effects of current on photosynthesis and distribution of seagrasses. *Aquat. Bot.*, 27, 57-78.

Hackney C.T. and Cleary W.J. (1987). Saltmarsh loss in southeastern North Carolina lagoons: importance of sea level rise and inlet dredging. *Jour. Coast. Res.*, 3, 93-97.

Harris P.S. (1991). The influence of seasonal variation in longshore sediment transport with applications to the erosion of the downdrift beach at Jupiter Inlet, Florida. *M.S. Thesis,* University of Florida, Gainesville, FL.

Hay M.E. and Sutherland J.P. (1988). The ecology of rubble structures of the South Atlantic Bight: a community profile. Biological Report 85(7.20), U.S. Fish and Wildlife Ser., Washington, DC.

Hoffman J.S. (1984). Estimates of future sea level rise. Pages 79-103 in *Greenhouse Effect and Sea Level Rise,* M. C. Barth and J. G. Titus, (eds). Van Nostrand-Reinhold Co., NY.

Hoffmeister J.E. (1974). *Land from the sea.* Univ. of Miami Press, Miami, FL.

Kirby R.R., Hobbs C.H. and Mehta A.J. (1989). Fine sediment regime of Lake Okeechobee, Florida. *UFL/COEL-89/000,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Longuet-Higgins M.S. (1970). Longshore currents generated by obliquely incident sea waves, I and II. *Journal of Geophysical Research,* 75 (33), 6778-89; 6790-801.

Marine Board (1987). *Responding to Changes in Sea Level: Engineering Implications,* Nat. Acad. Press, Washington, DC.

McPherson B.F., Sabanskas Maryann and Long W.A. (1982). Physical, hydrological and biological characteristics of the Loxahatchee River Estuary, Florida. U.S.G.S. Water Resources Rpt. 82-350.

Mehta A.J. (1990). Significance of bay superelevation in measurement of sea level change. *J. Coast. Res.*, 6(4), 803-813.

Mehta A.J., Montague C.L. and Parchure T.M. (1990a). Tidal inlet management at Jupiter Inlet, Florida: first progress report. *UFL/COEL-90/005,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Mehta A.J., Montague C.L., Thieke R.J. and Faas R.W. (1990b). Tidal inlet management at Jupiter Inlet: second progress report. *UFL/COEL-90/010,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Mehta A.J. and Montague C.L. (1991). Management of sandy inlets: coastal and environmental engineering imperatives. *Proceedings of Coastal Zone'91,* ASCE, New York, 628-642.

Mehta A.J., Montague C.L., Thieke R.J., Lin L.-H. and Hayter E.J. (1991a). Tidal inlet management at Jupiter Inlet: third progress report. *UFL/COEL-91/002,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Mehta A.J., Parchure T.M., Montague C.L., Thieke R.J., Hayter E.J. and Krone R.B. (1991b). Tidal inlet management at Jupiter Inlet: fourth progress report. *UFL/COEL-91/008,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Mehta A.J., Delcharco M.J. and Hayter E.J. (1991c). Tidal inlet management at Jupiter Inlet: fifth progress report. *UFL/COEL-91/012,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.

Mehta A.J. and Cushman R.M. eds. (1989). Workshop on sea level rise and coastal processes. *Rept. DOE/NBB-0086,* U.S. Dept. of Energy, Washington, DC.

Miller, R., (1991). Personal Communication, Jupiter Inlet (FL).

Montague C.L. and Wiegert R.G. (1990). Salt marshes. In: *Ecosystems of Florida.* R. Myers and J. Ewel eds., U. Central Fla. Press, Orlando, FL, 418-516.

Nelson W.G. (1985). Guidelines for beach restoration. Part I. Biological guidelines. *Rept. 76,* Fla. Sea Grant Coll., Gainesville, FL.

Nelson W.G. (1989). Beach nourishment and hard bottom habitats: the case for caution. In: *Beach Preservation Technology '89: Strategies and Alternatives in Erosion Control.* L.S. Tait ed., Florida Shore and Beach Preservation Association, Inc., Tallahassee, FL, 109-116.

Nelson D.A. and Dickerson D. (1988). Effects of beach nourishment on sea turtles. In: *Beach Preservation Technology 88: Problems and Advancements in Beach Nourishment.* L.S. Tait ed., Fla. Shore and Beach Preser. Assoc., Tallahassee, FL, 285-294.

Odum W.E., and McIvor C.C. (1990). Mangroves. Pages 517-548 in: *Ecosystems of Florida.* R. Myers and J. Ewel eds., University of Central Florida Press, Orlando, FL.

Odum W.E., McIvor C.C. and Smith III T.J. (1982). The ecology of the mangroves of south florida: a community profile. *FWS/OBS-81/24,* U.S. Fish and Wildlife Service, Office of Biological Services, Washington, DC.

Ross J.P. (1982). Historical decline in loggerhead, ridley, and leatherback sea turtles. In: *Biology and Conservation of Sea Turtles.* K.A. Bjorndahl ed., Smithsonian Inst. Press, Washington, DC, 189-195.

Seymour R.J. and Castel D. (1985). Episodicity in longshore sediment transport. *J. Wtrwy., Port, Coast and Oc. Engr.,* ASCE, III(3), 542-551.

Shepard F.P. (1954). Nomenclature based on sand-silt-clay ratios. *Jour. Sed. Pet.,* 24, 151-158.

Sonntag W.H. and McPherson B.F. (1984). Sediment concentrations and loads in the Loxahatchee River estuary. Florida, 1980-1982. U.S.G.S. Water Resources Rpt. 84-4157.

Trask P.D. (1932). *Origin and environment of source sediments of petroleum.* Gulf Publ. Co., Houston, TX.

U.S. Army Corps of Engineers (1966). Survey report on Jupiter Inlet, Florida. *Serial No. 73,* Jacksonville District, Jacksonville, FL.

U.S. Coast and Geodetic Survey (1913). *Register No. 3522,* Rockville, Maryland.

Van Dolah R.F., Knott D.F. and Calder D.R. (1984). Ecological effects of rubble weir jetty construction at Murrells Inlet, South Carolina; volume I: colonization and community development on new jetties. *Technical report*

EL-84-4. Prepared by South Carolina Wildlife and Marine Resources Department, Charleston, S.C., for the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Van Dolah R.F., Wendt P.H., Wenner C.A., Martore R.M., Sedberry G.R. and Moore C.J. (1987). Ecological effects of rubble weir jetty construction at Murrells Inlet, South Carolina; volume III: community structure and habitat utilization of fishes and decapods associated with jetties. *Technical report EL-84-4*. Prepared by South Carolina Wildlife and Marine Resources Department, Charleston, S.C., for the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wanless H., Rossinsky, V. Jr. and McPherson B.J. (1984). Sedimentologic history of the Loxahatchee River estuary, Florida. U.S.G.S. Water Resources Rpt. 84-4120.

Weggel J.R. and Perlin M. (1988). Statistical description of longshore sediment transport environment. *Journal of Waterway, Port, Coastal, and Ocean Engineering*. 114(2), 125-145.

Witham R. (1989). Beach preservation and sea turtle nesting. In: *Beach Preservation Technology '89: Strategies and Alternatives in Erosion Control*. L.S. Tait ed., Tallahassee, Florida, Florida Shore and Beach Preservation Association, Inc., 143-146.

Zieman J.C. (1982). The ecology of the sea grasses of south Florida: a community profile. *Rept. FWS/OBS-82/25*, U.S. Fish and Wildlife Ser., Washington, DC.

Zieman J.C. (1987). A review of certain aspects of the life, death, and distribution of the seagrasses of the southeastern United States 1960-1985. Pages 53-76 in *Proc. Symp. Subtropical-Tropical Seagrasses of the Southeastern United States*. Durako, M.J., R.C. Phillips, and R.R. Lewis III, eds. Florida Marine Research Publications 42.