Historical Findings on Ebb Shoal Mining

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ABSTRACT ∎

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Mining of ebb shoals has become more prevalent in recent years due to limited sources of beach quality sand available for beach nourishment projects. This paper examines eight ebb shoal mining projects completed since 1981 in an attempt to examine this relatively new practice of removing material from an inlet ebb shoal. A brief description of each inlet's history, morphology, and processes is given in an Appendix for background information and available information on the ebb shoal mining events at each inlet is presented in this paper. The eight projects presented range in size from 170,000 m³ removed from the ebb shoal at Boca Raton Inlet (Florida) to 6,235,000 m³ removed from the ebb shoal at Great Egg Harbor Inlet (New Jersey). The recent completion of many of these projects and lack of systematic monitoring has resulted in limited monitoring data to assess shoal mining impacts on the inlet system. With this in mind, impacts of ebb shoal mining inferred from the data and the level of monitoring at each project site are discussed. From this study, it has been determined that most ebb shoals are mined on the outer "passive" portion of the shoal feature. Ebb shoal sand was found to be compatible with the native beach material, indicating that the ebb shoal acts as a "sand bridge" between the updrift and downdrift beaches. The rate of recovery of the mined area appears to be a function of the degree to which the system equilibrium is perturbed, sand availability (longshore transport rate), storm frequency, and the depth of the mined area. Estimates of borrow area recovery were often overpredicted, probably due to poor longshore transport estimates. Further analysis is needed to determine ebb shoal mining impacts to navigation, inlet adjacent shoreline, ebb shoal equilibrium, and reusability of borrow area infill material. This paper is an attempt to evaluate the state-of-the-art in the practice of removing material from inlet ebb shoals and monitoring of these projects. A suggested monitoring plan for future ebb shoal mining projects is also presented.

ADDITIONAL INDEX WORDS: *Beach erosion, beach nourishment, tidal delta, longshore drift, coastal management, shore protection.*

PROBLEM STATEMENT

Removal of material from ebb and flood tidal shoals has occurred at many inlets, with ebb shoal sediment becoming the more prevalently used source of beach quality sand in recent years. This practice is referred to as shoal mining. Ebb shoal sediment, because of its accessibility and compatibility with native beach material, is used for shore protection and erosion mitigation projects as other sources of beach quality sand have become scarce. Flood shoal sediment is also used, but is usually finer and not as well-suited for beach nourishment as other sediment sources. This paper focuses on the review of projects that mined ebb shoals in order to evaluate mining impacts and determine monitoring required to assess ebb shoal mining practices.

Most ebb shoal mining projects are related to mitigating critical erosion on the downdrift side of an inlet. Other projects that have used the ebb shoal of a nearby inlet as source material include beach nourishment and shore protection projects not directly impacted by inlet processes. Ebb shoals have also been mined to provide a more direct ("straight") navigation channel. The *impacts* of removing "small" or

"large" quantities of sediment from an inlet system, however, have not been widely examined, analyzed, or quantified. Altering the sediment dynamics of an inlet system places it out of equilibrium and it is believed that an adjustment period is required to again reach equilibrium (DEAN, 1988). This affects both inlet navigability and adjacent shoreline stability. Lessons learned by *monitoring* present ebb shoal mining projects and *quantifying* the impacts will benefit future attempts to mine ebb shoals.

This paper presents available information on past ebb shoal mining events with special emphasis on the monitoring performed upon completion of the dredging. There is disparity in the level of monitoring performance from project to project. Eight ebb shoal mining projects that contain adequate documentation have been selected and reviewed for this paper. Most of the mined ebb shoals (6 of the 8) are located on the Gulf and Atlantic coasts of Florida. The remaining two ebb shoal mining projects are located in New York and New Jersey. All of these ebb shoal mining projects have been accomplished within the last 15 years, with the majority conducted since 1988. Quantification of impacts are given where available and qualitative impacts are also noted. The goal of this work is to determine future monitoring needs in order to

improve our understanding of the impacts of ebb shoal mining on an inlet system.

Ebb Shoal Mining Considerations

When considering the mining of an ebb shoal to provide sediment for a shore protection project, several questions should be addressed. Unfortunately, data required to answer these questions are frequently not planned for in the project budgeting process. Questions that should be addressed include:

● Is the ebb shoal borrow material suitable as project fill material?
● Where on the ebb shoal should the material be mined to minimize impacts to the inlet system?
● How does mining the ebb shoal positively or negatively impact navigation?
● How does mining the ebb shoal affect adjacent shoreline evolution?
● What impact does ebb shoal mining have on the entire ebb shoal system equilibrium?
● How does the ebb shoal borrow area recover and at what rate?
● Does the ebb shoal borrow area infill with the same material?

The opportunity to understand the effects of shoal mining by evaluating ebb shoal mining projects has been hampered by limited monitoring data documenting pre-project conditions and post-project system response. This lack of data has limited improvement of the engineering design process and assessment of the project performance. Regulatory concerns and design practices cannot be addressed until we have sufficient understanding of the impacts of shoal mining on the inlet system.

SHOAL MINING PROJECTS

Eight inlet ebb shoal mining data sets were found to be sufficiently complete to be reviewed. The locations of the ebb shoal mining sites are: Shinnecock Inlet, Long Island, New York; Great Egg Harbor Inlet, New Jersey; Jupiter Inlet, Florida; Boca Raton Inlet, Florida; John's Pass, Florida; Longboat Pass, Florida; New Pass (Sarasota County), Florida; and Redfish Pass, Florida (Figure 1). A brief description of each inlet's history, morphology, and processes is given in an Appendix for background information and available information on the ebb shoal mining events at each inlet is presented in this paper. Most of these projects were constructed between 1988 and 1995 and some include repeated mining episodes. The projects ranged in size from 170,000 m³ (222,400 c.y.) of material removed from the ebb shoal as Boca Raton, Florida to 6,235,000 m³ (8,155,000 c.y.) at Great Egg Harbor Inlet, New Jersey. The majority of the sand taken from the ebb shoals was placed on downdrift beaches. The sand placement beach area lengths ranged from approximately 610 m (2,000 ft) to 6.4 km (4 miles). The next section provides a summary of each of the eight ebb shoal mining projects.
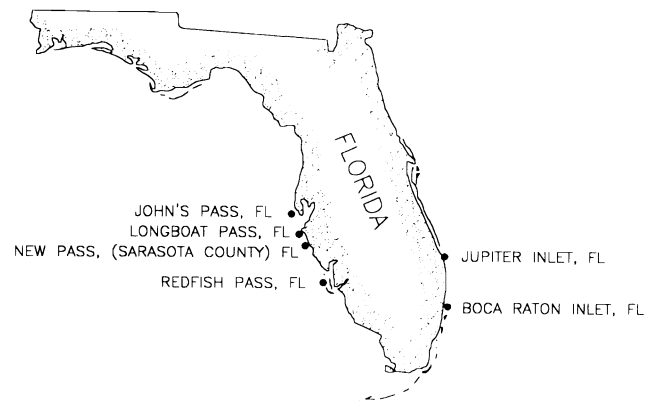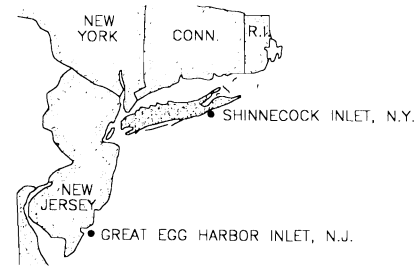

Figure 1.   Location of ebb shoal mining projects.

Shinnecock Inlet, Long Island, New York

Shinnecock Inlet is located in Southhampton, Long Island, New York, 153 km (95 miles) east of New York City and 60 km (37 miles) west of Montauk Point (Figure 2). It is the easternmost of six inlets along the barrier island known as Long Island and separates the Atlantic Ocean from Shinnecock Bay. Nautical charts exist for this general area dating back to Colonial times which indicate periodic inlet openings (shown on maps dated 1770, 1829, 1850–1890, and 1938–present) and closures (shown on maps dated 1839 and 1890–1938) (USAED NEW YORK, 1987). The hurricane of 21 September 1938 caused a breach through the barrier island to Shinnecock Bay and the formation of the present-day Shinnecock Inlet. This breach occurred at the location of an interruption in a 910-m-(3,000-ft-) long bayside, shore-parallel shoal feature, indicating the probable location of an earlier breach (USAED NEW YORK, 1987). Since the 1938 breach, local and federal interests have constructed various structures to maintain the inlet at its present location.

Ebb Shoal Morphology and Mining Events

By comparing bathymetric surveys from 1955, 1984, and 1985, the growth rate of the ebb shoal was computed to be approximately 76,500 m³/yr (100,000 c.y./yr) (USAED NEW YORK, 1987), but the overall size of the ebb shoal itself was
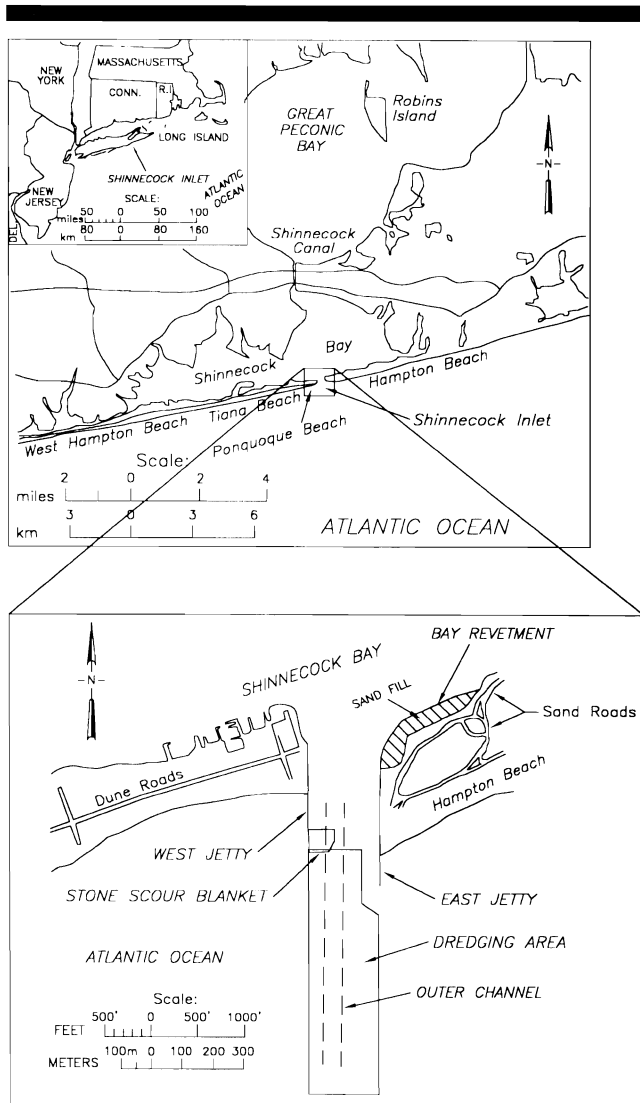
Figure 2. Location of Shinnecock Inlet, New York showing ebb shoal borrow area (after NERSESIAN and BOCAMAZO, 1992).

not computed. The ebb shoal at Shinnecock Inlet appears to be a relatively small, crescentic (wave-dominated) feature with a downdrift (westerly) asymmetry that encompasses the area of the design navigation channel. This configuration makes navigation difficult and dangerous. To use the natural channel on the southwest side of the inlet, vessels approach the inlet at an unsafe angle to incoming waves. The other choice is navigation through the design navigation channel, which is usually over the shallow depths of the ebb shoal with breaking waves.

Shoaling of the navigation channel and the configuration of the ebb shoal at Shinnecock Inlet have created a treacherous navigation path for fishing vessels. Only the most experienced captains will attempt to navigate the inlet on a "normal" day. Pleasure craft can only navigate the inlet on "calm" days. The Corps of Engineers performed an emergency

dredging operation at Shinnecock Inlet in 1984 (removing 123,900 m³ (162,000 c.y.) of material) to bring the inlet to a navigable depth. In 1990 and 1993 a total of 802,800 m³ (1,050,000 c.y.) of material was removed from the deposition basin which extends over a portion of the ebb shoal (Figure 2). The estimated infilling rate for this area was calculated using the transport ratio method and indicated that the deposition basin had a capacity of 351,700 m³ (460,000 c.y.), requiring dredging every 1.5 years (USAED NEW YORK, 1987). Monitoring of the 1990 and 1993 ebb shoal mining events consisted of hydrographic surveys of the borrow area yearly since 1989, a Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system survey of the entire inlet/ebb shoal system in July 1994; and yearly beach profile surveys west of Shinnecock Inlet.

Project Summary

The ebb shoal at Shinnecock Inlet was growing across the design navigation channel causing a hazard to navigation. Material was removed from the updrift side of the ebb shoal to "straighten" the navigation channel. Two shoal mining events were conducted and the sand was placed on the downdrift beach, stockpiled on the updrift beach, in the scour hole at the west jetty tip, and in the surf zone west of Shinnecock Inlet. The removal of a total of 802,800 m³ (1,050,000 c.y.) of material from the ebb shoal and navigation channel at Shinnecock Inlet in a three year period may have placed the inlet system in a non-equilibrium (sand deficient) condition. In DEAN (1988), the sand sharing system concept is discussed, suggesting that at tidal inlets, the ebb shoal is connected to and in balance with the adjacent shorelines. Any removal of sand from an inlet system lowers the elevation of that portion of the system, resulting in a flow of sand to restore local equilibrium.

The adjacent shorelines west *and* east of Shinnecock Inlet are eroding. The area east of Shinnecock Inlet had been accretional prior to the dredging events. However, based on monitoring surveys of the deposition basin (only), material is *not* accumulating in the deposition basin at the expected rate of 229,400 m³/yr (300,000 c.y/yr). The infilling rate is estimated to be closer to 51,200–61,200 m³/yr (67,000–80,000 c.y./yr) based on the yearly monitoring surveys (NERSESIAN, *personal communication*). This infilling rate is closer to the estimated shoal growth rate of 76,500 m³/yr (100,000 c.y./yr), not the expected infilling rate of 229,400 m³/yr (300,000 c.y./yr) based on transport volume estimates. Presently, it is not known where the material from the adjacent shorelines is redepositing. Perhaps the entire ebb shoal (which extends west of the deposition basin) is gaining a thin/thick veneer from the material lost from the east/west adjacent beaches. Another possibility is that the navigation channel dredged through part of the ebb shoal is more efficient and the material entrained in the ebb jet is being deposited further offshore.

Analysis of the SHOALS survey of Shinnecock Inlet conducted in 1994, including the ebb shoal, should provide an estimate of the present volume of the ebb shoal. The growth rate of the entire ebb shoal and the infilling rate of the deposition basin can be attained with analysis of repeated SHOALS or hydrographic surveys. Comparison of the present
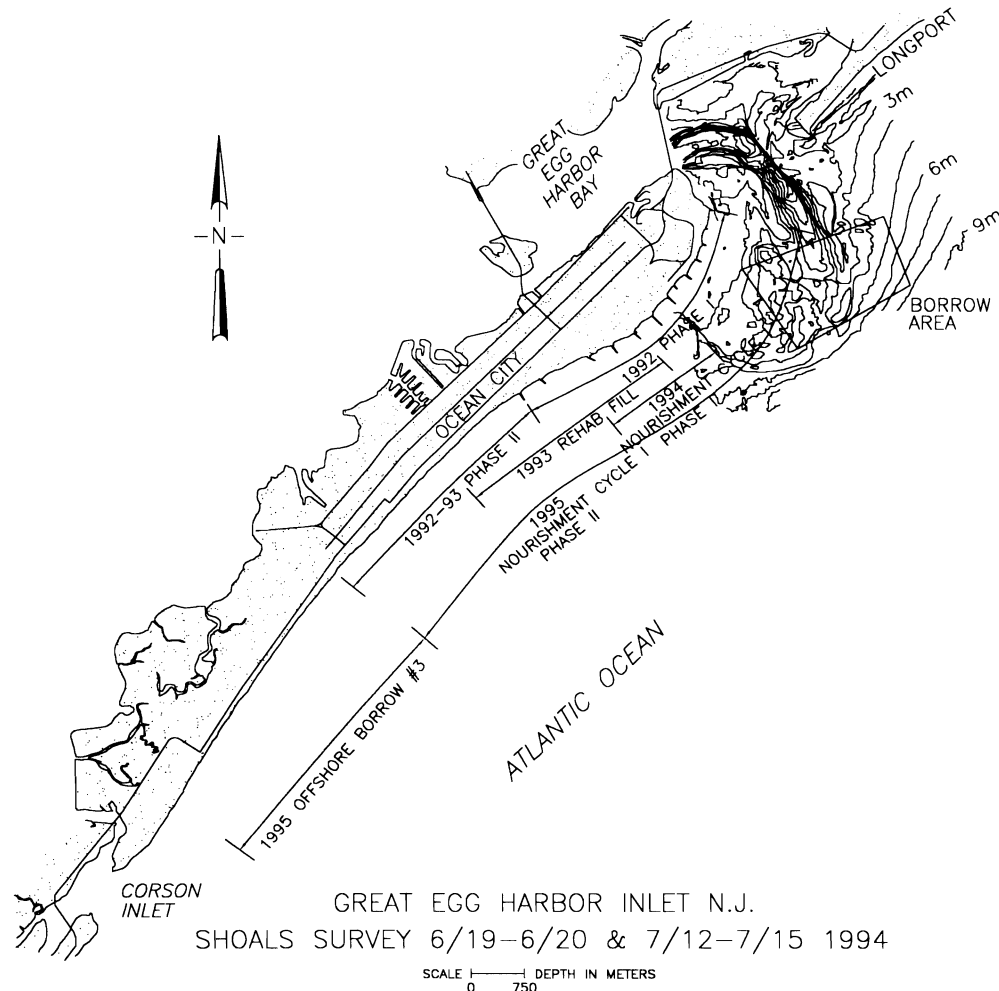
Figure 3. Location map of the ebb shoal, borrow area, and part of the fill placement area at Great Egg Harbor Inlet, New Jersey. The bathymetry data was collected by the SHOALS system.

ebb shoal volume to the equilibrium volume (calculated using the relationships proposed by WALTON and ADAMS (1976)) should provide an estimate of the equilibrium or non-equilibrium condition existing at Shinnecock Inlet. In addition, the gross and net longshore transport rates estimates need to be checked and verified or adjusted. It is clear that more detailed monitoring of this site is critical.

Great Egg Harbor Inlet, New Jersey

Great Egg Harbor Inlet is located about 16 km (10 miles) south of Atlantic City, New Jersey on the southern New Jersey coast (Figure 3). The inlet has a downdrift offset morphology, separating two barrier islands (Absecon Island and Pecks Beach). The Town of Longport occupies a narrow spit to the north, and the Town of Ocean City occupies the entire drumstick barrier island to the south. A natural inlet has existed in the vicinity of the present day Great Egg Harbor Inlet since at least the 1700's. From historic shoreline maps dating around 1840, there were two inlets with an island in

the center. By 1886 the northern spit grew to the south, closing the northern inlet. The inlet migrated to the north with growth of the southern spit, and by 1891, created the narrowest, historical throat width of approximately 610 m (2,000 ft). From 1899 to 1904, the inlet widened with continuing retreat of the northern spit. By 1920 the inlet widened and migrated north, with erosion of the northern spit and deposition on the southern shoreline. With continued fluctuation of the inlet adjacent shoreline, 20 groins were constructed between 1930 and 1960 at several locations in Ocean City, 12 of which are along the inlet adjacent shoreline. These groins have been modified since initial construction. A terminal groin was constructed at Longport to stabilize the north end of the inlet shoreline at about the same time as the first groins were constructed at Ocean City. Although the long term trend is northward migration of the inlet, erosion of the southern inlet adjacent shoreline occurred around 1979 due to southern migration of the main inlet ebb channel. This resulted in the placement of beach fill and 2 timber and stone groins on the south inlet adjacent shoreline.

Ebb Shoal Morphology and Mining Events

The ebb shoal at Great Egg Harbor Inlet has a wave-dominated form based on a classification by GIBEAUT and DAVIS (1993). The large ebb shoal is the dominant feature of the inlet with an asymmetrical, downdrift shape. The ebb shoal volume was estimated as 56,630,000 m³ (74,070,000 c.y.) by DOMBROWSKI (1994). There is no identifiable flood shoal, as the inlet opens into the marsh-filled area of Great Egg Harbor Bay. Two small shoals are located bayward of Longport on the north side of the inlet and shoals associated with the Rainbow Islands are located bayward of Ocean City. The main thalweg of the inlet is relatively straight between the two barrier islands, but curves to the south as it enters the bay. On the ocean side, the main ebb channel curves to the south as it enters the Atlantic Ocean.

Due to continued erosion of the Ocean City beachfront, another beach nourishment project was initiated in 1992, with the borrow material source being the south, seaward portion of the ebb shoal. Phase I of the project was constructed from February to October 1992, placing 1,988,000 m³ (2,600,000 c.y.) of material from Seaspray Road adjacent to the inlet, extending to the south to 15th Street. Phase II of the project placed 2,064,000 m³ (2,700,000 c.y.) of ebb shoal sediment from 16th Street southward to the southern limit of the project at 36th Street during the October 1992 to March 1993 time period. In December 1992, a severe storm eroded the newly placed beach fill, requiring a rehabilitation of the Phase I and II beach fill. From June to September 1993, the rehabilitation fill was pumped onto the beach between 5th and 23rd Streets. The placement of 646,000 m³ (845,000 c.y.) of ebb shoal sand on the beach was to serve as a storm erosion mitigation measure, covering the severely eroded areas of the center city beaches. In order to maintain project dimensions of berm height and width, a third beach fill (called Nourishment Cycle I, Phase I) was placed on the beaches between 1st and 11th Streets from October to December 1994, using an additional volume of 459,000 m³ (600,000 c.y.) of material dredged from the ebb shoal borrow area. Continued erosion of the Ocean City beaches required a fourth beach nourishment (Nourishment Cycle I, Phase II) from June to August 1995. The same ebb shoal borrow area used for the three previous beach nourishments supplied 1,078,000 m³ (1,410,000 c.y.) of material, that was again placed on the entire project length from Seaspray Rd to 36th Street. Additional fill was dredged from an offshore shoal (Borrow Area 3) and placed on the southern end of the island from 36th Street to 59th Street during the same period. All project data were supplied by Messers Jeff Gebert and Keith Watson, U.S. Army Engineer District, Philadelphia.

DOMBROWSKI (1994) estimated the volume of the entire ebb shoal to be 56,630,000 m³ (74,070,000 c.y.), but no volume estimate was available for the designated borrow area shown in Figure 3. Bathymetric surveys collected in June/July 1994, December 1994, and March 1995 indicate that different areas of the borrow area have been dredged for each of the four fills. Beach profiles are available from monitoring of the beach fill projects. Sediment data from the beach and borrow area were collected in 1986. The inlet throat composite mean

was reported as 0.25 mm (2.0 φ), with a standard deviation (sorting) of 0.27 φ (WEGGEL et al., 1986) and samples collected only in the borrow area had a composite mean of 0.19 mm (2.36 φ), and sorting of 0.59 φ (PHILADELPHIA DISTRICT, personal communication). A historic native beach composite for Ocean City was reported by McMASTER (1954) as having a mean of 0.18 mm (2.54 φ), and a sorting value of 0.37 φ. The project native mean was reported by WEGGEL et al. (1995) as 0.16 mm (2.64 φ), with a sorting of 0.46 φ.

Project Summary

The Great Egg Harbor Inlet ebb shoal has been mined three times to supply sand for the Ocean City Shore Protection Study and was mined for a fourth time in 1995. Material was removed from the designated borrow area at the seaward edge of the ebb shoal and placed on the downdrift beach to provide shore protection to Ocean City. The beaches of Ocean City have long been in an erosional state. Although the placement of material has provided storm protection, the beaches of Ocean City continue to erode. It is anticipated that this project will need frequent renourishment.

Preliminary analysis of this project performance is reported in WEGGEL et al. (1995). It is hoped that this project will be monitored for the long term, as the fourth (1995) ebb shoal mining/beach nourishment has only recently been completed. Monitoring is necessary in order to determine the recovery of the borrow area and the response of the adjacent beaches. Monitoring data that can be analyzed further include beach profiles, borrow area bathymetric surveys, aerial photography and possibly sediment samples. Analysis of these data will give borrow area infilling rates, sediment suitability, and adjacent beach response. Understanding the "big picture" of the inlet shoal and adjacent beach interaction should benefit future engineering activities at this project site.

Jupiter Inlet, Florida

Jupiter Inlet is the northernmost inlet in Palm Beach County, located on the southeast coast of Florida, around 160 km (100 miles) north of Miami. The inlet connects the Loxahatchee River and southern portion of the Indian River Lagoon system (Hobe Sound to Jupiter Sound) with the Atlantic Ocean. The present inlet throat and estuary has a west-northwest orientation, with an elongated bay area that is the intersection of five estuarine water bodies: 1) Jupiter Sound to the north, 2) the Loxahatchee River North Fork, 3) the main branch of the Loxahatchee River, 4) the Southwest Fork to the west, and 5) the dredged Intracoastal Waterway canal (Lake Worth Creek) to the south. The flood tidal shoal is also elongated, extending into the estuary past the U.S. 1 highway bridge (Figure 4). The inlet bisects two long, narrow barrier islands, Jupiter Island to the north, and an original mainland beach that was dredged to create the Intracoastal Waterway connecting the Loxahatchee River with Lake Worth in the vicinity of Juno Beach to the south. At present, the inlet has an updrift offset configuration.
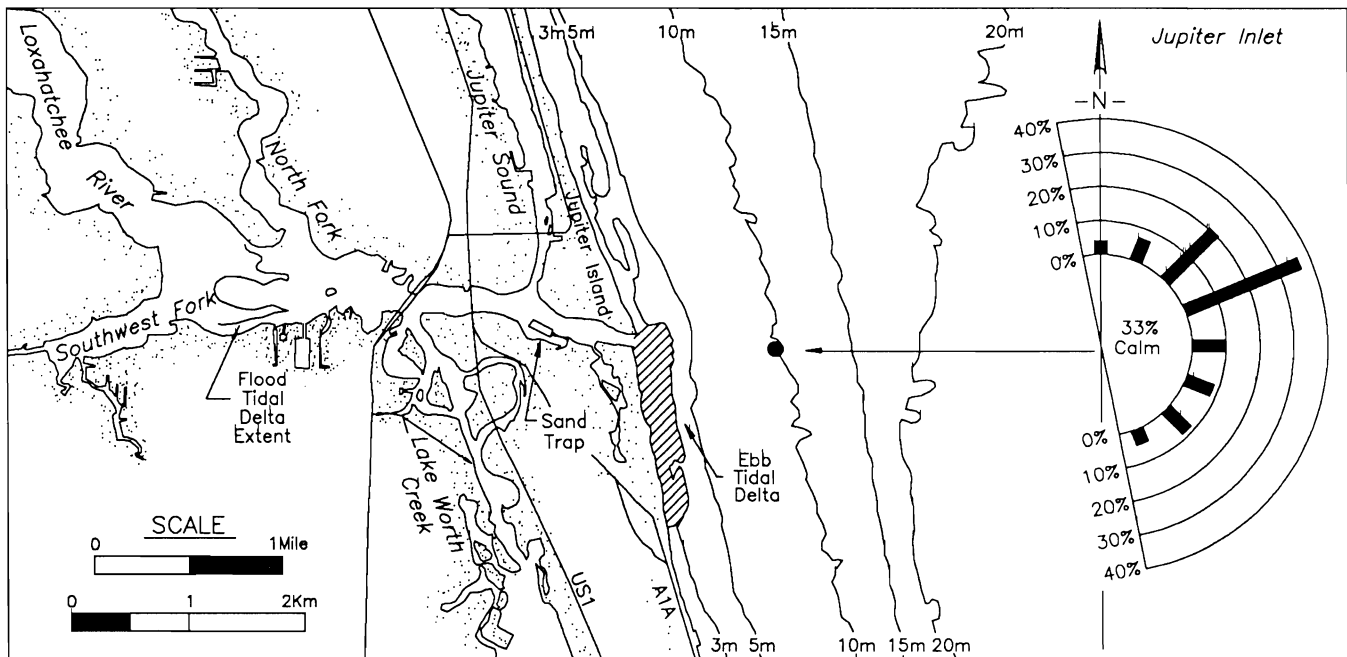
Figure 4. Location map of Jupiter Inlet, Florida showing the configuration of the channel and tidal shoals, with a wave rose based on new WIS data (from STAUBLE, 1993).

Ebb Shoal Morphology and Mining Events

The ebb tidal shoal is small and crescentic, with a down-drift asymmetry and channel axis in a southeasterly direction (Figure 5). The length of the ebb shoal (measured from the throat toward the offshore) is approximately 610 m (2,000 ft) and the width measured in the longshore direction is approximately 1,700 m (5,650 ft). The ebb shoal is a mixed-energy, wave-dominated shoal form, based on the GIBEAUT and DA-VIS (1993) classification. The estimated ebb shoal volume ranges widely from 200,000–300,000 m³ (262,000–392,000 c.y.) (BODGE and ROSEN, 1988; MARINO and MEHTA, 1986), to 765,000 m³ (1,000,000 c.y.) (DOMBROWSKI, 1994), to 382,000–765,000 m³ (500,000–1,000,000 c.y.) (MEHTA et al., 1992). MEHTA et al. (1992) suggest that the ebb shoal at Jupiter Inlet undergoes a decadal oscillation in sand volume, with low sand volumes during storm conditions and larger volumes during periods of low waves.

In April–May 1995, the ebb shoal at Jupiter Inlet was dredged. This ebb shoal mining project was designed to alleviate erosion of the beach on the downdrift (southern) shoreline. The Jupiter/Carlin Shore Protection Project supplied sand from the ebb shoal to the downdrift beaches, thus providing shore protection to this area from storm erosion. This sand source is in addition to the more-or-less annual dredging of the bayside sand trap and Intracoastal Waterway. The net longshore transport rate is estimated to be 176,000 m³/yr (230,200 c.y./yr) to the south. Natural sand bypassing accounts for 132,000 m³/yr (172,600 c.y./yr), mechanical bypassing from the sand trap accounts for 33,000 m³/yr (43,200 c.y./yr), and the remaining 11,000 m³/yr (14,400 c.y./yr) represents a deficit to the downdrift

shoreline (DOMBROWSKI and MEHTA, 1993). To mitigate for this deficit, the ebb shoal was mined. The ebb shoal material placed as beach fill was intended to act as a feeder beach along a 1.7 km (1.1 miles) stretch between Department of Natural Resources (DNR) benchmarks R13 and T19 including Carlin Park (Figure 5). A total of 374,600 m³ (490,000 c.y.) was proposed to be used for beach fill, and the remaining 7,700 m³ (10,000 c.y.) was to be used to restore the dunes between DNR benchmarks R19 and R29 for a total of 382,300 m³ (500,000 c.y.) (PALM BEACH COUNTY, 1995). However, the total ebb shoal volume placed on the downdrift beach was larger (461,000 m³ (603,000 c.y.)) because the borrow material was finer than the native beach sand (TRACY LOGUE, Palm Beach County, personal communication). The design included a 61- to 76-m-(200- to 250-ft-) beach width and a berm elevation of +2.7 m (+9 ft) National Geodetic Vertical Datum 1929 (NGVD). Additional material was placed on the northern end of the project from concurrent maintenance dredging of the Jupiter Inlet navigation channel. Dredging was limited to the seaward side of the ebb shoal (Figure 5). The dimensions of the borrow area are 95 m (310 ft) wide on the north end by 700 m (2,300 ft) in the alongshore direction, by 247 m (810 ft) wide on the south end. Most of the fill was dredged from the southern half of the borrow area. Post-construction monitoring of the beach sediment indicated that the sand dredged from the borrow had a composite mean of 0.18–0.21 mm (2.44–2.28 φ).

Project Summary

The purpose of the ebb shoal mining project at Jupiter Inlet was to bypass sediment to the eroding downdrift shoreline.
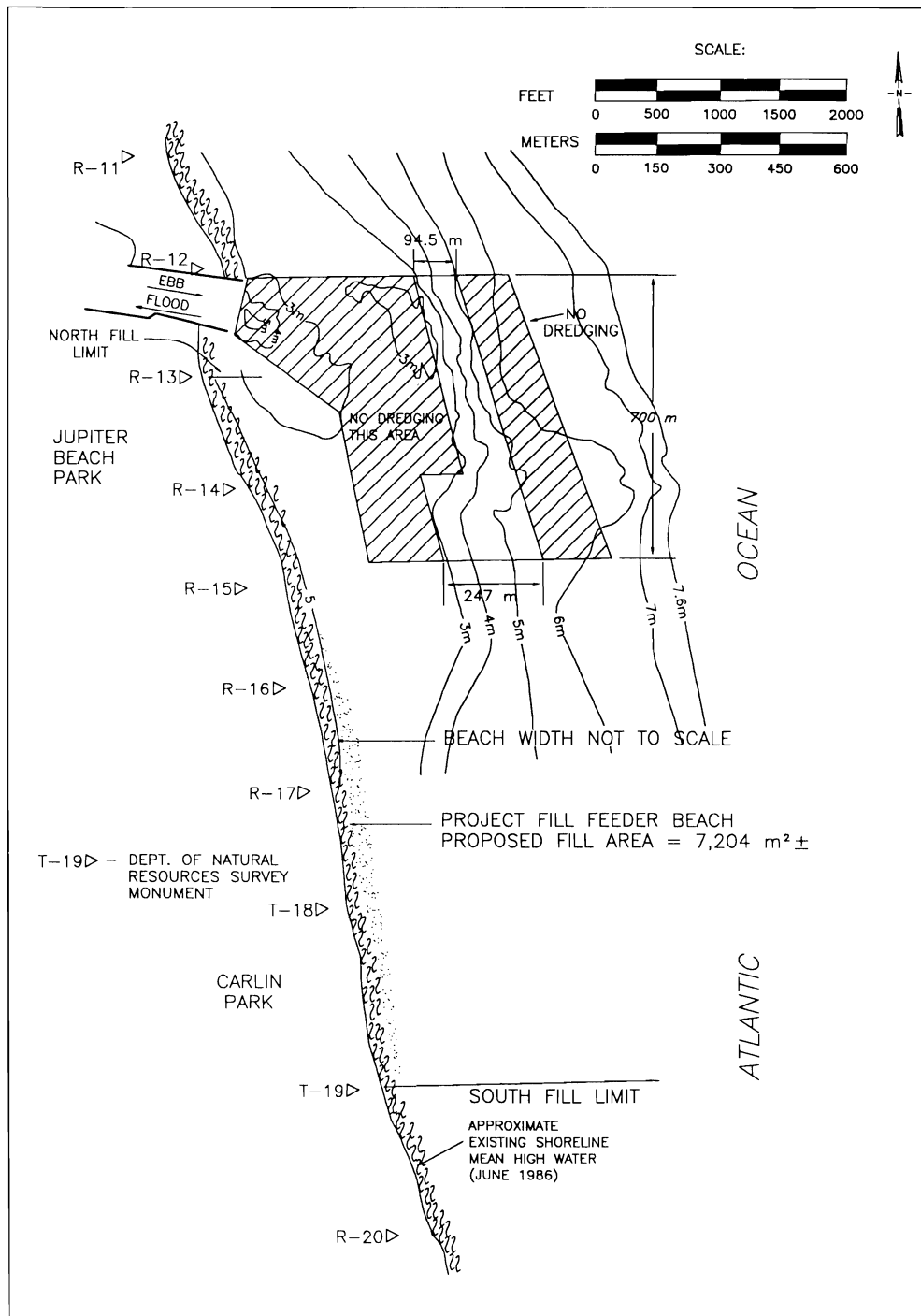
Figure 5. Bathymetry map, borrow area, and fill placement area at Jupiter Inlet (after PALM BEACH COUNTY, 1995).

Sand was dredged from the designated borrow area located near the seaward end of the ebb shoal. The outer edge of the ebb shoal is in close proximity to a reef and therefore was not dredged due to environmental concerns. The sand was placed on the downdrift beaches, including two park areas.

Monitoring of this project by Palm Beach County will be conducted for a one year period which started after project completion. Monitoring of the project includes beach profiles of the beach nourishment area (pre- and post-fill placement, and six and twelve months after fill placement), bathymetric surveys of the borrow area on the outer edge of the ebb shoal (pre-dredging, post-dredging and at one year), and possibly
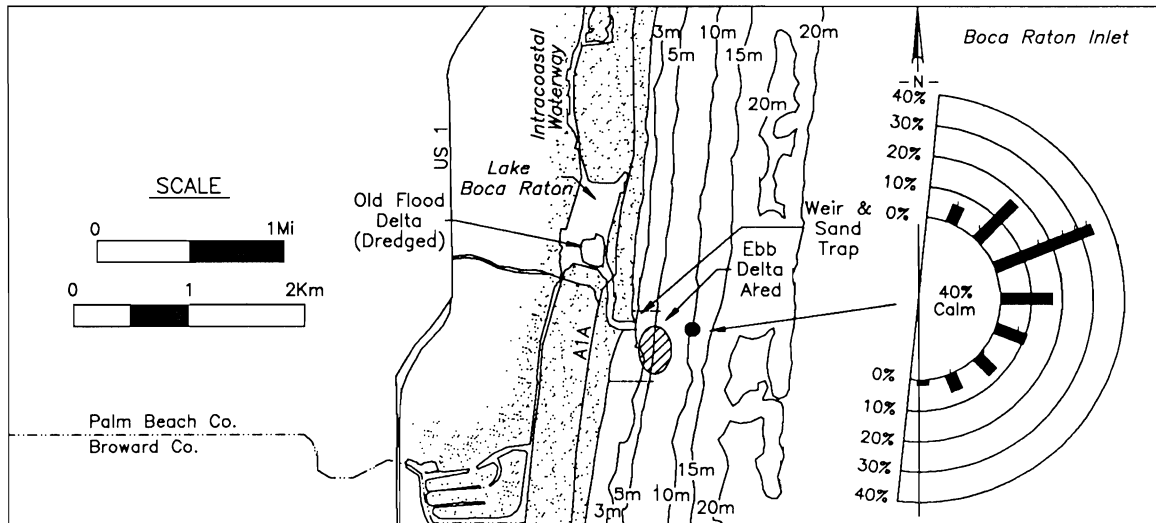
Figure 6. Location map of Boca Raton Inlet, Florida showing the configuration of the channel and tidal shoals, with a wave rose based on new WIS data (from STAUBLE, 1993).

sediment samples from the beach and borrow area. Dredged volumes, fill placement volumes, and fill and borrow area adjustments can be calculated from these data. Annual aerial photographs of the project will also be taken and can be used to assess shoreline and inlet change.

Boca Raton Inlet, Florida

Boca Raton Inlet is located in southern Palm Beach County, 64 km (40 miles) south of the City of Palm Beach. Boca Raton Inlet is a naturally occurring inlet that has frequently closed prior to the construction of two jetties and repeated channel dredgings. The inlet connects Lake Boca Raton with the Atlantic Ocean through a curved throat section that is shore-normal at the oceanward end and then trends northward around 183 m (600 ft) to the lake (Figure 6). The inlet width at the throat section is around 53 m (174 ft). The curved channel shoreline is armored, creating a fixed inlet width of approximately 67 m (220 ft). With jetty construction, an updrift offset of around 60 m (197 ft) developed as sand was trapped by the north jetty creating an accretional fillet. Erosion of the downdrift shoreline (South Inlet Park) enhanced the offset.

Ebb Shoal Morphology and Mining Events

The curved inlet throat at Boca Raton Inlet enters the southeast corner of the rectangular Lake Boca Raton and a flood tidal shoal was present in the Lake in a 1945 aerial photograph. Subsequent photographs indicate that the flood shoal has been removed by dredging to maintain navigation. A small ebb shoal of crescentic shape at the mouth of the jetties extended around 198 m (650 ft) offshore prior to jetty extension in 1975 and is now located off the seaward end of the south jetty and trends alongshore to the south around 579 m (1,900 ft) (STAUBLE, 1993). The small, crescentic-

shaped ebb shoal has a mixed-energy, wave-dominated shoal form, with a downdrift asymmetry. The main navigation channel curves to the downdrift side of the shoal, presenting a problem to inlet navigation.

The South Boca Raton Beach Restoration Project conducted in 1985 included the mining of sand from the ebb shoal and placement on the downdrift beach. There were two main purposes for this ebb shoal mining project: 1) to provide safe navigation over the growing ebb shoal and 2) to restore the eroding south beach (WALTHER and DOUGLAS, 1993). The ebb shoal was located offshore and southeast of the inlet throat, accreting after the extension of the north jetty in 1975, and eventually became a navigation hazard. The volume of sand mined from the shoal was 170,000 m^3 (221,000 c.y.) (COASTAL PLANNING AND ENGINEERING, 1992a). The borrow area dimensions encompassed almost the entire shoal (415 m by 137 m) (Figure 7). Pre-dredge depths over the shoal were −3.1 m (−12 ft) and post-dredge depths reduced the shoal to −6.1 m (−20 ft) (WALTHER and DOUGLAS, 1993). The sand was placed along 884 m (2900 ft) of shoreline south of the south jetty (COASTAL PLANNING AND ENGINEERING, 1992a). Another ebb shoal mining event was planned for Boca Raton Inlet in the fall of 1995 (PALM BEACH COUNTY, *personal communication*).

Between August 1985 and October 1990, six monitoring surveys of the ebb shoal have been performed, providing information on the infilling rate of the borrow site (COASTAL PLANNING AND ENGINEERING, 1992a). Around 66% of the shoal was recovered during this period (WALTHER and DOUGLAS, 1993). A 1990 survey indicated that the shoal depth had reached −2 m (−6 ft) in some areas, filling the borrow area and again presenting a hazard to navigation (Figure 8). Even with construction of the weir section in the north jetty, the ebb shoal has continued to receive sand, filling the borrow area and returning the ebb shoal close to its pre-dredge vol-
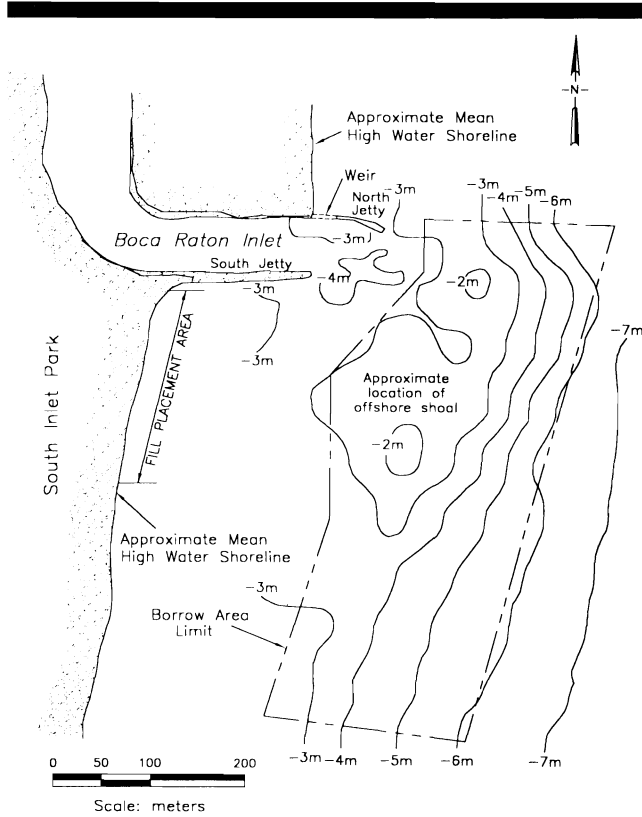
Figure 7. Pre-dredge bathymetry, borrow area, and fill-placement location at Boca Raton Inlet (after WALTHER and DOUGLAS, 1993).
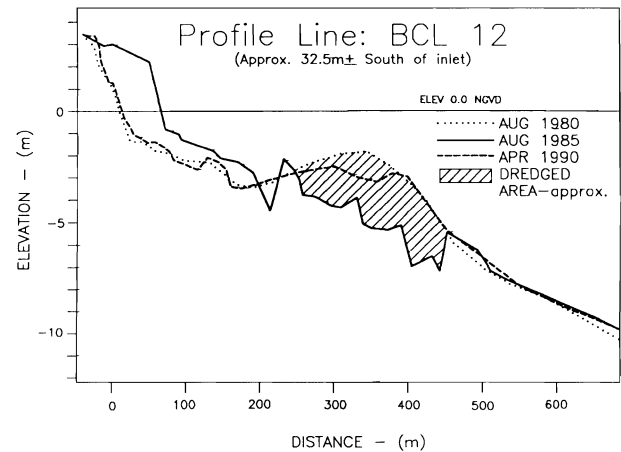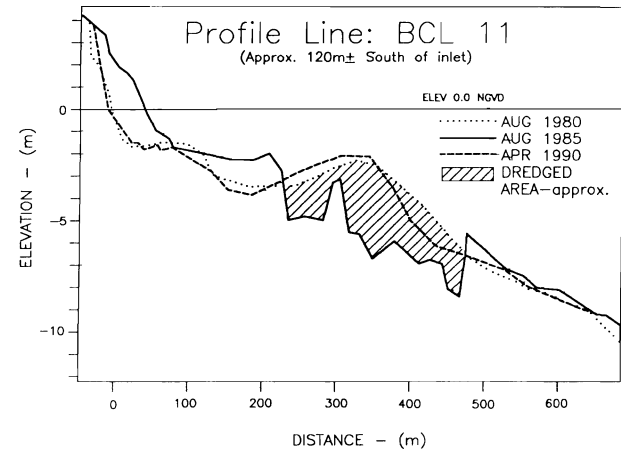

Figure 8. Profiles across the borrow area at Boca Raton Inlet showing pre- and post-dredging and five year infilling (from WALTHER and DOUGLAS, 1993).

ume. There appears to be little adverse impact from mining the shoal, which acts as a sink and is recovering.

Project Summary

Boca Raton Inlet has blocked longshore drift causing downdrift erosion. Since the north jetty extension in 1975, the north fillet has continued to grow, sand has moved to the ebb shoal, and the downdrift beach has continued to recede. The growth of the ebb shoal also created a navigation problem since the channel was positioned through the location of the ebb shoal. To mitigate this problem, a sand bypass system was established to dredge sand from a sand trap inside of the north jetty. In addition, shoal mining in 1985 removed nearly the entire shoal and placed it on the downdrift beach. This provided sand to the downdrift beach to supplement the dredging of the sand trap and other parts of the channel. The recovery of the shoal indicates that sand is still being deposited in the ebb shoal area.

Additional monitoring of the south beach fill placement area and the ebb shoal recovery is needed. Monitoring any new mining events should provide additional data to assess the impact of ebb shoal mining on the inlet system. The apparent recovery of 66% of the shoal in a 5 year period indicates that this shoal may be a continuing source for sand for borrow material.

John's Pass, Florida

John's Pass is located in Pinellas County on the west (Gulf of Mexico) coast of Florida (Figure 9). The Pass serves as a link between northern Boca Ciega Bay and the Gulf of Mexico for commercial fishing boats and pleasure craft, and separates Sand Key to the north from Treasure Island to the south. John's Pass was formed during the September 1848 hurricane and was named for John Levique, a local fisherman and grove owner (FULLER, 1955). (This hurricane also formed New Pass to the south.) Prior to this 80- to 100-year hurricane, small inlet openings and closures were common. Since this event, the inlet channel has remained fairly stable, only moving 100 m (330 ft) in about 100 years and requiring a relatively small amount of maintenance dredging.

Shoal Morphology and Ebb Shoal Mining Events

The flood shoal at John's Pass is large, vegetated, and very stable (DAVIS and GIBEAUT, 1990). MEHTA et al. (1976) computed the volume of the ebb shoal from 1951–1952 boat
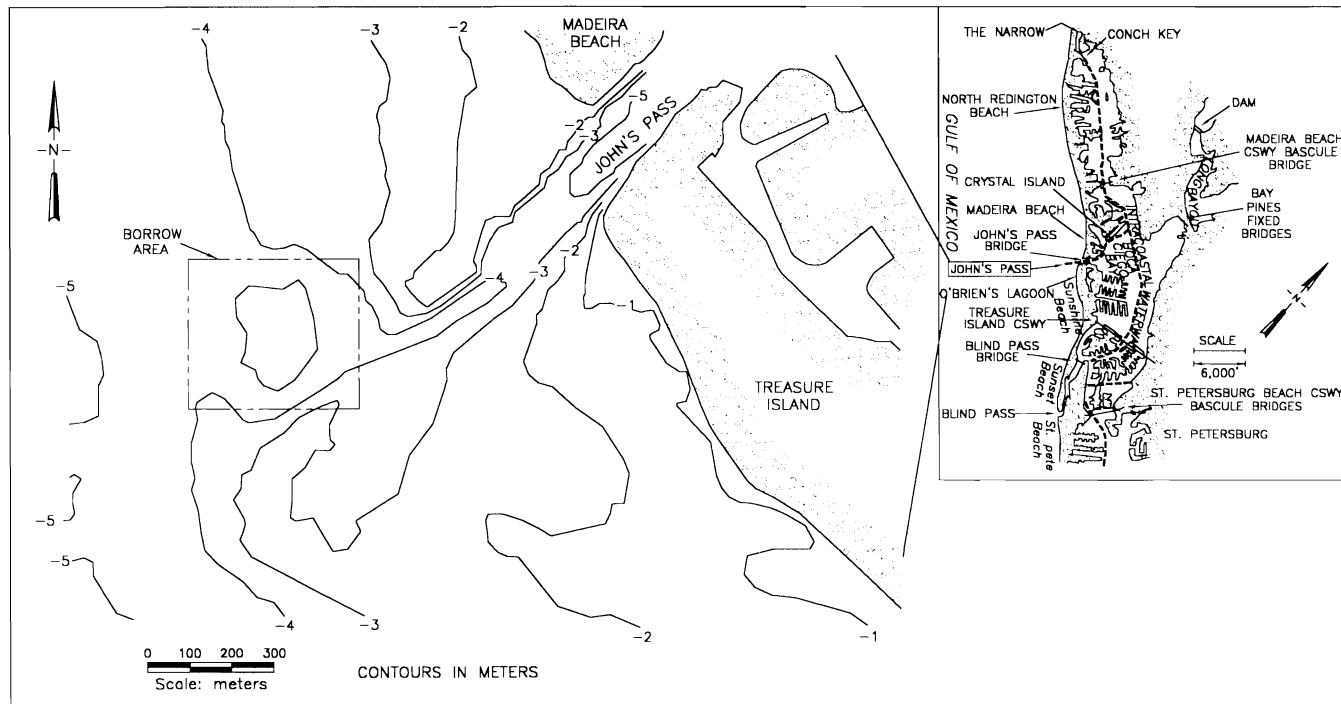
Figure 9. Location of John's Pass, Florida (after MEHTA *et al.*, 1976) showing ebb shoal borrow area (after WALTHER and DOUGLAS, 1993).

sheets of John's Pass using the methods of DEAN and WALTON (1973). The ebb shoal volume was approximated to be 4.6–5.4 × 10⁶ m³ (6–7 × 10⁶ c.y.).

The large ebb shoal at John's Pass was dredged in 1988 for the Sand Key Phase II nourishment project at Redington Shores. Approximately 407,300 m³ (532,800 c.y.) of material was placed on the beach at Sand Key in June 1988 (DEAN and LIN, 1990). The borrow area covered 165,950 m² (1,786,000 ft²) and was dredged from an average depth of 4 m to 6.5 m (datum not specified) (WALTHER and DOUGLAS, 1993) (Figure 9). The shoaling rate in the ebb shoal borrow area was approximated by comparing a 1988 pre-dredge survey with a 1992 post-dredge survey (COASTAL TECHNOLOGY CORPORATION, 1993). The average borrow area shoaling rate computed was 24,000 m³/yr (31,400 c.y./yr).

Project Summary

The ebb shoal at John's Pass was dredged to nourish the beach at Redington Shores. This project was unique in that the material was barged a long distance from the inlet and placed in an updrift location. The borrow area was on the outer edge of the ebb shoal, on the updrift side of the navigation channel. Little documentation of the borrow area recovery is readily available for this project. Further review of available literature and actual data is needed to determine the effects of this mining project on the inlet system. Because this inlet shoal was one of only two inlets that nourished updrift beaches, and the only inlet where the placement area was removed from the adjacent inlet shoreline, it presents an

interesting application of ebb shoal mining which merits further investigation.

Longboat Pass, Florida

Longboat Pass is located in southwest Florida along the Gulf of Mexico coast, 11 km (7 miles) south of the Tampa Bay entrance, in Manatee County, Florida (Figure 10). The pass connects the north end of Sarasota Bay, a large shallow lagoon, with the Gulf of Mexico and separates the long, narrow barrier islands of Anna Maria Island on the north and Longboat Key on the south. The pass is a straight, slightly downdrift offset inlet and is classified as a mixed-energy, tide-dominated inlet (GIBEAUT and DAVIS, 1993). During the late 1800's, the inlet had a more straight, wave-dominated to mixed-energy configuration (DAVIS and GIBEAUT, 1990).

Ebb Shoal Morphology and Mining Events

The ebb shoal shape at Longboat Pass is elongated gulfward, with an asymmetry to the south. The navigation channel is also offset to the south (Figure 10). The ebb shoal influence extends 1,830 m (6,000 ft) northward along Anna Maria Island and 3,200 m (10,500 ft) southward along Longboat Key (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). The total width of the ebb shoal is 5,030 m (16,500 ft) in the alongshore direction. The shoal extends 1,524 m (5000 ft) gulfward, based on the position of the 5.5 m (18 ft) depth contour. Depths range from 1 to 8 m (3 to 26 ft) over the ebb shoal. The flood shoal contains multiple lobes, formed by multiple
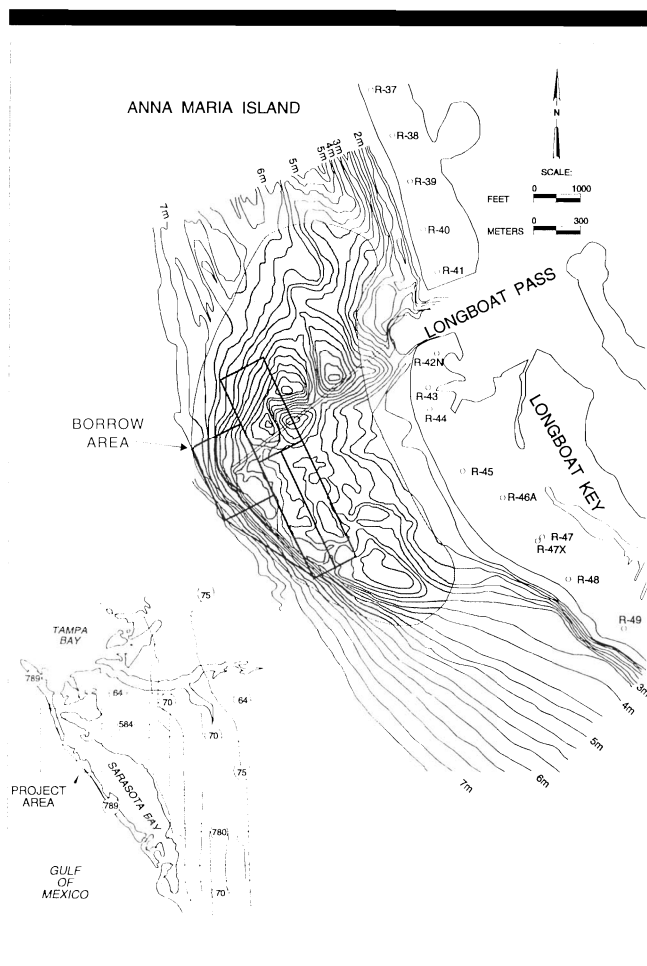
Figure 10. Location map of Longboat Pass ebb shoal, borrow area, and profile monuments (after APPLIED TECHNOLOGY AND MANAGEMENT, 1992).

Figure 11. Longboat Key project limits (after APPLIED TECHNOLOGY AND MANAGEMENT, 1993c).

breaches in the barrier island in the last 100 years (DAVIS and GIBEAUT, 1990). The volume of the ebb shoal was estimated in 1982 as 6.2×10^6 m³ (8.1×10^6 c.y.), and the flood shoal volume was estimated as 1.1×10^6 m³ (1.5×10^6 c.y.) (DEAN and O'BRIEN, 1987a). The total ebb shoal volume was estimated to be 4.9–5.1×10^6 m³ (6.4–6.6×10^6 c.y.) in 1990 (APPLIED TECHNOLOGY AND MANAGEMENT, *personal communication*). Fifty percent of this ebb shoal volume was located deeper than the -2.7-m- (-9-ft-) contour.

A long-term ebb shoal growth rate was estimated as 76,500–103,200 m³/yr (100,000–135,000 c.y./yr). (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). As reported in APPLIED TECHNOLOGY AND MANAGEMENT (1992), it was estimated that the ebb shoal in its pre-mining shoal condition impounded 36,000 m³/yr (47,000 c.y./yr) and 30,600 m³/yr (40,000 c.y./yr) was bypassed. Shoaling rates on the ebb shoal observed from bathymetric survey analysis indicated that in 1982 the ebb shoal growth rate was 61,200 m³/yr (80,000 c.y./yr). In 1985, the shoal growth rate slowed to 11,600 m³/yr (15,200 c.y./yr), and in 1990 a shoal growth rate of 30,600
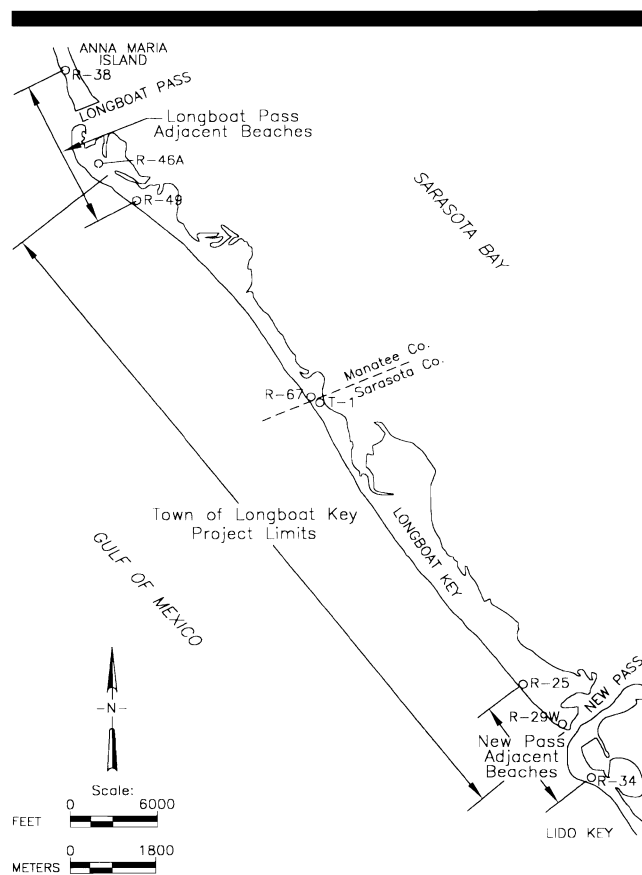
m³/yr (40,000 c.y./yr) was reported (APPLIED TECHNOLOGY AND MANAGEMENT, 1992).

The 1993 shoal mining/beach nourishment project for Longboat Pass/Longboat Key was designed to remove the outer area of the ebb shoal with an average cut depth of -6.4 m (-21 ft) (Figure 10). The purpose of the beach nourishment project was to provide shore protection to the eroding Longboat Key beaches. Sand was mined from the Pass to nourish the northern end of Longboat Key. The borrow source for the southern part of Longboat Key was the ebb shoal at New Pass (to the south of the project), as will be discussed in the next section (Figure 11). The Longboat Pass borrow area covered 554,400 m² (137 acres) of the outer portion of the ebb shoal. Studies on the use of the ebb shoal as a viable source of sand indicated that the shoal was a sand sink in the sediment budget, with an estimated average annual growth rate of 76,500–103,200 m³ (100,000–135,000 c.y.) (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). They estimated that the borrow area would fill at a rate of 91,800 m³/yr (120,000 c.y./yr). The 1988–1993 ebb shoal change (pre-mining) indicated that 1) the shore-perpendicular bar at the south end of Anna Maria Island migrated southward, 2) there was an area of erosion at the southeast corner of the ebb shoal, and 3) the outer edge of the ebb shoal was an area of accretion (APPLIED TECHNOLOGY AND MANAGEMENT, 1993a).
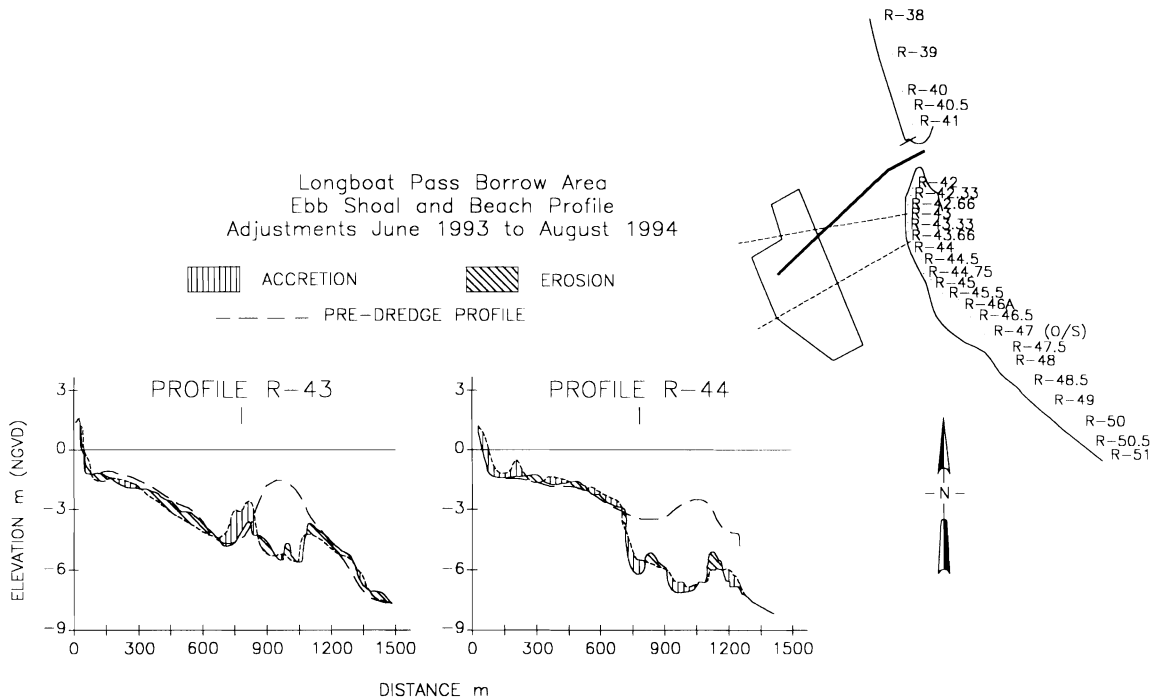
Figure 12.   Profiles across borrow area showing dredged area and 1-year adjustments (K. ERICKSON, *personal communication*).

From June to August 1993, 1,500,000 m³ (1,980,000 c.y.) was dredged from the ebb shoal at Longboat Pass. The fill was placed on Longboat Key as part of the beach restoration project (APPLIED TECHNOLOGY AND MANAGEMENT, 1993c). Monitoring of the project included bathymetric surveys, beach profiles, aerial photography, and sediment samples. Pre-dredge bathymetric surveys were taken in early June 1993 and post-dredge surveys were taken in August 1993 and August 1994. As part of the Longboat Key Beach Restoration Project, beach profiles were collected in December 1992 (pre-fill) and 1993 (post-fill) using DNR and intermediate Applied Technology and Management monuments (APPLIED TECHNOLOGY AND MANAGEMENT, 1993c). Sediment data were collected in 1989 to assess pre-dredging sediment grain sizes. Six vibracores were collected. Two additional cores were collected by the Jacksonville District in 1978 and 1988 and were also used in the borrow area assessment. Native beach sand data were collected along seven profiles on both Anna Maria Island and Longboat Key at cross-shore profile locations ranging from +2 to −4 m (+6 to −12 ft) (NGVD). Analysis indicated that the pre-mining shoal borrow composite had a mean grain size of 0.18 mm (2.5 φ), with a sorting of 0.79 φ. The analysis showed that the borrow material was slightly finer than the Longboat Key native composite, which had a mean of 0.21 mm (2.26 φ) (APPLIED TECHNOLOGY AND MANAGEMENT, 1991). Additional (monitoring) sediment samples from the borrow area should indicate the suitability of infill material.

Project Summary

The ebb shoal mining project at Longboat Pass provided a sand source for the Longboat Key Beach Restoration Project. The material was taken from the outer edge of the ebb shoal and was placed along the northern end of Longboat Key.

The recent mining of the Longboat Pass ebb shoal is in the process of being monitored, therefore results are preliminary. Monitoring will continue so that the results of this monitoring project will benefit future mining studies. While this project is in its early stages of monitoring, it appears that the shoal borrow area is already infilling as sand continues to be transported into the borrow area. Approximately 72,600 m³ (95,000 c.y.) accumulated in the borrow area in the first year after project completion (K. ERICKSON, *personal communication*). Figure 12 shows two profile locations across the borrow area. The bank slope adjustment was approximately 30: 1. Southerly sand transport was observed as the borrow area infilled. The fill placement area along the shoreline has experienced some "hot spots" of erosion, but there is no indication that the mining of the shoal has impacted or increased the erosion rate in critical areas.

Surveys of the entire inlet system and adjacent shoreline should continue until the borrow area has recovered significantly. Documented changes in the adjacent shoreline, inlet channel, and flood and ebb shoals, should facilitate efforts to understand the impacts of shoal mining on the entire inlet system. Sufficient baseline (pre-project) data should improve our ability to decipher which impacts can be correlated specifically with ebb shoal mining event.
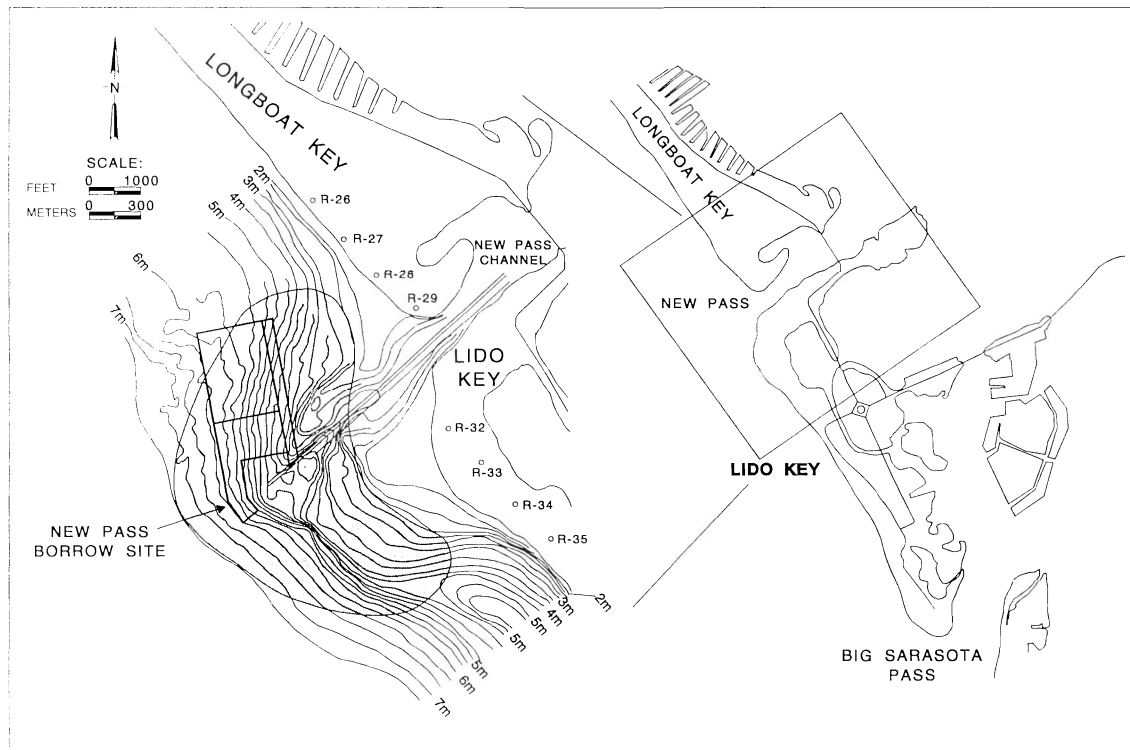
Figure 13. Location of New Pass, Florida showing ebb shoal borrow area (after APPLIED TECHNOLOGY AND MANAGEMENT, 1992 and 1993a).

New Pass (Sarasota County), Florida

New Pass is located in Sarasota County on the southwest (Gulf of Mexico) coast of Florida (Figure 13). The Pass serves as a link between Sarasota Bay and the Gulf of Mexico for recreational boaters and commercial fishermen, and separates Longboat Key to the north from Lido Key to the south. New Pass was formed in September 1848 when a hurricane breached the southern portion of Longboat Key (COASTAL PLANNING AND ENGINEERING, 1993). (This hurricane also formed John's Pass to the north.) New Pass was first dredged in 1926 to create a more stable channel location. During this time period (1920's) Lido Key was actually created when John Ringling, the owner of the series of detached mangrove islands surrounded by shallow seagrass beds, decided to connect the islands to form one larger island (Lido Key) (COASTAL PLANNING AND ENGINEERING, 1993). He filled the area between the mangrove islands with sand from Sarasota Bay.

Ebb Shoal Morphology and Mining Events

Initially, New Pass was considered a wave-dominated inlet with a limited ebb shoal and a narrow, deep channel. Presently the inlet is considered a mixed-energy inlet with a larger channel, increased tidal flow, and a correspondingly more prominent ebb shoal (DAVIS and GIBEAUT, 1990). The ebb shoal at New Pass is obviously characteristic of a mixed-energy environment, alternating between a crescentic, wave-dominated shoal feature and elongated, tide-dominated shoal

features (Figure 14). From this historical perspective it is observed that the channel and ebb shoal tend to migrate to the south. Periodically the channel breaks through the ebb shoal and the southern lobe welds to shore on northern Lido Key. The ebb shoal volume was estimated to be 4.2×10^6 m^3 (5.5 $\times 10^6$ c.y.) in 1992 (APPLIED TECHNOLOGY AND MANAGEMENT, 1992) and is growing at an estimated rate ranging from a low of 34,300 m^3/yr (44,900 c.y./yr) (COASTAL PLANNING AND ENGINEERING, 1993) to 71,100 m^3/yr (93,000 c.y./yr) (APPLIED TECHNOLOGY AND MANAGEMENT, 1994a), to a high of 90,600 m^3/yr (118,500 c.y./yr) (APPLIED TECHNOLOGY AND MANAGEMENT, 1994b).

The Longboat Key Borrow Area is located on the northern portion of the ebb shoal and was used to nourish the beaches of Longboat Key (Figure 13). The borrow area covers 425,000 m^2 (105 acres) and was dredged from February to May 1993 to nourish Longboat Key (APPLIED TECHNOLOGY AND MANAGEMENT, 1993c). A total of 720,000 m^3 (940,000 c.y.) was authorized to be mined from this borrow site and placed on the southern 8–10 km (5–6 miles) of Longboat Key. The cut depth was 5.5 to 7.0 m (18 to 23 ft).

Pre-project conditions of the beach and borrow area were determined from topographic surveys of the project (beach nourishment) area and hydrographic surveys of the borrow area collected from December 1992 to March 1993. During project construction, the "storm of the century" occurred on March 13, 1993 and removed virtually all of the sediment placed on Longboat Key, thus requiring resurveying of pre-
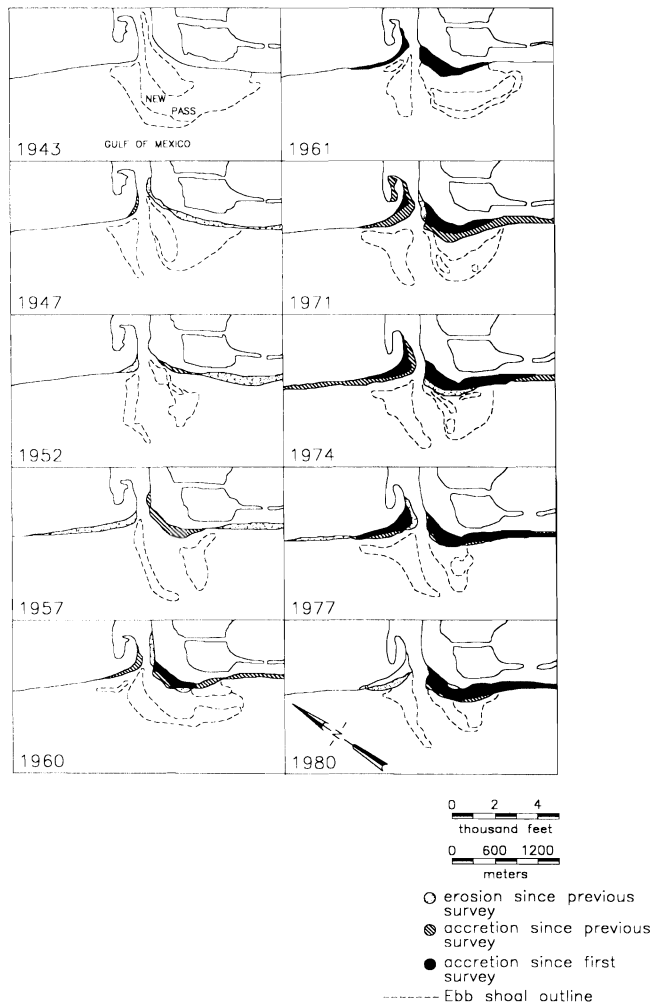
Figure 14. New Pass ebb tidal delta dynamics (from COASTAL PLAN-NING AND ENGINEERING, 1993).

project conditions (APPLIED TECHNOLOGY AND MANAGE-MENT, 1993c). Sediment samples from the beach and borrow area were also collected.

Monitoring of the New Pass ebb shoal mining/Longboat Key beach nourishment project included: hydrographic surveys of the borrow area immediately after project completion (June/July 1993) and after one year (August 1994); aerial photographs of Longboat Key and beach profiles at approximately 300-m (1,000-ft) intervals in July/August 1993, March 1994, and August 1994; sediment samples along Longboat Key every 1.6 km (1 mile) collected in October 1993; and SHOALS surveys of the entire inlet/ebb shoal system performed in March 1994, September 1994, and December 1994. Sediment traps were installed at 7 sites offshore of Longboat Key and were operational from October 1992 to August 1994. In addition, turbidity and directional wave sensors were installed by the University of Florida on 4 of the sediment trap sites in August 1993 for a one year period. Unfortunately, there were problems with the wave sensors and only a wave

height (no direction) time series was obtained (APPLIED TECHNOLOGY AND MANAGEMENT, *personal communication*).

Project Summary

The ebb shoal at New Pass was used as a sand source for the southern portion of the Longboat Key Beach Nourishment Project. Material was dredged from the outer portion of the ebb shoal, on the updrift (northern) side of the navigation channel. Similar to John's Pass, the material was backpassed to the updrift beach. However, the sand was used to nourish the beach adjacent to New Pass whereas material from the ebb shoal at John's Pass was barged upcoast.

APPLIED TECHNOLOGY AND MANAGEMENT (1993c) analysis of the monitoring data indicated that the beach fill material contained less than 1% fines and, except for one small area of the project, the material contains 2–4% shell. The March 1993 storm caused severe erosion along Longboat Key. The adjacent beaches experienced general erosion from December 1992 to September 1993, with the majority of the loss attributed to the March 1993 storm. From APPLIED TECHNOLOGY AND MANAGEMENT (1992), the predicted infilling rate of the ebb shoal borrow area was 53,500–91,700 m³/yr (70,000–120,000 c.y./yr). Based on repeated SHOALS surveys (IRISH and LILLYCROP, 1997) and standard hydrographic survey analysis (APPLIED TECHNOLOGY AND MANAGEMENT, 1993c), after one year very little change (infilling) was found in the borrow area. An additional SHOALS survey of the borrow area was conducted in the Fall of 1995, providing a longer time period for computing the infilling rate of the New Pass borrow area.

The monitoring data for this project should be extremely useful information for discerning ebb shoal mining impacts at New Pass. Analysis of the SHOALS surveys should provide a detailed estimate of the ebb shoal volume and infilling rate of the borrow area. The SHOALS program also installed a directional wave gage off Lido Key, just south of New Pass which has been in operation since May 1993. Wave direction can be obtained from this data source to estimate longshore transport rates. Beach profile data and aerial photography should indicate shoreline and volumetric accretion/erosion rates. Sediment samples from the borrow area would be a beneficial addition to this monitoring data set.

Redfish Pass, Florida

Redfish Pass is located on the southwest coast of Florida in Lee County, forming during a hurricane in the 1920's, and causing the separation of North Captiva Island from Captiva Island (Figure 15). The pass serves as an outlet from Pine Island Sound to the Gulf of Mexico. Historical charts from the 1800's indicate that Redfish Pass may have been the location of a former tidal inlet (DAVIS and GIBEAUT, 1990). This tide-dominated inlet has been fairly stable, but has recently tended to have a downdrift offset. The main channel has been stable since its formation in the 1920's; the minimum width has remained at 200–300 m (650–1,000 ft), and a maximum depth of 12 m (39 ft) was reached in 1955 (VINCENT and CORSON, 1980). LEADON (1995, *in preparation*) states that the natural channel has remained stable in terms
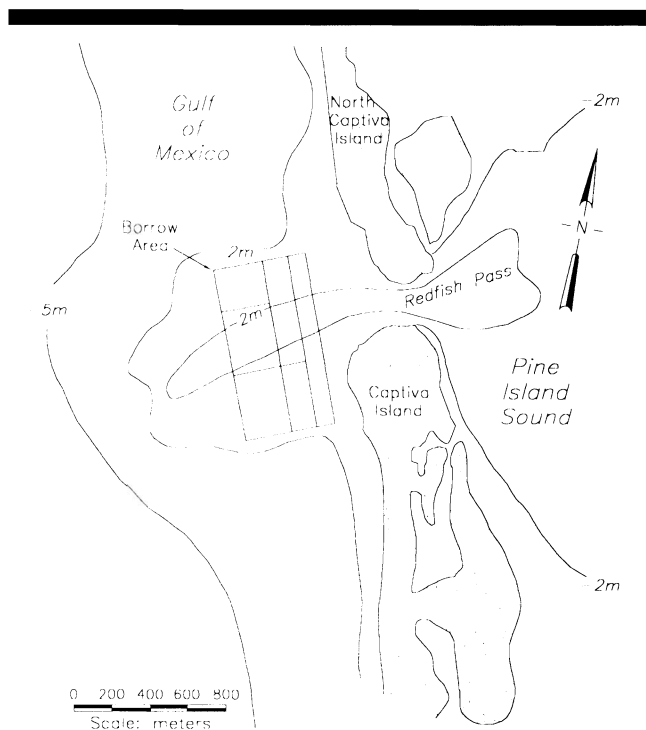
Figure 15. Location of Redfish Pass, Florida (after WALTHER and DOUG-LAS, 1993) showing ebb shoal borrow area location (after COASTAL PLAN-NING AND ENGINEERING, 1988).

of alignment and depth (5.5 m (18 ft) NGVD) so that dredging of the navigation channel has not been necessary.

Shoal Morphology and Ebb Shoal Mining Events

The ebb and flood shoals are large and were reported to contain 6,100,000 m³ (8,000,000 c.y) of material (UNIVERSITY OF FLORIDA, 1974). The flood shoal has multiple lobes and was fully mature (not growing further) by the 1950's. It is naturally stabilized by seagrass. The ebb shoal was still growing in the 1980's (therefore had a greater volume than the previously reported value), with a tide-dominated (elongated in the shore-normal direction) configuration. The large tidal prism at Redfish Pass contributes to the general tide-dominated morphology of the ebb shoal (DAVIS and GIBEAUT, 1990). The southern lobe is typically wider than the northern lobe. The ebb shoal was reported to contain 3,100,000 m³ (4,000,000 c.y.) of material in 1981 and was estimated to be accreting 95,600 m³ (125,000 c.y.) of material annually (TE-TRATECH, 1981). This rate of accumulation is higher than the estimated net longshore transport rate of 58,500 m³/yr (76,500 c.y./yr) to the south and must be indicative of a drift reversal in the vicinity of Redfish Pass with part of the gross transport reaching the ebb shoal. LEADON (1995, in prepa-ration) reports a smaller ebb shoal volume of approximately 2,171,000 m³ (2,840,000 c.y.).

The ebb shoal was mined in 1981 and 1988 to provide beach nourishment to Captiva Island. In 1981, approximately 501,200 m³ (655,500 c.y.) of material was removed from the

ebb shoal borrow area to nourish the northern end of Captiva Island (South Seas Plantation) (Figure 15). The monitoring program for the initial ebb shoal mining project was fairly extensive, consisting of pre- and post-construction surveys of the beach and borrow area 0, 6, 12, and 18 months after pro-ject completion, and pre- and post-construction (0, 6, 12, and 18 months after project completion) sediment sample data collection and analysis (STAUBLE and HOEL, 1986). The sur-vey limits extended beyond the boundary of the borrow area. Eleven beach profiles were taken within the 3.1 km (1.9 miles) beach nourishment project site and four control pro-files were taken downdrift (south) of the project site. Sedi-ment data were collected along 3 monitoring profiles and 1 control profile from 2 to −4 m (+6 to −12 ft) elevation (da-tum not specified), and at 5 locations in the borrow area (cen-ter and each corner).

In 1988, approximately 1,227,400 m³ (1,605,400 c.y.) of ma-terial was removed from the ebb shoal to nourish the south-ern part of Captiva Island. This ebb shoal borrow area is south of the previous (1981) ebb shoal borrow area. The mon-itoring program for the second ebb shoal mining project con-sisted of pre- and post-construction surveys of the beach and borrow area 0, 2, 4, and 6 years after project completion (LEA-DON, 1995 in preparation). According to LEADON (1995, in preparation) these surveys extend over a greater area than the post-1981 dredging surveys and include most, if not all, of the ebb tidal shoal.

According to WALTHER and DOUGLAS (1993), pre-dredge depths for the first (1981) mining event are not given in the literature, however, an average post-dredge survey depth of −4.5 m (−15.0 ft) (datum not specified) after 18 months is reported. Based on the dredging area (610 m by 460 m (2,000 ft by 1,500 ft)), volume dredged, and post-dredge depth, WAL-THER and DOUGLAS (1993) estimated that the pre-dredge depth was approximately 2.8 m (9.1 ft). From the monitoring surveys of the ebb shoal borrow area, it was determined that 80,850 m³ (105,700 c.y.) of material accumulated in the bor-row area in the 18 month period from February 1982 to Au-gust 1983 (rate of 53,900 m³/yr or 70,500 c.y./yr) (TACKNEY AND ASSOCIATES, 1983) and 112,420 m³ (147,000 c.y.) depos-ited from September 1985 to October 1987 (rate of 54,000 m³/yr or 70,600 c.y./yr) (YOUNG, 1988). During the initial 18-month monitoring period, a small amount of material (57,400 m³ (75,000 c.y.)) was lost from the beach nourishment project (STAUBLE and HOEL, 1986).

Pre-dredge depths for the second (1988) mining event are not given in the literature (WALTHER and DOUGLAS, 1993), however, an average post-dredge survey depth of −4.0 m (13.0 ft) (datum not specified) is reported. Based on the dredging area (1,650 m by 700 m (5,400 ft by 2,300 ft)), vol-ume, and post-dredge depth, Walther and Douglas estimated that the pre-dredge depth was approximately −3.5 m (11.5 ft). From the monitoring surveys of the ebb shoal borrow area, a total of 46,000 m³ (60,200 c.y.) of material accumu-lated in the two borrow areas in the 2-year period from April 1989 to April 1991 (rate of 23,000 m³/yr (30,100 c.y./yr)) (COASTAL PLANNING AND ENGINEERING, 1992b). A faster in-filling rate (53,900 m³/yr (70,500 c.y./yr)) was anticipated based on the entire longshore transport volume (58,500 m³/yr

(76,500 c.y./yr)) reaching the borrow area and a large percentage depositing in the borrow areas. However, material is still accumulating on the ebb shoal *outside* the borrow areas, leaving less material available to deposit *in* the borrow areas (WALTHER and DOUGLAS, 1993). The 1988 borrow area is recovering at a slower rate than the 1981 borrow area. Walther and Douglas attribute the faster recovery of the 1981 mining to its deeper cut depth. The 1988 mining site is also downdrift of the 1981 mining site and therefore might receive a smaller volume of the net littoral drift. LEADON (1995, *in preparation*) confirms that infilling is predominantly from the north. LEADON (1995, *in preparation*) attributes the perceived slower infilling rate after the 1988 mining to the more extensive survey coverage of the post-1988 surveys which include areas of erosion during the analysis period.

Adjacent shoreline erosion has been observed since the ebb shoal mining, but has not been definitively linked to the mining events (LEADON, 1995 *in preparation*). The Inlet Management Plan notes that the mining of the ebb shoal at Redfish Pass has "intensified the erosion problem and reduced the level of mitigation provided by the fill" (COASTAL PLANNING AND ENGINEERING, 1992b). LEADON (1995, *in preparation*) also notes that following the second ebb shoal dredging at Redfish Pass, erosion of the adjacent shorelines north and south of Redfish Pass have significantly increased and should be evaluated with further monitoring.

Project Summary

The ebb shoal at Redfish Pass was mined twice to provide sediment to the downdrift shoreline (Captiva Island). The first ebb shoal mining at Redfish Pass encompassed a small area on the outer edge of the ebb shoal, downdrift of the navigation channel. The borrow area limits for the second ebb shoal mining event encompassed nearly the entire ebb shoal, however, only the southernmost portion was used. Material from the first mining event was placed on the northern end of Captiva Island and material from the second mining event was placed on the central and southern portions of the island. Monitoring of both ebb shoal mining events indicates that material is accumulating in the borrow areas, however, the rate of accumulation in the second borrow area is slower than the first. This may be attributed to the deeper cut depth for the 1981 borrow area, the updrift location of the 1981 borrow area, or the larger survey coverage for the 1988 borrow area monitoring. The predominant infilling direction appears to be from the north and the ebb shoal in general is accretional. The fill placement area on Captiva Island has been erosional since the mining events, but the erosion has not been directly linked to the mining events. This project was one of the earliest documented ebb shoal mining projects, therefore provides the longest history for studying inlet system response. Further analyses of infilling rates and adjacent shoreline change is needed to assess long-term impacts of ebb shoal mining at Redfish Pass.

SUMMARY

Dredging material from inlet ebb shoals has been done in the past and is becoming a more frequent practice. The im-

pact of removal of material from inlet ebb shoals on the entire inlet system has not been closely monitored. At best, infilling rates for the borrow area itself are collected, adjacent beach profiles may be taken, and sediment samples are collected. These are not sufficient data to determine the impacts of a mined shoal on an inlet system. Complete and repeated hydrographic surveys of the entire inlet system are needed. Better estimates of the longshore transport rate, both net and gross, are very important prior to dredging a shoal in order to better predict the infilling rate of the mined area. Sediment samples before and after dredging are needed to determine: (1) the suitability of the material for beach nourishment initially and (2) the quality of the infill material for future nourishment projects. This paper presented the review of eight ebb shoal mining projects. A summary of inlet characteristics and mining events is presented in Table 1. The inferred impacts of mining material from ebb shoals, lessons learned from these projects, and a recommended plan for monitoring future ebb shoal mining projects are discussed herein.

Inferred Impacts from Historic Data

Due to the varying levels of monitoring performed at the eight projects studied, it is difficult to draw conclusions about shoal mining impacts on an inlet system. The monitoring period and level of effort given to the monitoring portion of each project was not consistent from project to project. In addition, the response of individual projects to the mining of a portion or all of the ebb shoal ranged from beneficial to detrimental.

Six of the eight projects placed sand on the downdrift beach, while two of the projects were sand sources for updrift beach fills. The two projects that provided sand to updrift beaches borrowed material from the updrift side of the ebb shoal. Only one project had the main purpose being navigation improvement by removing a portion of the ebb shoal to provide a "straight" navigation channel through the ebb shoal. The other seven projects were beach nourishment projects that used the ebb shoal as source material. Three of the eight projects were mined as recently as 1995: one as an initial ebb shoal mining and two as a repeated shoal mining. Four of the projects had single ebb shoal mining events and the other four involved two or more ebb shoal mining events. The scale of the projects, in terms of the percentage of the volume mined versus the total ebb shoal volume, ranged from 2 small projects (0–15% removed), to 4 medium projects (16–25% removed), to 2 large projects (> 25% removed). Only one project encompassed the entire ebb shoal area while the other seven projects were restricted to specific borrow areas within the ebb shoal complex.

Adjacent Shoreline Impacts

At some inlets, adjacent shorelines maintained a stable downdrift shoreline position due to the placement of mined material on the downdrift beach. Other inlets exhibited an increased downdrift erosion rate and the inception of erosion on the updrift side of an inlet following the mining of an ebb shoal. More analyses of these data are needed, however, it can be stated that the degree to which a system is shifted

Table 1. *Shoal mining data.*

	Shinnecock Inlet	Great Egg Harbor Inlet	Jupiter Inlet	Boca Raton Inlet	Johns Pass	Longboat Pass	New Pass	Redfish Pass
Volume of Shoal (m³)	Not given	56,630,000	200,00–765,000	600,000-840,000	4,600,000– 5,400,000	4,900,000– 6,200,000	4,200,000	2,171,000– 6,100,000
Length (m)	2,500		610	198	~1,100	1,524	1,160	12,000
Width (m)	3,700		1,700	580	~1,500	5,030	1,800	10,000
Date and Amount Mined (m³)	1) 1990 497,000 2) 1993 305,800	1) 2/92-10/92-Phase I 1,988,000 10/92–3/93-Phase II 2,064,000 2) 6/93-9/93 646,000 3) 10/94–12/94 459,000 4) 6/95–8/95 1,078,000	1) 1966–1988 sand-trap-22,900– 160,000 2) 1995-egg shoal 461,000	1) 1985 170,000	1) 1988 407,300	1) 1993 1,500,000	1) 1993 720,000	1) 1981 501,200 2) 1988 1,227,400
Mining Location on Ebb Shoal	Channel through center of ebb shoal	Center and south of channel, outer edge	Outer edge, restricted area near reef	Entire ebb shoal	North of channel, outer edge	Center and south of channel, outer edge	North of channel, outer edge	Center and south of channel, outer edge
Fill Placement Length (m)	1b) west beach-610 1d) west surf zone-1,200–1,400 2a) not given	1) Phase I-3,474 Phase II-3,353 2) 2,926 3) 1,585 4) 6,828	240–1,700	884		9,000	8,000	1) South Seas Plantation 3,050 2) Captiva Island ~8,000
Fill Placement Location	1a) scour hole 61,200 m³ 1b) west beach 76,500 m³ 1c) east jetty 99,400 m³ 1d) west surf zone 259,900 m³ 2a) west beach	1) Phase I Seaspray Rd-15th St Phase II 16th St–36th St 2) Dec 92 Storm Rehab 5th–23rd St 3) Renourish. Phase I 1st–11th St 4) Renourish. Phase II Seaspray Rd-36th St	South adjacent beach at Jupiter Beach Park to Carlin Park	South adjacent beach	Sand Key 5,000 m north of inlet	South adjacent beach on Longboat Key	North adjacent beach on Longboat Key	South adjacent beach Captiva Island
Borrow Area Infilling Rate (m³/yr)	51,200-61,200	Not calculated	Not calculated	66% in 5 yr	24,000	72,600	Minimal	1) 1981-54,000 2) 1988-23,000
Longshore Transport Rate (m³/yr) Direction	229,400 west	55,800 south	172,000-183,500 south	114,700-214,100 south	30,800-38,200 south	45,800 south	21,000-45,800 south	46,200-106,300 south
Mean Tidal Range (m)	Semidiurnal 0.9	Semidiurnal 1.2	Semidiurnal 0.8	Semidiurnal 0.9	Mixed 0.7	Diurnal 0.8	Diurnal 0.6-0.8	Mixed 0.5
Tidal Prism (m³)	6.2×10^6	5.7×10^7	2.9–3.1×10^6	4.4–5.5×10^6	5.7×10^6–1.4×10^7	8.4×10^6–4.1×10^7	8.7×10^6–1.1×10^7	1.2×10^7–1.6×10^7
Tidal Current (m/sec)	Flood 1.3 Ebb 1.2				Flood 1.0 Ebb 0.8	Flood 0.6-1.1 Ebb 1.1-1.2	Flood 0.8 Ebb 0.5	
Stability Ratio (1/M_{tot})	27-bar bypasser, poor stability	96-large ebb shoal, wave dominated, fair stability	17-very unstable	26-38.4-bar bypasser, poor stability	182-366-stable, tidal flow dominated	183-stable, tidal flow dominated	240-stable, tidal flow dominated	150-260-stable, tidal flow dominated
Inlet Classification	Updrift offset, wave dominated	Downdrift offset, wave dominated	Updrift offset, wave dominated	Updrift offset, wave dominated	Downdrift offset, tide dominated	Downdrift offset, tide dominated	Downdrift offset, mixed energy	Downdrift offset, tide dominated
Mean Wave Height (m)	0.7	0.6	0.5	0.5	0.8	0.6	0.6	0.6

from its dynamic equilibrium probably determines the degree to which the remaining portions of the inlet system respond (change), as discussed in the following section.

Inlet System Equilibrium Concept

Based on DEAN's (1988) sand sharing system concept, we need to understand that perturbations to any one part of an inlet system can alter the equilibrium of the system. The impact of such a perturbation will be felt and experienced by all other parts of an inlet system. Mining an ebb shoal can be a minor or major perturbation to an inlet system, depending upon the volume removed, location, frequency and depth of material taken as well as the system hydrodynamics.

Infilling Rates/Reuseability

WALTHER and DOUGLAS (1993) concluded from their work that a deeper cut is much more likely to have an adverse impact on downdrift beaches than a shallower cut. After shoal mining, a deeper borrow area will trap more sediment and reduce bypassing more than a shallow area, creating a sediment deficit to the downdrift shoreline. This could affect the performance of a project due to a measurable reduction in the bypassing rate. They conclude, "Large quantities of material in ebb shoals of tidal inlets are an appealing source of sand for beach nourishment projects. However, the use of an ebb shoal borrow area will likely result in increased downdrift erosion which can significantly reduce the value of beach nourishment. This increased erosion should be considered in comparing alternative sand sources for beach nourishment." A reliable estimate of the gross and net transport in the vicinity of a shoal mining project is a critical factor in predicting the infilling rate of a mined shoal. If the designer is depending on borrow area infill material for future projects, then a reliable estimate of the gross and net transport will allow him/her to predict when sufficient material will be available for future projects.

Lessons Learned

At the outset of this research effort, several questions were raised concerning the mining of ebb shoals. An attempt to address these questions follows:

● Is the ebb shoal borrow material suitable as project fill material?

All beach nourishment projects reviewed for this paper had fill factors around 1 indicating that the borrow material was compatible with the beach material. Ebb shoals, considered the "sand bridge" between adjacent beaches, contain grain size distributions closely compatible with the adjacent native beach sediment.

● Where on the ebb shoal should the material be mined to minimize inlet system impacts?

There is insufficient data to answer this question. Further studies on wave refraction effects, depth of mining, and borrow area position within the shoal complex are needed. Generally the shoals discussed in this paper were mined at the

deeper, oceanward side or what is suspected to be the "passive" zone.

● How does mining the ebb shoal positively or negatively impact navigation?

Only two projects were concerned with navigation improvements. Both of these projects had improved navigation after dredging. For the other six projects, changes in the channel shoaling rate induced by the shoal mining need to be analyzed.

● How does mining the ebb shoal impact adjacent shoreline evolution?

The eight inlets examined exhibited impacts ranging from increased erosion to stability of adjacent shorelines. Further analysis of existing data and data in the process of being collected will allow us to explain the dissimilar shoreline responses. Nodal points on the downdrift shoreline appear to be related to the shoal, and mining the ebb shoal may affect the location of these localized drift reversals.

● What impact does ebb shoal mining have on the entire ebb shoal system equilibrium?

It appears that limited effort has been expended to examine the "big picture" of shoal mining effects on the system equilibrium. Due to lack of systematic monitoring of the entire inlet system, it was difficult to assess the system response. Projects focused on the borrow area, rather than the entire ebb shoal, and beach profiles were often restricted to the fill placement area. A complete data set was rarely reported.

● How does the ebb shoal borrow area recover and at what rate?

The borrow area infilling rate appears to be a function of the longshore transport rate, depth of dredging, storm frequency, and sediment supply. The degree of the perturbation on the system equilibrium caused by mining the ebb shoal affects the rate of recovery of the inlet system in general and the borrow area in particular. Estimates of borrow area recovery were often overpredicted, probably due to poor longshore transport estimates. More emphasis is needed on monitoring borrow area recovery, especially if the borrow area will be reused in the future.

● Does the ebb shoal borrow area infill with the same material?

Sediment data were limited. Borrow areas that were used more than once were not resampled for analysis of borrow area recovery. Subsequent mining events in the same project area used different "undredged" locations within the borrow area and assumed the material was still suitable as fill material. Eventually, with dwindling sand supplies, this question will need to be addressed.

Recommended Monitoring Plan

Monitoring ebb shoal mining events should be included and budgeted for in the project design. It is our recommendation

that the following monitoring plan be considered for future ebb shoal mining events to provide consistent data for evaluation of shoal mining impacts and improve future shoal mining project designs.

Bathymetry

In order to get the full impact of the mining event on the entire inlet shoal system, bathymetric surveys of the entire inlet system (ebb shoal, flood shoal, channel, and adjacent shorelines), *not* just the borrow area, should be collected immediately before dredging, immediately after, and annually until the infilling rate diminishes to the long-term average, pre-dredge ebb shoal accumulation rate. A suggested data collection time-line could include annual surveys for the first two years, then every two years until year six, to establish a long-term growth rate.

Beach Profiles

Beach profiles should be collected to monitor adjacent shoreline impacts, beach nourishment project performance, and without-project native beach conditions. Beach profile surveys should be collected from immediately adjacent to the inlet to the location where the ebb shoal influence on the offshore contours is no longer observed (WALTON and ADAMS, 1976). Additional control profiles should be established up-drift and downdrift of this ebb shoal influence area. These data should be collected prior to project construction, immediately after project completion, and quarterly for two years and semiannually for three additional years. For details on suggested monitoring of beach nourishment projects see STAUBLE (1991a). A less-costly alternative would include semi-annual surveys through the first two years, then annual (late summer) surveys through year six.

Sediment Sampling

Pre-dredge sediment surveys of the borrow area and the placement location are needed to assess the suitability of the borrow material. Cores should be collected on representative areas of the ebb shoal to identify potential borrow area sand thickness. Sediment samples should be collected from the cores to characterize the borrow area sediment distributions. These distributions should then be compared to the native beach sediment distributions in the nourishment area (STAUBLE, 1991b). Borrow area grab samples should be collected 1 year after project construction or before any subsequent borrow area dredging to determine infilling sediment type for renourishment use and for determination of the degree of ebb shoal recovery towards its equilibrium or pre-dredge condition.

Aerial Photographs

Aerial photographs are useful for determining shoreline change positions before and after dredging, identifying ebb shoal-induced nodal points and hotspots of erosion, and identifying wave pattern alterations induced by the ebb shoal. It is recommended that aerial photographs be taken before and immediately after project construction, and annually for the life of the monitoring project. For details of aerial photograph collection and analysis, the reader is referred to STAUBLE (1991a).

Physical Processes

It is recommended that the local wave climate in the vicinity of the inlet be determined by using WIS data or installing a wave gage. These data are necessary for determining the longshore transport rates and wave refraction patterns with and without ebb shoal mining operations. This analysis will identify the borrow area infilling rate, potential focussing of wave energy, and ebb shoal mining impacts on adjacent shorelines.

Final Comments

Ebb shoal mining projects are all relatively "young" in terms of their history. Most of the projects reviewed for this paper have been conducted in the last eight years (since 1988). Several of these projects were mined in 1995 (Great Egg Harbor Inlet, Jupiter Inlet, Boca Raton Inlet, and others are still being monitored (New Pass (Sarasota County), Longboat Pass, Shinnecock Inlet, and Redfish Pass). It is our intention that the ebb shoal mining research conducted as part of the Coastal Inlets Research Program will provide the knowledge to properly design an ebb shoal mining project by assessing: 1) the equilibrium or non-equilibrium condition of an ebb shoal, 2) if an ebb shoal should or should not be mined, 3) where on the ebb shoal and to what depth should an ebb shoal be mined, 4) what volume of material can be safely mined without significantly disturbing the inlet system equilibrium (adjacent shorelines, navigation channel, flood shoal), and 5) how the borrow area will recover. Ebb shoal mining monitoring guidelines developed as part of this research will aid the designer in collecting the appropriate pre- and post-project data to evaluate the success of their project design.

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APPENDIX

Background information for each of the ebb shoal mining projects presented in the paper is included in this appendix in order to give a more complete understanding of the evolution of each individual inlet. Inlet processes, morphology, shoreline change, as well as any structural changes at each project site are presented. Figures referenced in the appendix are found in the paper.

Shinnecock Inlet, Long Island, New York

In 1939, local interests built a bulkhead on the west side of the 1938 breach to prevent westward migration of the inlet. In the 1940's and 1950's local interests added more structures (revetments, jetties, groins) and dredged a 2.7-m-(9-ft-)deep, 30.5-m-(100-ft-)wide, 610-m-(2,000-ft-)long channel. The channel was deepened and widened in 1958 and 1963, and maintenance dredging was performed in 1973 and 1978. Local interests also dredged a channel through the flood shoal in 1966 and 1969. The inlet width itself has also varied since initially opening. Since 1938, the width of the inlet has ranged between 150 m (500 ft) and 300 m (1,000 ft), but was stabilized to 240 m (800 ft) with construction of east and west rubblemound jetties in the 1950's.

Shinnecock Inlet was authorized as a federal navigation project under the River and Harbor Act of 1960 with three project purposes: navigation, water quality, and beach erosion. The project authorization was reduced to a navigation project purpose only by the 1983 Supplemental Appropriation Act and included a navigation channel, deposition basin, jetty rehabilitation, revetment construction, and a sand bypassing system. In 1984, prior to approval of the federal navigation project, the Corps of Engineers performed an emergency dredging operation at Shinnecock Inlet, removing 123,900 m³ (162,000 c.y.) of material from the inlet to a depth of −4.3 m (−14 ft) mean low water (MLW). The dredged material was deposited west of Shinnecock Inlet at −3.0 m (−10 ft) MLW. The federal navigation project at Shinnecock Inlet was approved in 1988 with the single project purpose (navigation) and construction began in 1990 with the dredging of approximately 497,000 m³ (650,000 c.y.) of material from the inlet channel and deposition basin which extends through the ebb shoal (Figure 2). The material was placed at four locations: 61,200 m³ (80,000 c.y.) was placed in a scour hole at the west jetty tip, 76,500 m³ (100,000 c.y.) was placed on the beach in the 610-m-(2,000-ft-)stretch immediately west (downdrift) of the inlet, 99,400 m³ (130,000 c.y.) was stockpiled east of the inlet for use as backfill for the east jetty reconstruction, and the remainder was placed in the surf zone, approximately 1.2–1.5 km (4–5,000 ft) west of Shinnecock Inlet, near Ponquogue Point. From 1992 to 1994, the east jetty was reconstructed, a 300-m-(1,000-ft-)long revetment was constructed east of the inlet to protect the bayside erosion area, and the jetty and revetment on the west side of Shinnecock Inlet were repaired. In March 1993, an additional 305,800 m³ (400,000 c.y.) of material was removed from the inlet channel and deposition basin and was placed in the most critical beach erosion area immediately west of the west jetty. The estimated infilling rate for this area was calculated in USAED, New York (1987) and indicated that the de-

position basin had a capacity of 351,700 m³ (460,000 c.y.), requiring dredging every 1.5 years.

Inlet Processes and Morphology

Waves in the study area are predominantly from southwest and southeast, with a mean significant wave height of 0.7 m (2.2 ft) at the U.S. Army Corps of Engineers Wave Information Studies (WIS) South Shore of Long Island Phase III Station 46 (JENSEN, 1983). Astronomical tides in the area are semidiurnal with a mean tide range at the entrance to Shinnecock Inlet of 0.9 m (2.9 ft) and a spring range of 1.1 m (3.5 ft). Tidal currents given in USAED NEW YORK (1987) were 1.2–1.3 m/sec (3.9–4.2 ft/sec) with a maximum value of 2.4 m/sec (8 ft/sec). JARRETT (1976) lists the maximum flood current as 1.3 m/sec (4.2 ft/sec) and the ebb current as 1.2 m/sec (3.9 ft/sec). Recent field work at Shinnecock Inlet using an Acoustic Doppler Current Profiler indicated an average maximum current velocity of 1.6 m/sec (5.4 ft/sec) for both flood and ebb tidal currents (CHU and NERSESIAN, 1992). According to NERSESIAN and BOCAMAZO (1992), maximum tidal velocities in the inlet can be as much or more than 2.1 m/sec (6.8 ft/sec). The spring tidal prism calculated by the cubature method was 6.2×10^6 m³ (2.19×10^8 ft³) as listed in JARRETT (1976). The stability ratio Ω/M_{tot} for Shinnecock Inlet is 27, where Ω is the tidal prism and M_{tot} is the net longshore transport rate based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974). This stability ratio value indicates that Shinnecock Inlet is predominantly a bar-bypass type inlet, with poor stability.

The net littoral transport direction along the south shore of Long Island is from east to west. In USAED NEW YORK (1987) a net longshore transport rate of 344,000 m³/yr (450,000 c.y./yr) to the west was estimated from the rate of migration of Fire Island and Rockaway Inlets. These inlets are located 72 and 129 km (45 and 80 miles) west of Shinnecock Inlet, respectively. The net longshore transport rate given in the authorized survey report for Shinnecock Inlet was 229,400 m³/yr (300,000 c.y./yr) to the west and was confirmed by a sediment budget analysis performed by RESEARCH PLANNING INSTITUTE (1983). The gross transport volume estimated to be 305,800 m³/yr (400,000 c.y./yr) was expected to be available for deposition in the sedimentation basin.

Sediment along the south shore of Long Island is coarsest at the easternmost end of the island (Montauk Point) with a mean grain size of 1 to 4 mm (0 to −2.0 ϕ) (USAED NEW YORK, 1987). Sediment in this area also contains the greatest amount of heavy minerals. In the vicinity of Shinnecock Inlet, the sediment is characterized by more of a pure quartz fraction and a mean grain size of 0.4 mm (1.3 ϕ). It is believed that no sediment samples were taken from the ebb shoal borrow area for comparison to native beach material because the project purpose was navigation only.

Shoreline Change

Volumetric shoreline change reported in USAED NEW YORK (1987) was calculated from beach profile data (1955, 1962, 1974, and 1984), aerial photographs (1953 and 1986), and dredge/fill records. NERSESIAN and BOCAMAZO (1992) also presented the mean high water shoreline positions adjacent to Shinnecock Inlet from 1953 to 1991. The oceanside area east of Shinnecock Inlet accreted during the observation period reported in USAED NEW YORK (1987) due to the effective trapping of littoral material by the east jetty. By 1973, the east fillet was at capacity, material was bypassing the east jetty, and the ebb shoal was growing (USAED NEW YORK, 1987). However, during the 1984–1991 time period the fillet east of Shinnecock Inlet experienced an average loss of approximately 75 m (250 ft) of shoreline over a 490–610 m (1,600–2,000 ft) stretch, and from 1991 to 1994, shoreline erosion immediately east of Shinnecock Inlet continued with the loss of an additional 45 m (150 ft), possibly in response to the removal of material from the deposition basin (ebb shoal) as was discussed in the section on ebb shoal mining events. However, the 1991–1994 recession may be attributed to seasonal variability and is not considered a "problem area" (NERSESIAN, personal communication). The bayside shoreline east of Shinnecock Inlet was eroding at a rate of 4,600 m³/yr (6,000 c.y./yr) during the 1953–1984 time period.

The area west of Shinnecock Inlet has experienced erosion and accretion, but the overall trend for the period 1955–1984 was erosion for approximately 1.5–1.8 km (5,000–6,000 ft) immediately west of Shinnecock Inlet. The first 1.8 km (6,000 ft) experienced an annual loss of 46,600 m³ (61,000 c.y.). At 1.5 km (5,000 ft) west of Shinnecock Inlet, observed accretion is possibly caused by natural sand bypassing around the inlet system to this location. At a distance of 1.8–11.0 km (6,000–36,000 ft) from the inlet, there is additional erosion with an annual loss of 52,800 m³ (69,000 c.y.). The erosion rate over this longer length is approximately 25% of the erosion rate in the critically eroding area adjacent to the west jetty. Further west, accretion is observed in the Westhampton groin field.

Great Egg Harbor Inlet, New Jersey

Inlet Processes and Morphology

Great Egg Harbor Inlet is considered to have a high wave energy climate, with a yearly mean significant wave height of 0.6 m (2.1 ft) at Phase III Station 61 (JENSEN, 1983). The mean tide range is 1.2 m (3.8 ft), with a spring range of 1.4 m (4.6 ft). The longshore transport rate was calculated by WEGGEL et al. (1986) to be 539,800 m³/yr (706,000 c.y./yr) to the north, and 595,600 m³/yr (779,000 c.y./yr) to the south, with a net of 55,800 m³/yr (73,000 c.y./yr) southward. The predominant wave direction is from the southeast, however, the southeast waves are smaller than the northeast storm waves. JARRETT (1976) reported the tidal prism for Great Egg Harbor Inlet as 5.7×10^7 m³ (2.0×10^9 ft³), with an inlet throat cross-sectional area of 6.5×10^3 m² (7.0×10^4 ft²).

The Great Egg Harbor Inlet morphology has a downdrift seaward offset, with an inlet throat length of around 1,000 m (3,300 ft) and a width at the narrowest part of the throat of 1,600 m (5,300 ft). The large ebb tidal shoal has a length (defined as the onshore/offshore dimension) of 2,500 m (8,200 ft), and a width (defined as the alongshore dimension) of 3,700 m (12,100 ft) based on the 1994 SHOALS survey shown in Figure 3. The stability ratio Ω/M_{tot} for Great Egg Harbor Inlet is 96, based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974). This stability ratio value indicates that Great Egg Harbor Inlet is wave-dominated, with only fair stability and a well-developed ebb shoal.

Shoreline Change

Erosion and storm damage have been an ongoing problem for the Ocean City beach front. From 1952 to 1982, 16 beach fills were placed on the north end of the island (WEGGEL et al., 1986). The sand source for most of these beach fills was sediment from the back bay area, which is finer than the native beach. For a period in the 1960's and 1970's, the City owned and operated its own dredge and conducted an ongoing nourishment project, pumping bay sediments onto the beach on an almost continuous basis until the demise of the dredge in the late 1970's (STAUBLE and HOEL, 1986). The 1982 beach fill again used a bay sand source from the inlet flood shoal area.

During the time period of beach erosion (1965–1984) the inlet thalweg migrated southwest toward Ocean City. WEGGEL et al. (1986) described the cyclic nature of this inlet shoreline change as 1) sand builds up on the north side of the channel from Longport beaches, 2) the channel is forced southward toward the Ocean City inlet shoreline, 3) storms move sand across the inlet from the shoal located on the south side of the main ebb channel, and 4) the shoal migrates onshore and welds to the beach, as the channel migrates northward again. While this cycle has an irregular rate, the last cycle appears to have taken 15 years (WEGGEL et al., 1986).

Jupiter Inlet, Florida

Jupiter Inlet has been a natural inlet existing since at least 1671, as shown on an early map (MEHTA et al., 1990). On a 1770 map the inlet was called Greenville Inlet, formerly called Jobe from the Spanish occupation of Florida, sometimes called Jove, and finally Jupiter by the English. The inlet was several hundred meters south of its present position in 1855, with the appearance that it had migrated to the south (downdrift direction over time). The main channel was oriented in a southeast direction. In 1892, St. Lucie Inlet located

about 30 km (18 miles) to the north, was cut through the barrier island, providing a new access to the Indian River Lagoon. (Jupiter Inlet had been the only access to the southern portion of this long narrow lagoon.) In 1896 the Intracoastal Waterway was dredged through the mainland to connect Jupiter Sound to Lake Worth Creek on the south side of the inlet and finally into Lake Worth. This provided a continuous inland waterway behind the inlet. An additional change to the lagoon hydrodynamics occurred when Lake Worth Inlet was cut 11 km (7 miles) to the south through the barrier island in 1918. During this period of construction of an inlet opening and lagoon connection (1896–1909), Jupiter Inlet frequently closed, requiring three emergency reopenings by the Federal Government. From 1906 to 1922 several local reopening projects were also undertaken. In 1921, the formation of the Jupiter Inlet District Commission occurred.

The first major engineering of Jupiter Inlet took place in 1922. The natural channel opening was oriented to the southeast, but it was moved 381 m (1,250 ft) to the north to realign the throat more to the east and improve inlet navigability. Two 120-m-(394-ft)long jetties were constructed, creating a 107-m-(350-ft-)wide throat width. Instability in the inlet throat prompted the extension of the north jetty by 60 m (197 ft), and the south jetty by 25 m (82 ft) in 1929. A problem developed with sand flowing around the south jetty and into the inlet, so an angular groin was built at the seaward end of the south jetty in 1940. By 1942 the inlet had closed again by natural longshore drift. A dredging project undertaken by the Jupiter Inlet District in 1947 reopened the inlet between the jetties for navigation. Dredging was again needed in the throat area in 1952 and 1956. Also in 1956, a new 90-m-(295-ft-)long sheet pile north jetty was constructed 30 m (98 ft) to the north of the existing north jetty. Channel dredging was again needed in 1958, and annually from 1960 to 1965 (MEHTA *et al.*, 1992). Downdrift (southern) shoreline erosion persisted, and in 1966 a regular sand bypassing program was initiated. A sand trap was dredged 300 m (1,000 ft) west of the inlet mouth, placing 185,800 m³ (243,000 c.y.) of sand on the south beach. In 1967, the angular groin was removed from the south jetty and both jetties were extended landward to prevent jetty flanking as the adjacent shorelines retreated. From 1967 to 1988 about 1,452,000 m³ (1,899,000 c.y.) of sand removed from the sand trap and from dredging of the Intracoastal Waterway at the inlet (MEHTA *et al.*, 1992) was placed on the downdrift beach south of the south jetty. Presently, the inlet has two jetties, creating a straight navigation channel in the throat, with a 107-m-(350-ft)wide throat width and a channel length of 825 m (2,700 ft) (STAUBLE, 1993). The navigation channel is 60 m (197 ft) wide and has a 2-m-(6.5-ft-)depth (MEHTA *et al.*, 1990).

Inlet Processes and Morphology

The wave rose calculated at the 10-m-depth fronting the inlet (STAUBLE, 1993) from the transformed revised Level 2 WIS data (HUBERTZ *et al.*, 1993), indicates a predominant direction of wave approach from north of shore normal, with 36.7% of all waves from 13.4 degrees north of shore normal and 20.5% from 30.4 degrees north of shore normal (Figure 4). This predominance of north-of-shore-normal wave approach can be used to explain the ebb shoal asymmetry to the downdrift (southern) side of the inlet. The mean significant wave height is 0.5 m (1.7 ft). The mean tide range is 0.8 m (2.5 ft), with a spring range of 0.9 m (3.0 ft) at the south jetty. The tidal prism ranges from 2,900,000 m³ (3,800,000 c.y.) (McBRIDE, 1987) to 3,100,000 m³ (4,100,000 c.y.) (JARRETT, 1976). The five river back bay system presents a complex area to calculate tidal prism. The cross-sectional area of the inlet throat was measured as 2.7 × 10² m² (2.91 × 10³ ft²) by JARRET (1976) and 4.2 × 10² m² (4.52 × 10³ ft²) by DEAN and WALTON (1973). Net longshore transport rates were reported as 172,000 to 183,500 m³/yr (225,000 to 240,000 c.y.) (McBRIDE, 1987; MARINO and MEHTA, 1986) to the south. Using the BRUUN and GERRITSEN (1960) and BRUUN *et al.* (1974) indicator of stability, Jupiter Inlet has a value of 17, which falls into the very unstable category, due to its relatively low tidal prism. This inlet also has the highest hydraulic ratio and the highest wave-dominance of the group of southeast Florida inlets reported in STAUBLE (1993).

Shoreline Change

As previously mentioned, in 1966 a sand trap located 300 m (1,000 ft) west of the inlet throat was constructed to mechanically-bypass sand to the south beach, and on average, the trap has been dredged every two years (JONES and MEHTA, 1980; DOMBROWSKI and MEHTA, 1993). In addition, the Intracoastal waterway is dredged by the Corps of Engineers on an as-needed basis and the sand is also placed on the south beach. The amount of sand dredged from the sandtrap and Waterway has ranged from a low of 22,900 m³ (30,000 c.y.) in 1952 to a high of 160,000 m³ (209,000 c.y.) in 1966 (MEHTA *et al.*, 1992). The placement area has been a 240-m (800-ft) stretch of beach south of the south jetty. Typically, a longer area of the beach is prone to erosion.

Boca Raton Inlet, Florida

Boca Raton Inlet is a natural intermittent opening at the south end of Lake Boca Raton, opening when high runoff from the lake occurred. The first recorded dredging to re-establish the inlet was in 1925–1926 by local interests. The channel was oriented in a southeastward direction. In 1930, two parallel jetties were constructed, oriented to the east (CARROLL and SPADONI, 1984). Soon after, a fillet formed on the north (updrift) side of the north jetty and a crescent-shaped ebb shoal formed 91 m (300 ft) offshore. Shoaling within the inlet continued even with the jetties in place (COASTAL PLANNING AND ENGINEERING, 1992a). Initial dredging of the structured inlet, removing 11,200 m³ (14,700 c.y.) occurred in 1943 (COASTAL PLANNING AND ENGINEERING, 1992a). In 1952, the jetties were repaired and the inlet was dredged by local interests. Again in 1957 the inlet was dredged and sand was placed on the south beach. Continuous shoaling of the inlet and south beach erosion resulted in the City of Boca Raton purchasing a dredge in 1972, gaining easement to the inlet jetties and maintenance access land. In 1975, the north jetty was extended 55 m (180 ft) in an effort to reduce channel shoaling, but this action is believed to have blocked the natural sand bypassing process. Between 1975 and 1979, the north beach advanced seaward 42 m (137 ft) from sand trapped by the north jetty, while the south beach receded 57 m (187 ft). This northside fillet growth and southside erosion continued until 1980, when the south jetty was nearly flanked on the landward end. To mitigate this problem, a 20-m-(65-ft-)long weir section was constructed in the north jetty to allow sand to flow over the jetty and impound on the northern edge of the inlet throat (SPADONI *et al.*, 1983). Additional stone was added to the landward end of the south jetty. The period between 1980 and 1988 saw periodic dredging of the weir sand trap. The city-owned dredge bypassed sand to the south beach as needed and also dredged sand from other places in the channel and from the ebb shoal for nourishment of the south beach, maintaining a 24-m-(77-ft-)wide beach. Inlet impacts extend 610–1,220 m (2,000–4,000 ft) downdrift of the south jetty (COASTAL PLANNING AND ENGINEERING, 1992a). Dredging continued on a regular basis with 50,200 m³/yr (65,700 c.y./yr) transferred between 1980 and 1985, 25,100 m³/yr (32,800 c.y./yr) transferred between 1985 and 1990 and 37,800 m³/yr (49,500 c.y./yr) transferred between 1990 and 1991 (COASTAL PLANNING AND ENGINEERING, 1992a).

Inlet Processes and Morphology

The wave rose for this inlet indicates that the prevailing wave approach angle is from 32.5 degrees north of shore normal and contains 34.1% of the waves (STAUBLE, 1993). The secondary angle of wave approach is almost equally divided between the angles of 52.1 degrees and 9.9 degrees north of shore normal, with 17.5% and 16.9% of the waves respectively. These three north of shore normal directions account for 68.5% of all waves approaching the shoreline. This rose differs from the other nearby inlets to the north because of an increase in the percentage of waves approaching from nearly shore normal (STAUBLE, 1993). The mean significant wave height for this inlet is 0.5 m (1.6 ft) (STAUBLE, 1993). The tidal range has a mean of 0.9 m (2.8 ft) with a spring tide of around 1.0 m (3.3 ft).

The tidal prism ranges from 4.4–5.0 × 10⁶ m³ (1.55–1.75 × 10⁸ ft³) as reported in COASTAL PLANNING AND ENGINEERING (1992a) to 5.5

$\times 10^6$ m^3 (1.94 $\times 10^8$ ft^3) reported in MARINO (1986). The cross-sectional area is equal to 180 m^2 (MARINO, 1986). Longshore drift rates were reported to range between 114,700 and 214,100 m^3/yr (150,000–280,000 c.y./yr) to the south (STAUBLE, 1993). Others report a range of 92,500 to 154,000 m^3/yr (121,000–201,000 c.y./yr) to the south (COASTAL PLANNING AND ENGINEERING (1992a) and WALTHER and DOUGLAS (1993)). A stability ratio (Ω/M_{tot}) of 31, which indicates an inlet that becomes a bar bypasser, with highly changeable channels and basically poor stability without engineering structures was computed for Boca Raton Inlet based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974).

Inlet morphology measurements include an inlet throat length of 183 m (600 ft) and a width of 67 m (220 ft) (STAUBLE, 1993). The ebb shoal length in the offshore direction measured from the throat is 198 m (650 ft), with an alongshore width of 580 m (1,900 ft). The ebb shoal is asymmetrically-shaped (offset to the south of Boca Raton Inlet). The estimated ebb shoal volume reported in STAUBLE (1993) ranges from 600,000 to 800,000 m^3 (785,000 to 1,046,000 c.y.). Using specific shoal data collected in 1978 and 1981, the ebb shoal volume was computed to be 610,000 m^3 (798,000 c.y.) by DOMBROWSKI (1994), and from 1981 data was computed to be 840,000 m^3 (1,100,000 c.y.) by DEAN and O'BRIEN (1987b).

Shoreline Change

Surveys of the shoreline taken upon completion of the north jetty (May 1975), completion of the weir section (January 1980), and in August 1982 indicate that the area adjacent to the north jetty extending 380 m (1,250 ft) to the north and seaward to the −2-m (-6-ft) contour had gained around 89,600 m^3 (117,200 c.y.) of sand. An 800-m (2,640-ft) stretch north of this area experienced erosion (STROCK AND ASSOCIATES, 1983). Prior to sand mining (from 1975 to 1979), STOCK AND ASSOCIATES (1982) reported an average erosion rate of 25,300 m^3/yr (33,130 c.y./yr) and a shoreline recession rate of 4.6 m/yr (15.1 ft/yr) on the south beach, extending 1,610 m (5,280 ft) south of the south jetty. With the increased dredging and placement of material on the south beach, the measured erosion rate decreased.

John's Pass, Florida

John's Pass was opened by a hurricane in 1848 and drains the northern part of Boca Ciega Bay into the Gulf of Mexico. In 1960, 71,900 m^3 (94,000 c.y.) was dredged from the channel at John's Pass and placed on the ebb shoal complex, 610 m (2,000 ft) offshore and south of the dredged channel (USAED JACKSONVILLE, 1969). In 1961, a 140-m-(460-ft-)long curved north jetty was constructed and 22,900 m^3 (30,000 c.y.) of material dredged from the navigation channel was placed on the beach north of John's Pass (MEHTA et al., 1976). By 1964, a navigation project was initiated for John's Pass and in 1966, an additional 72,600 m^3 (95,000 c.y.) was dredged from the navigation channel and placed offshore. By 1968, O'Brien's Lagoon formed in the northern reach of Treasure Island, an area sheltered from direct wave attack by the 1960 and 1966 dredged material placements. In 1966, a 280-m-(920-ft-)long revetment was constructed along the south bank of John's Pass, to prevent erosion. In 1971, 57,300 m^3 (75,000 c.y.) of material was dredged from a shore-connected bar at John's Pass and used to nourish Treasure Island (MEHTA et al., 1976).

Inlet Processes and Morphology

Originally, John's Pass was considered a mixed-energy inlet with a downdrift offset. Since the 1970's it has been considered a tide-dominated inlet, as the cross-sectional area, tidal prism, and ebb shoal have increased in size (DAVIS and GIBEAUT, 1990). In 1873, the inlet throat cross-sectional area was 474 m^2 (5,100 ft^2) and the minimum inlet throat width was 130 m (425 ft). By 1974, the cross-sectional area had steadily increased to 883 m^2 (9,500 ft^2) and the minimum inlet throat width was 180 m (590 ft). Blind Pass, to the south, has diminished in size and tidal prism as John's Pass has enlarged. The continual increase in cross-sectional area at John's Pass has captured a greater tidal prism volume and has allowed John's Pass to dwarf Blind Pass' interaction with Boca Ciega Bay

(DAVIS and GIBEAUT, 1990). The tidal prism at John's Pass computed for a 10-day period in 1974 was approximately 5.7 $\times 10^6$ m^3 (2 $\times 10^8$ ft^3) (MEHTA et al., 1976). The spring tidal prism computed by JARRETT (1976) using the cubature method, and NOS current data was approximately 1.4 $\times 10^7$ m^3 (5 $\times 10^8$ ft^3). Tides at John's Pass are mixed (diurnal and semidiurnal) with a spring tide range of 0.7 m (2.3 ft) (NOS Tide Tables). Tidal current studies have been performed at John's Pass in 1960, 1966, 1968, and 1974 using floats and current meters (MEHTA et al., 1976). Current velocities reported in JARRETT (1976) have a maximum flood current of 1.0 m/sec (3.4 ft/sec) and a maximum ebb current flow of 0.8 m/sec (2.5 ft/sec). MEHTA et al. (1976) concluded that the 1960 and 1966 placement of dredged material in the offshore disposal site may have caused the currents to hug the south shoreline of John's Pass. The dominant direction of wave approach is 45 deg north of shore-normal, indicating a net transport to the south (WALTON, 1973). The mean significant wave height and mean peak period are 0.8 m (2.6 ft) and 4.8 sec, respectively measured from wave information at the WIS Gulf Coast Station 39 (HUBERTZ and BROOKS, 1989) in a water depth of 11.0 m (36 ft). This is close to a Phase III wave height in approximately 9.1 m (30 ft) of water. Estimates of net longshore transport range from 30,800 m^3/yr (40,300 c.y./yr) to the south (WALTHER and DOUGLAS, 1993) to 38,200 m^3/yr (50,000 c.y./yr) to the south (DAVIS and GIBEAUT, 1990). The gross longshore transport rate is estimated to be 157,400 m^3/yr (205,500 c.y./yr) (WALTHER and DOUGLAS, 1993). The net sediment transport rate along Treasure Island is estimated to be 38,200 m^3/yr (50,000 c.y./yr) to the south (MEHTA et al., 1976). Based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974), a stability ratio (Ω/M_{tot}) of around 182 was calculated for John's Pass, indicating a stable inlet with a relatively fixed entrance condition and a dominance of tidal flow.

Shoreline Change

Hydrographic surveys conducted by the U.S. Coast and Geodetic Survey (1873, 1926, and 1939) and the U.S. Army Corps of Engineers (1950 and 1964–1965) were analyzed by the Jacksonville District (USAED JACKSONVILLE, 1969) and tabulated by MEHTA et al. (1976) to determine shoreline change rates near John's Pass. Data from 1873 to 1965 show that the area north of John's Pass has experienced erosion, but accreted during the period 1950–1965 possibly due to other mitigating factors. The area immediately south of the inlet (first 1,220 m (4,000 ft)) has accreted steadily, but the remainder of Treasure Island has experienced erosion.

Longboat Pass, Florida

Longboat Pass is a naturally occurring inlet that has been in its present location since documented history (APPLIED TECHNOLOGY AND MANAGEMENT, 1993a). Longboat Pass was present on an 1876 USC&GS map with a spit on the south side. In 1883, two inlets existed, the present inlet and a breakthrough of southern Anna Maria Island. By 1913, the north inlet closed and Anna Maria Island was again a continuous island. The first bridge between Anna Maria Island and Longboat Key was constructed in 1926, but was destroyed by a storm in 1932 (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). As a result of the storm, the south end of Anna Maria Island was again breached and formed a second inlet throat. Between 1935 and 1939 accretion was measured on both the north end of Longboat Key and the south end of Anna Maria Island (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). Erosion of both adjacent shorelines occurred in 1939, when the Intracoastal Waterway was dredged, joining Jewfish and Pickett Keys in Sarasota Bay. In 1957, a 229-m-(750-ft-)long north jetty was constructed at the south end of Anna Maria Island and acted as a terminal groin (APPLIED TECHNOLOGY AND MANAGEMENT, 1993a). In 1958, a second bridge was built to connect Anna Maria Island and Longboat Key.

The Pass became a Federal project in 1977, and a 46-m-(150-ft-)wide navigation channel was dredged with a −4.3 m (−14 ft) MLW project depth. The navigation channel is located in the center towards the south side of the inlet throat. The inlet throat ranges from 194 to 274 m (637 to 900 ft) wide and 366 to 500 m (1,200 to 1,640 ft) long, with a channel design depth of 4.3 m (14 ft) (DAVIS and GIBEAUT,

1990 and APPLIED TECHNOLOGY AND MANAGEMENT, 1992). An initial dredging volume of 235,100 m³ (307,500 c.y.) was removed from the navigation channel. Of this quantity, 64,000 m³ (83,800 c.y.) was placed on the north end of Longboat Key, 143,600 m³ (187,800 c.y.) was placed on the south end of Anna Maria Key at Cortez Beach, and 27,500 m³ (36,000 c.y.) was placed in the bay (DEAN and O'BRIEN, 1987; APPLIED TECHNOLOGY AND MANAGEMENT, 1992). With the large amount of sediment moving through the Longboat Pass system, the navigation channel has required dredging every 4–5 years to maintain the channel location and depth. The dredged material has been placed on the adjacent beaches. The channel was dredged in 1982, with 126,200 m³ (165,000 c.y.) of material removed from the channel and placed on Longboat Key (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). A third dredging event occurred in 1985, when 126,300 m³ (165,200 c.y.) of material was removed from the channel and placed on Anna Maria Island. The fourth dredging in 1991 removed 15,300 m³ (20,000 c.y.) of channel material, placing 7,650 m³ (10,000 c.y.) on Anna Maria Key, and 7,650 m³ (10,000 c.y.) on Longboat Key (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). The frequent placement of dredged material has stabilized the southern 2.4 km (1.5 miles) of Anna Maria Island and the northern 1.8 km (1.1 miles) of Longboat Key, but a high erosion risk area still remains further south on Longboat Key (1.8 to 4.0 km (1.1 to 2.5 miles) south of Longboat Pass).

Numerous bathymetry maps exist for Longboat Pass including 1874–1876, 1924–1926 (USC&GS), 1955–1956, and 1962–1964 (USGS/USC&GS) (APPLIED TECHNOLOGY AND MANAGEMENT, 1993a). The ebb shoal was surveyed in December 1988, December 1991–January 1992, May 1992, December 1992–June 1993, post-fill July 1993, August 1993, April 1993 and August 1994 (APPLIED TECHNOLOGY AND MANAGEMENT, 1993a,c). Historic beach profiles were collected in 1974 and 1986 by the Florida Department of Natural Resources (DNR), Division of Beaches and Shores, and in 1991 by the Jacksonville District using DNR monuments.

Inlet Processes and Morphology

The significant mean wave height in the vicinity of Longboat Pass calculated from the 20-year WIS data is 0.8 m (2.6 ft) (HUBERTZ and BROOKS, 1989), with a peak period of 4.8 sec measured from the WIS Gulf Coast Station 41 at a deepwater depth of 32.9 m (108 ft). A rough estimate of a Phase III wave height in around 9.1 m (30 ft) of water is 0.6 m (2.0 ft) which is around 75% of the deepwater height. The predominant wave approach direction is from the northwest (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). The tide range for this diurnal Gulf coast inlet is 0.8 m (2.5 ft) on the Gulf of Mexico side and 0.7 m (2.2 ft) within Sarasota Bay (DAVIS and GIBEAUT, 1990). Spring tidal prism measurements range from 8.4 × 10⁶ m³ (2.98 × 10⁸ ft³) (DAVIS and GIBEAUT, 1990) to 4.1 × 10⁷ m³ (14.48 × 10⁸ ft³) (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). Maximum flood tidal current velocities were reported as 0.6 m/sec (2.1 ft/sec) in 1987 by DAVIS and GIBEAUT (1990) and 1.1 m/sec (3.5 ft/sec) by APPLIED TECHNOLOGY AND MANAGEMENT (1992). The maximum ebb current velocities were reported as 1.2 m/sec (3.9 ft/sec) in 1987 by DAVIS and GIBEAUT (1990) and 1.1 m/sec (3.7 ft/sec) by APPLIED TECHNOLOGY AND MANAGEMENT (1992). The inlet cross-sectional area was reported as 833 m² (8,970 ft²) in 1987 (DAVIS and GIBEAUT, 1990).

The net longshore transport rate for Longboat Pass reported in DAVIS and GIBEAUT (1990) and DEAN and O'BRIEN (1987a) is approximately 45,800 m³/yr (60,000 c.y./yr) southward. A stability ratio (Ω/M$_{tot}$) of around 183 was calculated for Longboat Pass based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974), indicating a stable inlet with a relatively fixed entrance condition and a dominance of tidal flow. Southerly transport is found along the southernmost 1,830 m (6,000 ft) of Anna Maria Island. A more detailed sediment budget lists the longshore transport rate for south Anna Maria Island as 45,100–106,300 m³/yr (59,000–139,000 c.y./yr) to the north, and 72,600–128,500 m³/yr (95,000–168,000 c.y./yr) to the south, with a net of 24,850 m³/yr (32,500 c.y./yr) to the south (APPLIED TECHNOLOGY AND MANAGEMENT, 1992).

On Longboat Key, the longshore transport rates are 61,300 m³/yr

(80,200 c.y./yr) to the north and 87,000 m³/yr (113,800 c.y./yr) to the south, with a net of 25,700 m³/yr (33,600 c.y./yr) to the south (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). A strong southward transport is found along the shoreline starting between 1,525–3,050 m (5,000–10,000 ft) south of the pass on Longboat Key. The sediment transport pattern has a local northward drift reversal along the northernmost 1,525 m (5,000 ft) of Longboat Key, leading to the development of a northward-growing spit known as Beer Can Island and a nodal point between DNR benchmarks R48 and R51, 1,525–2,440 m (5,000–8,000 ft) south of the pass. The probable cause of the observed nodal point and local northward drift reversal is wave refraction over the ebb shoal (APPLIED TECHNOLOGY AND MANAGEMENT, 1993a). The Jacksonville District has periodically placed dredged material from the inlet navigation channel maintenance operations on Longboat Key between DNR benchmarks R42 and R48 to mitigate the higher erosion in this nodal area (APPLIED TECHNOLOGY AND MANAGEMENT, 1992).

Shoreline Change

Historic shoreline volume changes between 1946 and 1985 showed a gain of 2,982,000 m³ (3,900,000 c.y.) on the 2,750-m (9,000-ft) stretch north of the inlet (Anna Maria Island), and a loss of 382,300 m³ (500,000 c.y.) on the 2,960-m (9,700-ft) stretch south of the inlet (DEAN and O'BRIEN, 1987a). Erosion rates for Longboat Key of 3.8–8.4 m³/yr (5–11 c.y./yr) were measured between 1974 and 1986 (APPLIED TECHNOLOGY AND MANAGEMENT, 1992).

New Pass (Sarasota County), Florida

In 1964, New Pass was commissioned as a federally-authorized navigation inlet with a 46-m (150-ft) wide, 3-m (10-ft) deep entrance channel and a 30.5-m (100-ft) wide, 2.4-m (8-ft) deep inner channel extending to the Intracoastal Waterway (COASTAL PLANNING AND ENGINEERING, 1993). Since New Pass was commissioned, the channel has been dredged six times (1964, 1974, 1977, 1982, 1985, 1991) for a total volume of 1.2 × 10⁶ m³ (1.6 × 10⁶ c.y.) (APPLIED TECHNOLOGY AND MANAGEMENT, 1993b). Most of the material (84%) has been placed to the south along Lido Key and the remainder (16%) has been placed to the north along Longboat Key. In 1970, a rock groin was built on the north side of the inlet to protect the Sands Point Condominium pool and anchor the north side of New Pass from erosion. In 1982, the channel was realigned 107 m (350 ft) to the south to follow the natural channel alignment and thereby reduce the frequency and cost of maintenance dredging. Shoreline erosion along Lido Key was thought to be caused by this realignment because it is believed that the contractor may have dredged the channel further south than the authorized dredge limits (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). The 1991 dredging included the addition of a 1,370-m-(4,500-ft-)long, 30.5-m-(100-ft-)wide settling basin adjacent to the navigation channel in a further attempt to reduce the frequency of maintenance dredging.

Inlet Processes and Morphology

COASTAL PLANNING AND ENGINEERING (1993) used WIS wave information from Station 41 (HUBERTZ and BROOKS, 1989) to represent waves in this study area. Waves from the northwest direction are largest and have the highest percent occurrence, therefore the net longshore transport direction is to the south. Waves from the southwest are not as large as waves from the northwest, but have a large percent occurrence. Thus, there is a high variability in the longshore transport direction at New Pass. The mean significant wave height and mean peak period are 0.8 m (2.6 ft) and 4.8 sec, respectively measured from wave information at the WIS Gulf Coast Station 41 (HUBERTZ and BROOKS, 1989) at a deepwater depth of 33 m (108 ft). A rough estimate of a Phase III wave height in around 9.1 m (30 ft) of water is 0.6 m (2.0 ft) which is around 75% of the deepwater height. Tides in the vicinity of New Pass are mixed (semidiurnal and diurnal). The diurnal component dominates with a mean range reported as approximately 0.6 m (2.1 ft) (COASTAL PLANNING AND ENGINEERING, 1993) and 0.8 m (2.5 ft) (DAVIS and GIBEAUT, 1990). The tidal prism has been estimated to be between 8.7 × 10⁶

m^3 (3.1×10^8 ft^3) (DOMBROWSKI, 1994) and 1.1×10^7 m^3 (4.0×10^8 ft^3) (JARRETT, 1976). Maximum tidal currents were reported as 0.8 m/sec (2.7 ft/sec) on flood and as 0.5 m/sec (1.7 ft/sec) on ebb (JARRETT, 1976).

As previously stated, the net longshore transport at New Pass is to the south. The rate of transport reported in the literature ranged from 21,000 m^3/yr (27,500 c.y./yr) (DEAN and WALTON, 1973) to 45,800 m^3/yr (60,000 c.y./yr) (DEAN and O'BRIEN, 1987a; DAVIS and GIBEAUT, 1990). APPLIED TECHNOLOGY AND MANAGEMENT (1992) estimated that the longshore transport is 30,600–38,200 m^3/yr (40,000–50,000 c.y./yr) to the south. A stability ratio (Ω/M_{tot}) of around 240 was calculated for New Pass, indicating a stable inlet with a relatively fixed entrance condition and a dominance of tidal flow based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974).

Six sediment samples were taken along Lido Key in August 1991 to determine sediment characteristics of the native beach south of New Pass. The average grain size of the samples was 0.24 mm (2.1 ϕ) with a moderate shell content (COASTAL PLANNING AND ENGINEERING, 1993). Note that, to the authors knowledge, beach nourishment work along Lido Key using borrow material from the New Pass ebb shoal has not occurred. Sediment samples were taken along Longboat Key by the U.S. Army Corps of Engineers and by Applied Technology and Management during the 1989–1991 time frame (Applied Technology and Management, personal communication). Vibracores taken on the ebb shoal were used to determine the sediment characteristics of the ebb shoal borrow areas. Vibracore samples taken from the ebb shoal at New Pass in October 1991 had a composite mean grain size of 0.22 mm (2.2 ϕ) and a sorting value of 1.51 ϕ (APPLIED TECHNOLOGY AND MANAGEMENT, 1992). COASTAL PLANNING AND ENGINEERING (1993) reported that the composite mean grain size was 0.25 mm (2.0 ϕ), with the mean grain size for individual cores ranging from 0.15 mm to 0.47 mm (2.7 to 1.1 ϕ). The ebb shoal core samples indicate that the shoal sediment is generally well-sorted with a low content of fine sediment (COASTAL PLANNING AND ENGINEERING, 1993). An overfill factor of 1.1 was recommended for the beach fill project design (APPLIED TECHNOLOGY AND MANAGEMENT, 1992).

Shoreline Change

Between 1883 and 1942 the inlet migrated 300 m (1,000 ft) to the south and the shorelines north and south of the inlet eroded as ebb and flood shoals were established at New Pass (COASTAL PLANNING AND ENGINEERING, 1993). After 1942, the shoreline immediately adjacent to the inlet was sheltered by the ebb shoal and experienced an accretional period. Quoting from the Inlet Management Plan for New Pass (COASTAL PLANNING AND ENGINEERING, 1993) "The shoreline near the inlet responds to changes in the offshore bathymetry of the ebb shoals and the existence of swash channels along the beach. When the shoals shift or diminish or when swash channels are created, the area erodes. Building shoals refilled swash channels and caused accretion of the beach." The shoreline beyond the influence of the shoals was erosional. Most significant erosion occurred at a nodal point which exists near the central portion of Lido Key due to the drift reversal caused by the ebb shoal wave sheltering effect. A more detailed discussion of shoreline change north and south of New Pass follows.

Shoreline change north of New Pass (Longboat Key) that is within Sarasota County will be discussed. Since 1883 Longboat Key has been losing sand (COASTAL PLANNING AND ENGINEERING, 1993). Large fluctuations occur near the inlet, possibly in response to ebb shoal evolution and inlet modifications. The south end of Longboat Key has experienced large fluctuations, initially losing material as the ebb shoal formed and then gaining material because the ebb shoal sheltered it from direct wave attack. Between 1883 and 1942, the Longboat Key shoreline erosion rate was 1.1 m/yr (3.6 ft/yr), retreating most near the inlet as a spit formed at the southern end of Longboat Key and the ebb shoal was being established. From 1942 to 1952 the overall shoreline was relatively stable (negligible erosion rate), but actually the southern end of Longboat Key closest to New Pass gained 5.0 m/yr (16.4 ft/yr). From 1952 to 1971 the shoreline

north of New Pass was accretional (0.2 m/yr (0.6 ft/yr)) with the largest accretion rates closest to the inlet. From 1971 to 1977 the Longboat Key shoreline was erosional (2.6 m/yr (8.4 ft/yr)), but the area closest to New Pass gained 0.8 m/yr (2.5 ft/yr). From 1977 to 1987 the erosion rate appears to have diminished to 1.0 m/yr (3.2 ft/yr), however, dredged material was placed in the area in 1982. The erosion rate near New Pass was 2.2 m/yr (7.1 ft/yr). From 1987 to 1991 the Longboat Key shoreline appears to have been accretional (1.5 m/yr) (4.9 ft/yr)), but again, dredged material was placed in this area in 1990. The erosion rate near New Pass was 0.5 m/yr (1.6 ft/yr).

Similar to Longboat Key, Lido Key has been historically accretional near New Pass. As previously mentioned, Lido Key has an erosional "hot spot" in the center and is generally erosional along the southern half of the island. Lido Key was a series of mangrove islands for most of the 1883 to 1942 time period. Erosion along the northern portion of Lido Key was 1.0 m/yr (3.4 ft/yr) during this time period and the southern portion retreated at a higher rate (2.8 m/yr) 9.1 ft/yr. From 1942 to 1952, the overall shoreline accreted at a rate of 0.9 m/yr (3.1 ft/yr). The area closest to New Pass advanced while the central portion eroded significantly and the southern portion advanced. From 1952 to 1971, shoreline advancement along Lido Key of 3.4 m/yr (11.1 ft/yr) was partly due to dredged material placement (360,100 m^3 (471,000 c.y.)). From 1971 to 1977, Lido Key accreted 0.2 m/yr (0.7 ft/yr) on average, with the greatest gains closest to New Pass. Dredged material placement (183,500 m^3 (240,000 c.y.)) during this time period may account for some of the shoreline advancement. From 1977 to 1987, Lido Key eroded 1.0 m/yr (3.3 ft/yr) with the northernmost area (near New Pass) retreating 1.9 m/yr (6.3 ft/yr) and the central "hot spot" area retreating 7.6 m/yr (25.0 ft/yr). During this time period, 520,700 m^3 (681,000 c.y.) of dredged material was placed on Lido Key. Lido Key gained sand in recent years (1.4 m/yr (4.5 ft/yr) from 1987 to 1991), but part of this gain was due to the placement of 183,500 m^3 (240,000 c.y.) of dredged material during this time period.

Redfish Pass, Florida

Redfish Pass was opened by a hurricane in the 1920's and connects Pine Island Sound with the Gulf of Mexico. STAUBLE and HOEL (1986) state that the northern tip of Captiva Island has experienced significant erosion as Redfish Pass has evolved. The Captiva Erosion Prevention District formed in 1959 (Florida Legislative Act) to take measures to prevent further erosion of Captiva Island (COASTAL PLANNING AND ENGINEERING, 1988). Timber groins, a terminal rock groin at Redfish Pass, rock revetment, concrete seawall, sandbag breakwaters, and a sand beach fill borrowed from the bay side of the island were all constructed during the 1961 to 1980 time frame to combat the erosion along Captiva Island, however, erosion of the downdrift beaches continued. In recent years (1981 and 1988), beach fill material was dredged from the ebb shoal to nourish the beaches of Captiva Island as was addressed in the section on ebb shoal mining. The nourishment of Captiva Island (using material from the ebb shoal at Redfish Pass) was part of a beach erosion control project authorized under provisions of Section 201 of the Flood Control Act of 1965 (COASTAL PLANNING AND ENGINEERING, 1988). The authorized project involved Federal participation in beach erosion control measures for parts of the Gulf Shore of Lee County by providing a protective and recreational beach.

Inlet Processes and Morphology

Redfish Pass is normally exposed to moderate wave energy (TANNER, 1960). COASTAL PLANNING AND ENGINEERING (1988) used wave information from the WIS Gulf Coast Station 41 (HUBERTZ and BROOKS, 1989) at a water depth of 32.9 m (108 ft) (H_{mo} = 0.8 m (2.6 ft)) to estimate wave conditions in the vicinity of Captiva Island/Redfish Pass. Waves near the midpoint of Captiva Island are estimated to have a mean breaking wave height of 0.6 m (2 ft) and wave period of 5.5 sec. Tides in the vicinity of Redfish Pass are mixed (semidiurnal and diurnal). The diurnal component dominates with a mean range of approximately 0.5 m (1.7 ft). Redfish Pass has a tidal prism between 1.2 and 1.6×10^7 m^3 (4.2–5.7×10^8 ft^3) as reported in DOMBROWSKI (1994).

COASTAL PLANNING AND ENGINEERING (1988) states that previously reported net longshore transport rates to the south range between 46,200 m³/yr (60,400 c.y./yr) and 106,300 m³/yr (139,000 c.y./yr). Based on littoral drift roses, the net longshore transport rate reported by COASTAL PLANNING AND ENGINEERING (1992b) is 58,500 m³/yr (75,500 c.y./yr) to the south. A reliable estimate of gross transport is not available. WALTHER and DOUGLAS (1993) assumed transport across the ebb shoal was at a rate equal to the net longshore transport rate of 58,500 m³/yr (76,500 c.y./yr). A stability ratio (Ω/M_{tot}) of between 150 to 260 was calculated for Redfish Pass, indicating a stable inlet with a relatively fixed entrance condition and a dominance of tidal flow based on BRUUN and GERRITSEN (1960) and BRUUN et al. (1974).

Sediment from the ebb shoal borrow area was collected as part of the first ebb shoal mining/beach nourishment project for Redfish Pass/Captiva Island (TACKNEY AND ASSOCIATES, 1982). Twenty-seven vibracores were taken in 1979 and 8 vibracores were taken in 1980 (COASTAL PLANNING AND ENGINEERING, 1988). Grain size analyses were done on samples taken from the cores. The ebb shoal sediments were found to contain shell and coarse to fine grain sand with a mean of 0.44 mm (1.20 ϕ) and a sorting value of 1.72 ϕ (STAUBLE and HOEL, 1986). The native beach material had a mean of 0.38 mm (1.53 ϕ) and a sorting value of 1.63 ϕ. The ebb shoal borrow material used for the 1981 beach nourishment project was almost identical to the native beach material (in terms of mean and sorting values), but the borrow material contained excess coarse shell material and was deficient in sand. An overfill factor of 1 was assumed adequate and conservative (COASTAL PLANNING AND ENGINEERING, 1988). It is believed by the authors that this information was used for the second (1988) ebb shoal mining, without taking additional cores from the ebb shoal or from the 1981 ebb shoal borrow area (infill material).

Shoreline Change

The shoreline south of Redfish Pass, the downdrift shoreline, is an erosional shoreline. In their report, COASTAL PLANNING AND ENGINEERING (1988) includes computations of historical (1967 to 1980) shoreline change for Captiva Island done by TETRATECH (1981) as well as shoreline change computations after the 1981 ebb shoal mining/beach nourishment project (1981–1987). It was determined that the historical shoreline erosion rate for the northern portion of Captiva Island is generally higher (8.8–12.5 m³/m/yr (3.5–5.0 c.y./ft/yr)) than the southern portion of Captiva Island (4.5–9.8 m³/m/yr (1.8–3.9 c.y./ft/yr)), excluding end effects where the erosion is much higher. The shoreline erosion rate after dredging/fill placement in 1981 was higher than the historical shoreline erosion rate. The erosion rate for the northern portion of Captiva Island was 7.3–23.3 m³/m/yr (2.9–9.3 c.y./ft/yr). The erosion rate for the southern portion of Captiva Island was 0.3–31.4 m³/m/yr (0.1–12.5 c.y./ft/yr). However, the northernmost portion of Captiva Island accreted, indicative of a local drift reversal. From this analysis, COASTAL PLANNING AND ENGINEERING (1988) concluded that the expected shoreline erosion rate after the 1988 beach nourishment project, would be 10.5 m³/m/yr (4.2 c.y/ft/yr) for the northern half of Captiva Island and 5.8 m³/m/yr (2.3 c.y/ft/yr) for the southern half of Captiva Island. The shoreline north of Redfish Pass is reported to have been stable from 1979 to 1988 (WALTHER and DOUGLAS, 1993).