Reprinted from: Viggósson, G. (ed.), 1994. *Proceedings of the Hornafjördur International Coastal Symposium* (Höfn, Iceland, 20-24 June 1994). [Proceedings available from the Icelandic Harbour Authority, Vesturvör 2, 202 Kópavogur, Reykjavik, Iceland]

# Tidal Inlets in Florida: Their Morphodynamics and Role in Coastal Sand Management

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## ABSTRACT

FINKL, C.W., Jnr., 1994. Tidal inlets in Florida: Their morphodynamics and role in coastal sand management. *Proceedings International Coastal Symposium* (Hornafjördur, Iceland, 20-24 June 1994), pp. 67-85.

Inlets, passes and cuts are a common feature of Florida shores: the Atlantic coast is punctuated by 19 man-made and natural inlets whereas there are more than 40 inlets along the Gulf coast. Erosion of sandy beaches on the downdrift (south) sides of inlets stabilized by jetties is a chronic problem that requires remediation. In order for erosion control measures to be effective, coastal protection measures must consider inlet stability and the coastal geological framework because different morphodynamic systems (barrier island chains, marsh and mangrove coasts, rocky shores, reef-fronted mainland, and keys) influence strategies for littoral sand management. The limited reserves of offshore borrow materials suitable for beach renourishment and the loss of nearshore sediments to deep offshore regions by tidal jets at inlets and turbidity plumes requires alternative sand sources and enhanced sand bypassing techniques. Environmental impacts, socio-economic, and political constraints of sand management schemes are related to the on-going "sand wars", and consideration of ecologically-favored alternatives. Beach replenishment combined with enhanced sand bypassing is a preemptive strategy over conventional techniques.

**Additional Index Words:** *Beach erosion, borrow material, coastal erosion, coastal management, dredging, environmental monitoring, navigational entrance, sand management, tidal pass, shoreline stabilization.*

## INTRODUCTION

Erosion of sandy beaches, a world-wide problem (BIRD, 1985), is related to long-term (background) relative sea-level rise (RSL). East- and west-coast Florida beaches (Figure 1) are no exception to this general trend. Attempting to determine the causes of localized short-term beach erosion, researchers now focus attention on shorelines adjacent to inlets because navigational entrances interfere with natural sediment transport processes. Inlets stabilized by jetties disrupt the natural sand supply to downdrift beaches and are estimated to be responsible for 85% of the erosion problem along the Florida east coast (DEAN, 1990). The nexus between beach erosion and stabilized inlets is not confined to the sandy barriers of Florida and has been established for many coastal segments the world over (BRUUN, 1978). There is thus much interest in new or improved methods that bypass larger quantities of sand around inlets.

This paper briefly reviews some salient properties of tidal inlets in Florida, particularly those inlets along the Atlantic east coast, and discusses new management techniques for bypassing sand around navigational entrances. Because emphasis is placed on stabilization techniques that operate in harmony with natural coastal processes, relevant aspects of the geological evolution and framework of the Florida coast are reviewed as they influence strategies for coastal sand management.

## THE COAST OF FLORIDA

The Florida peninsula exhibits a wide range of coastal environments (Figure 1), with numerous dredged and natural inlets, 19 on the east coast and over 40 on the west coast (STAUBLE, 1993). Sandy barrier islands occur on Atlantic and Gulf coasts and have been referred to as the Northwest Barrier Chain, West-Central Barrier Chain, and Florida East Coast Barrier Chain (HINE *et al.*, 1986). Marshes are associated with the Big Bend

Coast (between Tallahassee and Tampa) and the Ten Thousand Island Mangrove Coast along the southwestern part of the peninsula. Rocky shores are associated with the living coral reefs of the Florida Keys (LIDZ and SHINN, 1991) and parts of the Southeast Mainland Coast (FINKL, 1993) where rock outcrops are associated with the Pleistocene Anastasia Formation and Recent Sabellariid worm reefs in the surf and subtidal zones (KIRTLEY and TANNER, 1968).

Inlets and passes are primarily associated with the barrier chains and southeast mainland coast (Table 1). The Atlantic coast is exposed to high energy conditions (average breaker heights exceed 50 cm) whereas moderate energy conditions (average breaker height ranges between 10-50 cm) characterize much of the West-Central Barrier Chain and "zero" energy conditions (average breaker height 4-5 cm) along the Northwest Barrier Chain (TANNER, 1985). These microtidal, mixed energy coasts (*cf* HAYES, 1979) have mixed and semi-diurnal tides; net littoral drift is to the south, although both coasts experience seasonal reversals. Flood-tidal deltas along the west-central Florida coast are relatively inactive due to small tidal ranges, sheltered lagoons, and ebb-dominated inlets (DAVIS, 1989). Because variation in ebb-tidal morphology is caused by fluctuations in wave and tidal energies (MORANG, 1992), slight shifts in the energy spectrum induces large changes in delta configuration. GIBEAUT and DAVIS (1933) report that, in general, wave- and tide-dominated inlets respectively have over-and undersized ebb-tidal plan areas relative to their throat cross-sectional areas and tidal prisms. Although many of the well-known inlets along the Florida coast are associated with the sandy barrier chains, there are numerous inlets and passes along marsh and mangrove coasts.

## EVOLUTION OF THE SOUTHEAST COAST

The southeast Florida coast, which embraces the seaward parts of Palm Beach, Broward and Dade counties (Figure 1), is regarded by state management agencies as a barrier island coast. The "barrier islands," as identified by the Florida Department of Natural Resources, are comprised by that section of the coastal zone lying between the Intracoastal Waterway (ICWW) and ocean beaches. Such administrative divisions should not, however, be confused with natural topographic, geomorphological, or geologic units. Although useful for regulatory purposes, application of the term "barrier island coast" implies a range of environmental conditions and processes, as described by DOLAN *et al.*

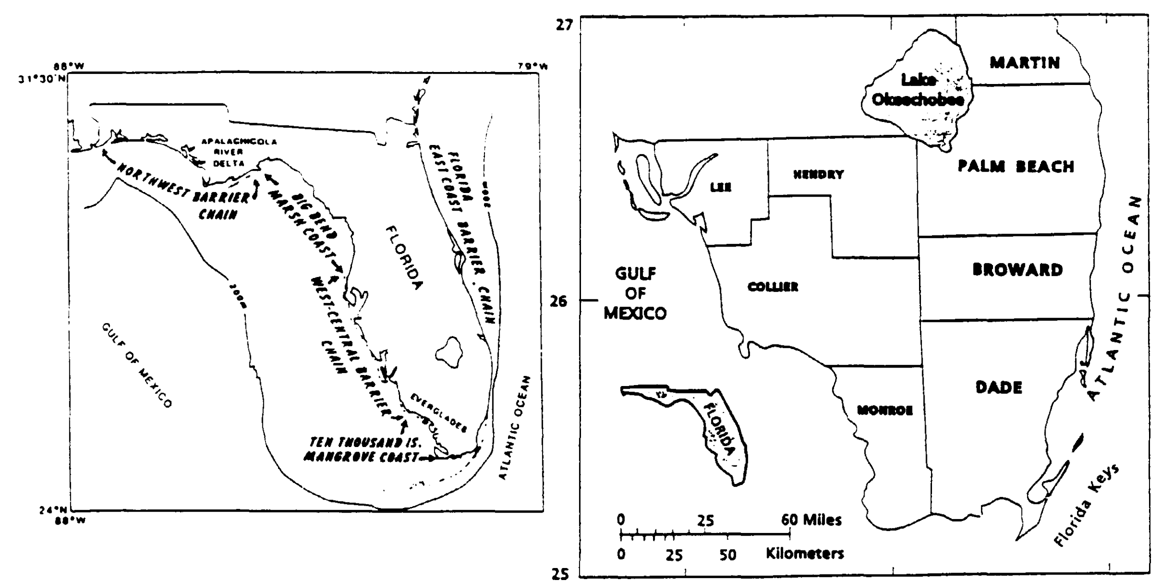


Figure 1. Map of Florida showing the main coastal morphologic systems, edge of the continental shelf along the 200 m isobath (left), and detailed study areas along the southeast mainland coast (right).

Table 1. List of some Florida inlets and selected morphometric properties.

| Inlet, Pass, Entrance, or Channel | Year of Data Collection | Channel Width (m) | Channel Depth (m) | Ebb-Delta Volume ($10^6 m^3$) | Flood-Delta Volume ($10^6 m^3$) | Spring Tide Amplitude (cm) | Net Littoral Drift ($m^3$) |
|---|---|---|---|---|---|---|---|
| **Central West Coast** | | | | | | | |
| Hurricane | 1984 | 220 | 2.1 | 0.758 | 1.988 | 88 | 57,300 |
| Dunedin | 1984 | 20 | 1.8 | 0.917 | 1.835 | 87 | 76,400 |
| Clearwater | 1984 | 411 | 2.6 | 5.367 | 0.688 | 86 | 76,400 |
| John's | 1984 | 180 | 6.1 | 3.838 | 0.382 | 81 | 38,200 |
| Blind | 1984 | 182 | 1.2 | 1.262 | Nil | 80 | 38,200 |
| P-A-Grille | 1976 | 820 | 5.4 | 2.759* | Nil | 79 | 76,400 |
| Bunces | 1984 | 500 | 6.5 | 1.753 | Nil | 79 | 76,400 |
| Egmont | 1984 | 1280 | 6.4 | 267.594 | Nil | 76 | 84,040 |
| Longboat | 1984 | 210 | 6.5 | (1982) 6.216 | (1982) 1.147 | 77 | 45,840 |
| New Pass (Sarasota ) | 1982 | 137 | 4.6 | 3.364 | 4.740 | 77 | 45,840 |
| Big Sarasota | 1982 | 457 | 6.7 | 10.367 | 5.428 | 77 | 45,840 |
| Midnight | 1982 | 15 | 1.2 | 0.122 | 0.994 | 78 | 53,480 |
| Stump | 1981-1983 | 195 | 2.5 | 0.983* | NA | 78 | 30,560 |
| Gasparilla | 1982 | 548 | 4.0 | 2.659 | 1.835 | 78 | 76,400 |
| Boca Grande | 1985 | 914 | 9.8 | 122.099 | Nil | 79 | 84,040 |
| Captiva | 1982 | 548 | 4.6 | 9.152 | 2.064 | 79 | 76,400 |
| Redfish | 1982 | 182 | 4.6 | 2.141 | 1.988 | 79 | 76,400 |
| Blind (Lee) | 1985 | 20 | ? | 0.135* | NA | 79 | 84,040 |
| Big Carlos | 1982 | 410 | 3.4 | 6.147 | 3.211 | 82 | 42,020 |
| New Pass (Lee) | 1982 | 250 | 2.1 | 0.321 | 0.279 | 82 | 42,020 |
| Big Hickory | 1975 | 23 | 1.5 | Nil | 0.036* | 82 | 42,020 |
| Wiggins | 1981 | 90 | 2.0 | 0.136 | Nil | 83 | 64,940 |
| Clam | 1979 | 13 | 1.2 | 0.005* | 0.031 | 84 | 69,940 |
| Gordon | 1982 | 164 | 2.4 | 0.443 | 0.092 | 87 | 53,480 |
| Little Marco | 1981 | 240 | 1.5 | 0.639* | NA | 95 | 53,480 |
| Big Marco | 1982 | 347 | 3.0 | 11.68 | 2.599 | 95 | 53,480 |
| Caxambas | 1982 | 460 | (1978) 3.0 | 1.562* | Nil | 102 | 42,020 |

Table 1. List of some Florida inlets and selected morphometric properties, continued.

| Inlet, Pass, Entrance, or Channel | Year of Data Collection | Channel Width (m) | Channel Depth (m) | Ebb-Delta Volume ($10^6 m^3$) | Flood-Delta Volume ($10^6 m^3$) | Spring Tide Amplitude (cm) | Net Littoral Drift ($m^3$) |
|---|---|---|---|---|---|---|---|
| **Atlantic (East) Coast** | | | | | | | |
| St. Mary's | 1974 | (1985) 123 | 15 | 90.305 | Nil | 210 | 420,000 |
| Nassau | 1973 | (1985) 1837 | 6.5 | 30.942 | NA | 190 | ? |
| St. John's | 1978 | (1987) 656 | 13.7 | 132.936 | 0.764 | 170 | 366,720 |
| St. Augustine | 1979 | (1985) 328 | 5.2 | 84.346 | (1970) 0.535 | 160 | 366,160 |
| Matanzas | 1978 | (1985) 164 | 2.7 | 4.813 | 0.306 | 150 | 336,160 |
| Ponce de Leon | 1974 | (1984) 262 | 4.1 | 1.910 | Nil | 80 | 328,000 |
| Port Canaveral | 1979 | (1986) 164 | 14 | 4.278 | NA | 120 | 275,000 |
| Sebastian | 1974 | (1986) 160 | 2.6 | 0.764 | Nil | 80 | 229,200 |
| Fort Pierce | 1975 | (1986) 195 | 4.2 | 22.462 | 6.036 | 90 | 172,000 |
| St. Lucie | 1987 | (1986) 590 | 1.9 | (1964) 16.292 | 2.292 | 110 | 175,720 |
| Jupiter | 1978 | (1986) 65 | 2.8 | 0.306 | ? | 90 | 175,720 |
| Lake Worth | 1967 | (1986) 246 | 11.5 | 2.979 | NA | 80 | 175,720 |
| S. Lake Worth | 1969 | (1986) 60 | 3.1 | 1.069 | NA | 90 | 175,720 |
| Boca Raton | 1981 | (1986) 50 | 3.4 | 0.840 | Nil | 80 | 114,600 |
| Hillsboro | 1961 | (1981) 49 | 3.2 | 2.063 | Nil | ? | 76,400 |
| Port Ever-glades | 1978 | (1981) 69 | 14.5 | Nil | Nil | ? | 38,200 |

Data extracted from: Marino (1986), Dean and O'Brien (1987), and Davis and Gibeaut (1990).
* = Based on ebb-tidal area, not volume
NA = Not Applicable
Nil = Flood-tidal delta not pesent or volumes fluctuate and are insignificant in comparison to the magnitude of the littoral drift.
(1986) = Years in parentheses refer to data that was estimated from aerial photography, as in the case of channel widths for east coast inlets, or to information that was collected at specified times.

(1980), which are not applicable here. Unanticipated results may, for example, follow management practices based on the assumption that this coastal zone will react to certain stimuli (*e.g.* chronic shore erosion, secular and punctuated sea-level rise, or storm surge events) in a known manner as on other types of barrier islands (see for example, PILKEY *et al.*, 1984). Because barrier island evolution follows specific pathways (*e.g.* SWIFT, 1975; FIELD and DUANE, 1976) that respond to the rate and amplitude of relative sea-level change, tide and wave regimes, sediment supply, slope and width of the continental shelf, local relief of bottom topography, and rock outcrops, it thus seems reasonable to anticipate different response patterns on these subtropical mainland coasts.

### Geological Framework of Coastal Environments

The northern Atlantic coast of Florida is commonly depicted as one comprised by chains of barrier island (*e.g.* GIERLOFF-EMDEN, 1961; TANNER, 1985) separated by large capes or headlands (*e.g.* Cape Canaveral), whereas the southern coast is mainland and keys (FINKL,1985, 1992, 1993). The northern Atlantic barrier coast gradually merges with the mainland in the southern part of Palm Beach County (FINKL, 1993). The geographical demarcation of processes associated with barrier island systems from those associated with mainland coasts and keys require, however, further and more detailed investigation. The elucidation of these coastal frameworks is important because barrier islands, mainland coasts, and keys develop their own sets of morphodynamic processes that respond differently to coastal engineering works. True barrier islands, which are susceptible to a wide variety of geomorphic processes (*e.g.* island lowering and thinning, washover, and migration), react in a manner that is distinct from processes associated with mainland rock-cored coastal segments (older perched beaches, dunes and keys) that characterize much of coastal southeast Florida.

### Definition and Recognition of Coastal Barriers

Summarizing the barrier system in terms of interactive sedimentary environments, OERTEL (1985) lists six elements required to impose the designation "barrier island" on littoral sand bodies: (1) mainland, (2) backbarrier lagoon, (3) inlet and inlet deltas, (4) barrier island, (5) barrier platform, and (6) shoreface. Application of the principles of morphodynamic and sedimentary evolution of each element, as it affects adjacent environments, is crucial to the understanding of barrier island systems.

Preliminary investigations suggest that the southeastern Florida coast may be more complex than originally perceived (*e.g.* WHITE, 1970) because brackish- or salt-water backbarrier lagoons, for example, were absent or intermittently present from the coastal system prior to inlet cutting or canalization that was introduced in the 1920s. In a natural barrier island setting, these coastal elements exist as open-water lagoons or expandable tidal lagoons with salt marshes. The presence of backbarrier lagoons is essential to the concept of barrier islands because every element of the barrier island system influences or is influenced by the backbarrier lagoon (OERTEL, 1985).

The presence of natural inlets is necessary to establish the barriers as islands rather than barrier spits. About a century ago, Florida had eleven natural inlets along the 585 km of ocean shoreline between the Georgia border and Miami. Natural inlets along the 250 km of microtidal shoreline between Ponce de Leone Inlet at Daytona Beach and Jupiter Inlet near Palm beach were intermittently breached, depending on weather conditions. In the decade beginning in 1920, several new inlets were opened: Lake Worth Inlet (1920), Bakers Haulover Inlet (1927), Port Everglades (1928), and Ft. Pierce (1930). There are now nineteen permanent inlets on the east coast, the last one (Sebastian Inlet) cut in 1948 (Table 2). The cutting of inlets has transformed certain coastal segments into barrier islands, an artificial creation (FINKL, 1993).

Inlet cutting also contributes to the misidentification of coastal types in another important way because cuts through long barrier spits disrupt the nearshore sediment regime. Origins of east coast inlets, whether natural or cut by blasting and dredging, are summarized in Table 2. With time, the beheaded spits migrate shoreward and eventually become welded to the mainland (Figure 2), as in the case of New River inlet (FINKL,1985, 1993). Charts prepared by the U.S. Coast and geodetic Survey (USCGS) in the late 1800's and early 1900's (*e.g.* USCGS, 1884, 1887, 1928) show these natural coastal barriers as long southward downdrift-trending spits. Barrier islands, the subaerial expression of an accumulation of sediments between two inlets and between the shoreface and the backbarrier lagoon, are not evident on early (*i.e.* pre-19th Century) charts (see following discussion).

**Lithologic Control of Coastal Barriers**

The barrier platform, the substructure which supports the barrier island, is critical to the evolution of a barrier island system (GILL, 1967; KRAFT, BIGGS and HALSEY, 1973; BELKNAP and LEATHERMAN, 1985). Platforms are provided in various forms from pre-Holocene topographic highs on submerged mainland surfaces as in the barrier island chains off Virginia and Georgia. Unconsolidated sediments derived from glacial moraines and outwash plains provide the platforms off the southern coast of New England (McCORMICK and TOSCANO, 1981), as do fluvial sediments in the western Netherlands (VAN DER VALK, 1992). Lithified materials constitute bedrock control for west Florida barrier island systems (*e.g.*, EVANS *et al.*, 1985; DAVIS and KUHN, 1985). Outcrops of the Anastasia Formation along the east Florida shoreline (WHITE, 1970; LOVEJOY, 1992) suggests bed-rock control of coastal barrier evolution. This formation (Anastasia), a late Pleistocene coquinoid limestone, appears to be a nearshore (high-energy) de-

Figure 2. Barrier spits in the vicinity of Fort Lauderdale, Florida, *circa* 1925. The ICWW has not yet been dredged through the fresh water marshes and no inlet is cut through the bay mouth barrier into Lake Mable, now the turning basin of Port Everglades. (Right) A large barrier spit, beheaded and destabilized by the New River Inlet, has moved shoreward across the New River Sound to become welded to the Lake Mabel bay mouth bar. The spit is again destabilized by the cutting of a small canal on the south side of Lake Mabel to provide inland access to New River Sound. (Left) A continuation of the barrier spit southwards past the Dania Cutoff Canal. The spit terminated about 5 km south near Dania Beach Boulevard where the New River Sound opened to the Atlantic Ocean. (Modified photograph from 1925 print by Fairchild Aerial Surveys, Inc., Long Island City, New York).

posit but there is still some speculation concerning the exact environment of deposition (LOVEJOY, 1992). It now constitutes the rock core of many of the newly created "barrier islands" (*e.g.* Hutchinson Island, Singer Island, Hillsboro Beach, Fort Lauderdale Beach, Dania Beach).

The geological development of the present southeast Florida coast was strongly influenced by pre-Holocene topographic highs upon which coastal barriers were built. They provided a stable base where sediments could accumulate and as sea level rose in the mid-Holocene, the rock-cored sedimentary accumulations were bypassed with bays and estuaries forming on the landward sides of islands, spits, and bars. The lithified remains of older shorelines associated with lower stands of Pleistocene sea level also served as traps for coastal sediments driven shoreward by Holocene sea-level rise. The submerged paleoshorelines are separated by interreefal "soft bottoms" of relatively thin sand sheets up to 10 or 15 m in thickness (DUANE and MEISBURGER, 1969). The present natural shore consists of one or two meters of beach sand that overlies lithified sands, beachrocks, and coquina belonging to the Anastasia Formation. Rock outcrops are common along the coast at about the mean tide level but there are notable outcrops at one or two meters above sea level (*e.g.* Blowing Rocks and Jap Rock in Palm Beach County) as well as underwater where they form hard grounds. Patchy Sabellariid worm reefs along the surf zone comprise a unique rocky habitat.

**Destabilization of Barrier Spits by Inlet Cutting**

Aerial photos (dating back to the early 1920's) and historical maps of the Fort Lauderdale area show well-developed coastal spits, bars, and deltas prior to man-made developments. The New River, which drained eastwards from the Everglades, fed into New River Sound. The sound averaged one or two meters depth and flowed south, landward of the barrier spit, before emptying into the Atlantic Ocean near Dania, five or six kilometers from Ft. Lauderdale.

Coastal features such as spits and bars, which existed in a natural condition of dynamic equilibrium, were destabilized almost immediately after inlets were cut and fortified by rock jetties. Cutting and stabilization of some of the larger inlets (*e.g.* Port Everglades) typically took a year or two because a large amount of rock (Anastasia Formation) had to be blasted prior to dredging. After the inlet was opened, however, the destabilized coastal spits migrated shoreward across the sounds and eventually became welded to the mainland (*cf* Figure 2). Initial phases of this process took about three to five years and within two decades the process was nearly complete with only small segments of the spits remaining as barriers in front of landlocked portions of the former sound. In the case of New River Sound, the entire sandy spit migrated 100 m shoreward in about 5 years. Thus, about $6 \times 10^6$ $m^3$ of sand comprising the spit* were either welded to the mainland making new beaches, entrained in the littoral drift system, or lost to deeper water beyond the third reef. Cross-shore transport of eroded beach fill materials has been essentially confirmed from analysis of thematic mapper satellite imagery of this area (FINKL and DaPRATO, 1993; DaPRATO and FINKL, 1994). The height and width of the present dune-beach system (the older perched strand) has decreased since 1926 by about 30% so that the volume of sand withdrawn from the Port Everglades to Dania coastal segment over the last 65 years resulted in a net loss of at least $10 \times 10^6$ $m^3$ (including additions by littoral drift).

In the example of South Lake Worth Inlet, the downdrift Boynton Beach eroded 280 m landwards from the time of inlet cutting and stabilization in 1929 to 1955 (BRUUN *et al.* 1966). Extreme rates of shoreline recession along the southeast coast approached 4 m $yr^{-1}$ after inlet cutting and stabilization. Mitigation of the beach erosion problem thus clearly focuses on stabilized inlets.

## MORPHOLOGICAL PROPERTIES OF INLETS AND ASSOCIATED FEATURES

Broadly defined as waterways through a coastal obstruction such as a barrier reef or island (BATES and JACKSON, 1987), *tidal inlets* are usually associated with narrow waterways between islands, connections between a bay or

* Calculations of sediment volumes are based on analysis of aerial photographs (*circa* 1925; see Figure 2) and charts showing the location of the barrier spit. The spit was about 100 m wide by 4-9 km long and, judging from water depth to bedrock and height of the dunes, approximately 4 m thick giving a sediment volume on the order of $4\text{-}6 \times 10^6$ $m^3$. In contrast, the older perched barrier which today forms the mainland beach at John U. Lloyd State Beach Park, was then about 150-200 m wide by 5 m or so thick by at least 9 km long giving a sediment volume around $6\text{-}10^6$ $m^3$.

lagoon, or similar body of water with a larger body of water such as a sea or lake. Inlets tend to be associated with littoral drift shores but are not restricted to them occurring also along rocky coasts (BRUUN, 1978). The term *pass* refers to a relatively stable navigable channel that connects a body of water with the sea; *e.g.* a narrow opening between closely adjacent islands or through a barrier reef, island, bar, or shoal (BATES and JACKSON, 1987). Both inlets and passes are distinct coastal geomorphic features that are comprised by several elements; a gorge or main tidal channel, which may be straight or slightly sinuous; flanking shallow shoulders or shoals; adjacent barrier beaches, which under littoral drift develop as updrift and downdrift points; flood tidal delta on the lagoon or bay side; and ebb-tidal delta on the ocean side (FISHER, 1982). Flood and ebb deltas develop distinctive morphology in response to tidal current, quantity of longshore drift; magnitude of the tidal current; or geometry of the bay or lagoon (BRUUN andGERRITSEN, 1958).

Inlets initially form as interruptions in a developing barrier beach as openings remaining as a baymouth spit develops, or by breakthroughs by storm waves or hurricane surge. On littoral drift shores inlets tend to be inherently unstable. More permanent inlets persist in dynamic equilibrium between littoral and tidal currents, and wave action, although they may migrate along the coast. LUCKE (1934) noted characteristic patterns as inlets migrated along a barrier island chain, *viz.* some inlets open simultaneously and remain stationary; some inlets open simultaneously and migrate rapidly; while others open successively and migrate rapidly. Evidence of migrating inlets in the geologic record indicates that barrier beach deposits are replaced with inlet deposits to the depth of the inlet channel, which often reaches beyond the base of barrier deposits (JOHNSON, 1919; KRAFT; BIGGS, and HALSEY, 1973).

Jetties or other engineering structures attempt to provide safe navigational entrances for commercial and recreational fleets. Stabilization of these dynamic geomorphic features, however, often disrupts the natural coastal sedimentation system and results in channel shoaling, excessive updrift accumulation of material, and beach erosion on the lee side of jetties.

## TIDAL INLETS IN FLORIDA

The length of the Florida coastline is commonly estimated to be about 2160 km (*Personal Communication*, Florida Department of Natural Resources, 1994). Determination of ocean frontage is relatively easy along the barrier chains but becomes more difficult along marsh and mangrove coasts where the shoreline makes a tortuous path around numerous mud banks and small islands. Estimates of shoreline length are thus fairly accurate along sandy beaches where there are state range markers every 333 m. Total shoreline length of barrier sections approaches three times the ocean frontage because of additional shore on the back or bay sides of barriers as well as mainland shore on the landward sides of lagoons. Accurate determination of total shoreline length in the Ten Thousand Islands Mangrove Coast and Big Bend Marsh Coast becomes somewhat problematic due to the complex planimetric con-

Table 2. Opening and stabilization in tidal inlets along the Florida east coast.

| Inlet | Origin | Opened | Jettied |
|---|---|---|---|
| St. Mary's | N | | 1881-1904 |
| Nassau Sound | N | | |
| Ft. George - St. John's | N | | 1881 |
| St. Augustine | D | 1940 | 1941, 1957 |
| Matanzas | N | | |
| Ponce de Leon | N | | 1968-1971 |
| Port Canaveral | D | 1950 | 1953-1954 |
| Sebastian | D | 1948 | 1952, 1955 |
| Ft. Pierce | D | 1921 | 1921 |
| St. Lucie | D | 1892 | 1926, 1929, 1982 |
| Jupiter | N | | 1922 |
| Lake Worth | D | 1917 | 1918, 1925 |
| South Lake Worth | D | 1927 | 1927 |
| Boca Raton | D | 1925 | 19301931 |
| Hillsboro | N | | 1952, 1966 |
| Port Everglades | D | 1926 | 1926-1928 |
| Bakers Haulover | D | 1925 | 1925, 1975, 1986 |
| Government Cut | D | 1902 | 1902, 1907 |

Compiled from: Marino and Mehta (1986).
D = Dredged, cut. N = Natural

figuration of these areas. Shoreline lengths here are thus approximations between straightline 1 km segments.

A century ago, there were 11 natural inlets and passes along the 584 kilometers of ocean shoreline between the Georgia state line and Miami (STEVENS, 1990). There are now 19 inlets along the Florida east coast, an average of one inlet per 31 km of coast. Actual inlet spacing is, of course, highly irregular. In the 1880's there were no permanent natural inlets within the 246 km ocean shoreline between Ponce de Leon Inlet at Daytona Beach and Jupiter Inlet near Palm Beach. By the turn of the century, the entrance channels to St. Mary's and St. John's Rivers had been stabilized by jetties and two new inlets had been dredged (St. Lucie Inlet and lake Worth Inlet) (Table 2). Navigation improvements to the Miami Harbor were completed by 1913. Beginning in 1920 and continuing into 1940, local port authorities opened five new inlets along the east coast: Palm Beach Harbor (1920), Bakers Haulover (1925), South Lake Worth (1927), Port Everglades (1926), and Fort Pierce (1921). Matanzas Inlet and Nassau Sound are the only remaining unimproved natural inlets on the Florida east coast. Two natural inlets south of Miami (Norris Cut and Bear Cut) separate Fisher Island, Virginia Key, and Key Biscayne. These low coral islands are part of the keys carbonate reef system and form the 8-km wide southern part of Biscayne Bay.

Table 3. Stability parameters for some tidal inlets in florida.

| Inlet | W | L | $\eta$ |
|---|---|---|---|
| **Atlantic Coast** | | | |
| Nassau Sound, North | D | I | DC |
| Nassau Sound, South | D | D | U |
| Ft. George | D | - | D |
| St. Augustine | - | D | DC |
| Matanzas | - | - | DC |
| Ponce de Leon | I | - | DC |
| Sebastian | I | I | - |
| Boca Raton | - | D | - |
| Hillsboro | I | I | DC |
| **Gulf Coast** | | | |
| Redfish | - | I | - |
| Gasparilla | I | - | DC |
| Stump | D | I | DC |
| Midnight | - | - | DC |
| Longboat | I | I | DC |
| Pass-A-Grille, North | - | D | U |
| Pass-A-Grille, South | - | D | U |
| Clearwater | D | D | U |

Notation:
W = minimum width of main channel
L = minimum length of main channel
$\eta$ = mean change in geographical position of the main channel as a whole
I = increasing in width or length
D = decreasing in width or length
U = upcoast movement of $\eta$
D = downcoast movement of $\eta$
Modified from: Vincent, Corson and Gingerich (1991)

### Stability of Tidal Inlets

Early efforts to estimate inlet stability focused on relationships between channel cross-sectional area (*e.g.* ESCOFFIER, 1940), and adaptations of previous investigations (*e.g.* O'BRIEN, 1966; O'BRIEN and DEAN, 1972; SORENSEN, 1977). The stability index $\beta$, for example, is a measure of the maximum volume of sediment that an inlet throat can absorb within the critical cross-sectional area. If this critical volume is exceeded, deposition ensues; continued deposition leads to inlet closure. Another measure of inlet stability considers the relative ability of a channel to transport sediment, estimated in terms of the tidal prism ($\Omega/M_{tot}$); it is an index that describes the type of sediment bypassing at inlets. An index value > 150 defines a stable inlet with a relatively fixed entrance, a small bar, and good flushing (tidal flow dominant). When inlet flow is large compared with the sediment load from littoral drift, the inlet remains fairly stable ($100 < \Omega/M_{tot} < 150$). When $\Omega/M_{tot} < 20$, it represents very unstable inlets that close easily and have large longshore sediment flows relative to tidal flooding. This latter stability type refers to "bar bypassers," inlets with avulsing channels and poor stability. Inlets are thus related to three kinds of stability, *viz.* (1) bypassing stability (littoral transport bypasses the inlet), (2) locational stability (rate of channel migration), and (3) cross-sectional stability (dynamically stable cross-sectional area). These approaches attempt to relate the hydraulic characteristics of an inlet to stability, *i.e.* whether the inlet remains open or closes in response to environmental changes associated with flushing capacity and sedimentation.

VINCENT, CORSON and GINGERICH (1990) alternatively consider the inlet stability problem in terms of spatial parameters that are related to changes in channel position and horizontal topology. Based on the analysis of aerial photography, these researchers estimate inlet stability from changes in (1) geographic position (2) channel location about a pivotal point, (3) channel meandering (*in situ* sinuosity), and (4) channel stretching (or foreshortening). In addition to these horizontal topologic changes are variations in the channel depth and width, and bar configuration. Although the methodology is somewhat convoluted and the stability limits arbitrarily defined, these workers were able to detect a range of inlet instabilities. There was, however, an interesting lack of correlation for inlet response to regionally homogeneous wave climates which suggests that inlet morphodynamics over-ride wave-induced sediment transport. Analysis of regional trends implied substantial environmental controls in inlet evolution (Table 3). The more northern Florida east coast inlets (Nassau Sound to St. Augustine), for example, trend toward decreasing widths, although trends for channel length and movements are mixed. Inlets associated with the central portion of the East Coast Barrier Chain (Matanzas to Hillsboro) trend towards increasing width and downcoast migration. As a group, the Florida east coast inlets are width stable, position stable, and orientationally unstable. The southern group of inlets along the reef-fronted and sandy mainland coast tends to be more unstable in terms of relative channel length and orientation. Inlets associated with the West-Central Barrier Chain on the Florida Gulf coast show no strong regional trends and are stable in terms of channel width, length, geographic position, and orientation.

## SEDIMENT BUDGETS AND INLETS

Sediment budgets have been worked out for many of the Florida east coast inlets (see for example: FLORIDA ENGINEERING & INDUSTRIAL EXPERIMENT STATION, 1965; COASTAL & OCEANOGRAPHIC ENGINEERING LABORATORY, 1969; MOORE, 1979, COASTAL PLANNING & ENGINEERING, 1985; CUBIT, 1986; COASTAL TECHNOLOGY 1988; OLSEN ASSOCIATES, 1990; HARRIS, 1991; MEHTA, DelCHARCO, and HAYTER, 1991). Nevertheless, there is still incomplete understanding of regional sedimentary dynamics in terms of gross littoral patterns, temporal sequestering in storage basins, and loss to the littoral system due to offshore transport. Jettied inlets along the southeast Florida coast generally constitute end members for drift cells. Sediments comprising the so-called longshore "river of sand" reside in beach deposits, in flood-and ebb-tidal deltas, and in offshore inter-reefal depressions.

### Flood-Tidal Deltas, Ebb-Tidal Deltas, and Sand Traps

The ebb-tidal delta, a dominant feature of most coastal inlets (MOSSA, MEISBURGER and MORANG, 1992), occurs when sediment is deposited offshore of the mouth or navigational entrance. Sediment removed from the littoral drift system typically accumulates in a crescent- or kidney-shaped feature, a platform where sediments are transported from the updrift beach to the downdrift side of the inlet (OERTEL, 1988). Factors affecting the use of this material in beach renourishment projects include ratio of stored sediment to amount needed, accessibility, grain size, tidal range, and wave climate for dredging. Adverse impacts related to shoal removal may be related to navigability of the inlet or increase in wave energy reaching the shore (MEHTA, DelCHARCO and HAYTER, 1991).

General characteristics of the Florida continental shelf environment, relevant to sedimentary transport, include a narrowing in shelf width from north to south, at least to the Lake Worth Inlet after which it narrows to a nearly constant width of about 2900 m. The spring tide range in the northern inlets is somewhat higher than in those from Sebastian Inlet to the south (see Table 2), and there is a general but non-uniform decrease in ebb-shoal storage and littoral drift rate from north to south (MARINO, 1986).

Shore erosion is also related to the cutting of new inlets where none previously existed. WALTON (1974), for example, illustrates one impact of inlet cutting where the St. Lucie Inlet (opened in 1892 and later jettied in 1926-1928) caused a 1000 m retreat of the southern downdrift shoreline, the majority of which took place prior to 1948 for an astonishing annual rate of shoreline recession of 20-25 m $yr^{-1}$. No ebb-tidal delta existed prior to inlet cutting. The southern lobe of the ebb shoal that developed in direct response to inlet cutting now lies directly over the location of the pre-construction shoreline (MARINO, 1986). Although there was significant shoreline retreat, some of the sand eroded from downdrift beaches was washed through the inlet and deposited in the lagoon behind the northern part of Jupiter Island. Sand sequestered in this way contributed about 500,000 $m^2$ to the island's areal extent (MARINO, 1986).

MEHTA *et al.* (1991) interestingly report that when waves are from the northeast, sand is often transported around the south jetty and into the inlet by eddy currents during ebb-tidal flows. These patterns of sediment transfer around the jetties thus seem to control the influx of sand into interior traps and flood-tidal shoals thereby contributing to downdrift beach erosion south of the jetty. Loss of sand from the downdrift beach, due to jetty construction, is also related to offshore transport of sand into deeper water (COASTAL and OCEANOGRAPHIC ENGINEERING LABORATORY, 1969).

**Sediment Transport at South Lake Worth Inlet**

Erosion south (downdrift) of the inlet occurred soon after cutting in 1927 (EDGE, 1986). sand quickly impounded along the north jetty and drifted into the inlet creating a large flood-tidal delta. Systems designed to reduce the adverse impacts of the inlet on sediment transport were implemented by 1932, including hard engineering structures such as seawalls, groins, and revetments. A sand bypass system attempted to establish littoral equilibrium across the inlet. Most attempts failed to have significant impact on beach erosion south of the inlet. Recommendations for improved sand management in the 1960's (*e.g.* BRUUN *et al.*, 1966) included curved extensions to the north jetty, increased capacity of the fixed sand bypass plant, and construction of a mobile bypass system. In spite of attempts to increase sand bypassing, the net deficit in downdrift sediment supply caused continued beach erosion for several km south of the inlet so that today there is an 88 m landward offset of the mean high water lines between the north and south beaches adjacent to the inlet.

Net littoral drift occurs from north to south near the inlet. A portion of the southward drifting sand is directed seaward to the ebb-tidal delta by the inlet's tidal jet. A northward elongation of the ebb shoal extends about 985 m north of the inlet in response to drift reversal during summer. Northward extension of the shoal is influenced by changes in the littoral cell from sand impounding against the north jetty. Sediments in the littoral system that continue to drift south are (1) impounded against the north jetty fillet, (2) mechanically transferred south of the inlet by the sand bypassing plant, (3) carried landward or seaward of the inlet by flood and ebb tidal currents, or (4) naturally bypassed to the south of the inlet.

Sand accretion north of the inlet extends the shoreline approximately 65 m seaward from its pre-inlet location. Sediments carried into the inlet are deposited in a flood-tidal delta that contributes to the areal expansion of Beer Can Island to the north of the inlet interior. Material entering the 8nlet that does not shoal or settle in the sand trap, which is periodically dredged, is swept seaward by ebb-tidal currents. Sand deposited alongshore of the shoal accumulates 700-1000 m south of the inlet. Strong currents in the inlet (2.6 m $sec^{-1}$ during spring tides jets a significant portion of the drift seaward of the terminal lobe (approximately -4.6 m MSL) during ebb tides. Sand transported beyond the so-called "closure depth" is effectively removed from the near shore transport system (DEAN, 1987).

**Characteristics of the Ebb-Tidal Delta**

The ebb shoal developed shortly after inlet cutting 1927. BODGE (1990) reports that the shoal contains between 1.2 and 2.3 x $10^6$ $m^3$ of sediment, accreting at a rate of about 9740 $m^3$ $yr^{-1}$. The shoal, which occurs as a wide plateau between -1 to -3 m isobaths, moves landward in the summer months in response to increased onshore transport due to southeast trade winds and swell (BODGE, 1990). Sediments comprising the shoal are poorly to well graded sands with varying proportions (generally less that 10%) of shell. These sediments are a potential source of sand for beach renourishment.

**Sediment Budget at South Lake Worth Inlet**

BRUUN (1964) estimates a gross sediment transport volume of approximately 160 x $10^3$ $m^3$ moves past the inlet in the littoral drift system each year. From his studies of gross transport, Bruun suggested that 53 x $10^3$ $m^3$ are mechanically bypassed annually, 38 x $10^3$ $m^3$ are directed seaward beyond the -2 m isobath, and 69 x $10^3$ $m^3$ shoals in Lake Worth. Completing the most recent evaluation of the inlet's sediment budget, BODGE (1990) reports that differences between his and Bruun's budgets can be attributed to the 1967 jetty modifications. Bodge estimates the average rate of ebb-shoal accumulation to be about 30 x $10^3$ $m^3$ from 1927 to 1955 and 10 x $10^3$ $m^3$ thereafter for rates of about 1 x $10^3$ $m^3$ current annual accretion. His estimates of decreasing annual flood-shoal accretions range from 42 x $10^3$ $m^3$ from 1927 to 1945, 30 x$10^3$ $m^3$ from 1946 to 1966, and 3.8 x $10^3$ $m^3$ per year from 1966 to 1990.

These sediment budgets indicate that beaches north of the inlet accrete at an average rate of about 11% of the net drift rate, *i.e.* 16.8 x $10^3$ $m^3$ $yr^{-1}$, or prograde 1.3 m $yr^{-1}$. The computed drift rates south of the inlet range from 109 x $10^3$ m3 $yr^{-1}$. The inlet thus acts as a littoral barrier to approximately 16% of the net drift toward the south (BODGE, 1990). According to Bodge's budget, the inlet removed about 17% of the net drift from 1955 through 1975 and approximately 42% of the net drift from 1955 through 1975 and approximately 42% of the net drift from 1929 to 1955. In sum, erosional rates of the downdrift beach range from 0.3 m to 1.3 m $yr^{-1}$ with a net loss to the littoral system south of the inlet as large as 3.4 x $10^6$ $m^3$ since construction of the inlet.

### Downdrift Impacts of the South Lake Worth Inlet

Changes in the natural sediment transport system are reflected in nearshore morphologic features, distribution of coastal vegetation, and wave and current patterns. Aerial photographs and on-site visual observations suggest that the shoreline exists in a stable to accretional condition for 1 or 2 km north of the inlet. This area (Manalapan Beach) has accreted about 30 x $10^3$ $m^3$ of sand since the 1967 jetty improvements (CAMPBELL, 1985). Shore profiles with a dissipative to intermediate longshore bar-trough domain, similar to the types described by CARTER (1988), north of the inlet are characterized by well-vegetated backshore dunes, wide terraced berms, a low-angle forehsore, and multiple inner sand bars in the surf zone. Profiles down to the -6 or -7 m isobath are, however, steeper than those documented in 1929 (USACE, 1961). Profiles south of the inlet are characterized by higher angled, erosional dune scarps, narrower to non-existent berms and steep foreshores. The nearshore is more typically intermediate to reflective. Evaluation of bathymetric surveys from 1883 to 1990 suggest that the inner and outer longshore bars have migrated shoreward becoming welded to the mainland as part of a hydrodynamic re-adjustment of nearshore deposits similar to that described by FINKL (1992, 1993) for barrier spits in the vicinity of inlets at New River (now closed) and Port Everglades. Rock reefs (comprised of worm rock or the Anastasia Formation) thinly overlain by cover sands are frequently exposed by erosional processes in many locations both above and below mean sea level (MSL). Exposure of these shore parallel rock outcrops shows how they affect the location and migration of alongshore channels (STROCK, 1982).

## CAUSES OF BEACH EROSION IN SOUTHEAST FLORIDA

The relative sea-level rise in this region, estimated to be in the range of about 1-4 mm $yr^{-1}$ (WANLESS, 1989), causes maximum background shoreline regression rates of about -0.3 to -0.4 $yr^{-1}$ (DOLAN; HAYDEN, and MAY, 1983) for the Florida Atlantic coast. The construction of deep navigational entrances, such as those serving Port Everglades and the Port of Miami, which are dredged to about -15 m, inhibits natural sand bypassing. Long jetties, particularly those on the updrift (north) sides channels, promote offshore sand transport further exacerbating inadequate downdrift sand supply.

### The Relation Between Coastal Engineering Works and Beach Erosion

When deployed in an appropriate manner, coastal structures (*e.g.* groins; floating, offshore, or submerged breakwaters) mitigate erosion induced by waves and current (COE, 1986). One innovative example is the Prefabricated Erosion Prevention Reef (PEP Reef), a submerged breakwater installed off Palm Beach in 1988. The PEP Reef reduced offshore sediment losses that were associated with normal summer storms and was also effective during the high energy conditions resulting from Hurricane Andrew, a major storm that made landfall in Miami (AMERICAN COASTAL ENGINEERING, 1992). Jetties, on the other hand, are primarily designed to direct and confine water flow into a channel and to prevent or reduce shoaling of the channel by the littoral current (COE, 1984). Although they stabilize inlets on open coasts, they invariably interrupt littoral drift patterns causing much of the critical erosion of sandy beaches on the Florida east Coast (DEAN, 1990). Erosion immediately downdrift of the lee jetty typically takes the form of a log-spiral curve, as described by SILVESTER and HSU (1993), and extends for a distance of at least 700-1,000 m downbeach.

Recent studies (*e.g.* DEAN, 1990) suggest that the effects of erosion caused by navigational entrances may, in extreme circumstances, extend 10-15 km downdrift.

Even though shoreline changes in the vicinity of inlets show periodic advance and retreat, the overall long-term trend is one of pervasive downdrift erosion (COASTAL TECHNOLOGY, 1988). Because most inlets along the southeast Florida coast mimic this general trend, coastal specialists advance the question, "What can be done to alleviate the downdrift erosion caused by jettied inlets?"

## ALTERNATIVE SAND SOURCES FOR BEACH REPLENISHMENT

Sand in the south Florida environment hardly seems to be a scarce commodity. Although there are large sand deposits sands inland, along the coast, and offshore, materials suitable for beach replenishment are not overly abundant due to stringent specifications. Ideal deposits are largely composed of fine to medium sand-sized grains (0.074 - 2.0 mm median diameter) that are loose, with few rock fragments and little or no organic matter; fine-grained components (silts and clays) should account for no more than 7.5% by weight (COE, 1984). Additionally, south Florida beach sands often exceed 50% by weight carbonate content. The wide variety of potential local sources includes inland quarry sands, previous spoil materials, dredged material from the ICWW or port expansion projects, flood-and ebb-shoals at inlets, and inter-reefal sands offshore.

Inland sand sources have low silt and organic matter contents. Grain sizes, however, tend to be smaller than native beach sands and this is a serious disadvantage because the finer particles will winnow out by wave action and possibly adversely impact living coral reefs.

Most previous spoil materials have already been developed, are generally inaccessible, or are unusable as beach fill. Aside from deposits associated with flood-tidal deltas and some channel deposits in or near the ICWW (*e.g.* Jupiter Inlet-Hobe Sound), the waterway contains few coarse-grained deposits of sufficient volume to warrant development as beach fill. It is perhaps worth noting that the ICWW is largely cut through bedrock to a maintained channel depth of about 4 m. The rock-cut channel is stable (does not meander) and mainly accumulates fine-grained sediments that are often polluted due to the scavagening effects of clay minerals and other chelates (complex organo-metallic macromolecules). A similar situation occurs in Port Everglades where the turning basin floor had to be blasted prior to dredging to its present depth of 10-13 m. Sediment sources from here are clearly limited.

The lack of suitable sand sources inland turns attention offshore where suitable beach-fill materials are sequestered in ebb-tidal deltas and inter-reefal tracts (FINKL, 1981). MARINO and MEHTA (1989) estimate that there is nearly 420 x $10^6$ $m^3$ of ebb -shoal storage along the Florida east coast. There are, unfortunately, disadvantages associated with the mining of large sediment volumes from ebb-shoals. Previous experience has shown, for example, that mining shoals modifies the bottom topography so that sheltering effects are lost. Instead of damping wave energy, the reduced shoals allow increased wave energy to reach the shore causing shoreline retreat. Other hazards of dredging in a high energy zone over ebb shoals include possibilities of increased turbidity, siltation of coral reefs, and burial of hard grounds. Also, if large quantities of shoaled sediments are removed, there is no guarantee of full replacement along this sediment-starved coast. Ebb-shoal mining thus needs to be regarded with caution.

Although originally assumed that immense offshore sand sources could provide suitable fill *ad infinitum*, it is now clear that offshore sand sources are finite. The usefulness of inter-reefal sediments as beach fills is also limited by intercalated organic matter and rock, silts, and clay. Estimated sedimentary reserves have been categorized on the basis of less than 5% rock content, and sands with less than 7.5% silt content. Remaining offshore sand deposits may be adequate for only one more replenishment operation at John U. Lloyd State Beach park and Hollywood. Thus, it is not the total amount of offshore sand that is available for replenishment but rather amounts that are "acceptable". Current estimates of acceptable beach fill materials stored offshore in inter-reefal tracts along Broward County range from 3.8 x $10^6$ $m^3$ for John U. Lloyd Beach (COASTAL PLANNING & ENGINEERING, 1985).

Aragonite (crystalline $CaCO_3$), widely available on the Bahama banks with reserves estimated to be on the order of 70-90 x $10^9$ t (EARNEY, 1980), is a potential sand source. Placement costs (about \$13 $m^{-3}$) are, however, double the cost of natural offshore fill materials that could be placed several times a year by small hopper dredgers with pump-out capabilities (BRUUN, 1992). Aside from the high placement costs, there are also environmental considerations that require assessment. Among these are possible adverse impacts on sea turtle nesting habitats along southeast Florida beaches. Sea turtles are an endangered species that depend on Florida beaches for suitable materials in which to dig nests. Parameters related to successful pippin in beach sands include: incubation temperatures, levels of relative humidity and oxygen within pore spaces, grain-size distributions, compaction, steepness of the beachface, width and elevation of the berm, among others (MRSOVSKY, 1987; MORTIMER, 1990).

## ENHANCED SAND BYPASSING OPTIONS FOR FLORIDA INLETS AND NAVIGATIONAL ENTRANCES

Sand management strategies are becoming increasingly more important as a coastal management tool. Rising sea levels, increased shore erosion, decreasing supplies of suitable fill materials (both on- and offshore), and increasing concerns over environmental impacts associated with coastal protection measures are reasons for renewed interest in these coastal problems. Attempts by coastal engineers to alleviate coastal erosion hazards in the southeastern Florida urban coastal corridor originally focused on "hard stabilization" measures (*e.g.* groin fields, jetties) but more recent efforts by "soft stabilization" techniques feature artificial beach replenishment. Although "successful" in some cases (*e.g.* Miami Beach) and useful as a temporary protective measure against critical erosion, the method is not without criticism (*e.g.* LEONARD, CLAYTON, and PILKEY, 1990; PILKEY, 1990). Innovative erosion control techniques (*e.g.* jet pumping, fluidization of bed sediments) show promise for increasing sand bypassing around stabilized inlets. When enhanced bypassing is combined with periodic beach replenishment, shoreline erosion may be significantly mitigated (BRUUN and WILLEKES, 1992).

Engineering schemes need to be implemented within a regional geological framework and be compatible with societal needs and perceptions of "acceptable" solutions to the beach erosion problem. Although the socioeconomic constraints are not yet fully articulated, engineering and scientific endeavors are advancing toward technical solutions. A range of possible engineering methods are continually presented as possibilities and although it may be desirable to have a national policy on erosion control, it will be up to local authorities to decide which strategies are most appropriate for their coastal jurisdictions.

Attempts to increase the efficiency of sand bypassing involve a variety of inlet modification schemes. Curved jetties (*e.g.* Baker's Haulover) have proven useful in this regard as have weir jetties (*e.g.* Boca Raton Inlet, Hillsboro Inlet). Although local circumstances vary, many mechanical bypassing systems are improved by relocating the bypass equipment, extending the boom length, mobilizing the bypass intakes on rails or cranes, deploying mobile jet pumps, or by installing seabed fluidizers (BRUUN and ADAMS, 1988; BRUUN, 1990). Such efforts may increase bypassing efficiency to 80% or more, certainly better than at some inlets where present efficiencies range from 30% to 50%. Still other techniques feature spudded platforms with jet pumps that can follow the sand supply. The use of small coastal dredgers for profile nourishment is encouraged by BRUUN (1992) who reports successful economic operations in Australia, Denmark and The Netherlands.

Notwithstanding innovative techniques that involve the installation of beach dewatering systems (to stabilize the berm) or bubble curtains (to inhibit seaward sediment transport) or artificial seaweeds (to dampen wave energy), sand management strategies along the southeast Florida coast will, in future, focus on new technologies for modification of existing jetties or bypassing plants as well as testing the feasibility of fluidizing channel bed or shoal materials which can be entrained by longshore currents to bypass navigational entrances. The implementation of combined multiple technologies is a future trend because beach replenishment alone does not provide adequate shore protection for the project design life (LEONARD; CLAYTON, and PILKEY, 1990).

## ENVIRONMENTAL IMPACTS OF SAND MANAGEMENT

Environmental impacts associated with beach replenishment, and occurring between the offshore borrow site and target beach, may involve the following major habitats: borrow and sandy beach benthic communities, coral reefs and hard grounds, sea grass beds, worm reefs, and pelagic environments. Recent studies show, for example, that physical changes at borrow sites influence recolonization, successional sequences, and the subsequent structure of climax communities (GROBER, 1992).

The environmental impact of beach replenishment on coral reef communities has been a long-term concern, especially because the patchreefs are already stressed by pollution, are impacted by heavy recreation use, and because cold shelf water in the winter limits their northern extent. In addition to these secular and often cumulative impacts, the added stress associated with periodic offshore dredging activities could be the *coup de grace* for these fragile coral reef communities. DODGE *et al.* (1991), investigating the reefs offshore from John U. Lloyd State Beach Park, report no obvious renourishment-associated damage or pattern of ecological degradation. Potential onshore environmental degradation involves a complicated set of circumstances where the water column, seagrass beds, hard grounds (submarine outcrops of the Anastasia Formation), Sabellariid worm reefs, and beach are often adversely impacted by turbidity, siltation, or heavy burial by sediments (MAUCK and FLETEMEYER, 1987; NELSON and MARTIN, 1985).

## DISCUSSION

Recent attempts to mitigate the chronic impacts of shoreline retreat along Florida's developed coasts focus on the replenishment of eroded beaches downdrift from inlets. With the exception of the Miami Beach renourishment project, most beaches have not persisted the 10-year design life. Chronic erosion along some coastal segments requires mitigation to ensure the integrity of coastal infrastructure. The beach replenishment process is scrutinized because of potential environmental impacts and because the supply of suitable offshore borrow material is dwindling. The future of many beaches depends on the successful deployment of new techniques that incorporate jet pumps on movable bypassing plants or bed fluidizers that increase the efficiency of sand bypassing. These new methods of sand bypassing may be used in conjunction with more frequent replenishment by small hopper dredges with over-the-bow pump-out capabilities.

Because beaches erode and eventually disappear, in spite of protection by periodic beach renourishment or seawall projects, some researchers have sounded retreat from the coast (*e.g.* PILKEY, 1990). An acceleration of future rates of global sea-level rise (RIND, 1987), would also make Florida coasts more vulnerable to crescendo (storm and tide) events.

The backdrop to the erosion problem and its mitigation is the geological framework which conditions the effectiveness of remediation. Although future trends in sea-level change are uncertain, most estimates suggest an average rate of eustatic increase of about 1 to 2 mm $yr^{-1}$ (BARNETT, 1990). Analyzing post-1870 European tide gauge records, WOODSWORTH (1990) found little evidence for a significant acceleration in regional mean sea level, exclusive of minor positive accelerations between 4 and 9 x $10^{-3}$ mm $yr^{-1}$ in four of the longest records (Brest, Amsterdam, Sheerness and Stockholm). These estimates of sea-level rise are far less than those previously reported for global warming scenarios (*e.g.* HOFFMAN; WELLS, and TITUS, 1983). There are, however, uncertainties regarding the causes of variations in relative sea-level change, including probabilities of direction and rate of change (SHLYAKHTER and KAMMEN, 1992; MILLER and VERNAL, 1992).

The true coastal barriers, mainly long spits, were destabilized by inlets in the early part of this century. They became welded to the mainland almost immediately after inlet cutting and stabilization by jetties so that today the shore more closely approximates a key rather than a true barrier island which overlies a considerable thickness of unconsolidated sediments. Engineering solutions and management options are clearly different for a key. The usual sequence of island thinning and then rollover, which is a geomorphological response of a true barrier island to sea-level rise, is impossible here whereas overstepping is likely if sea-level rise is rapid enough. Because these beaches are essentially perched on the Anastasia Formation, the thin sand cover (including beaches and dunes) may be washed away, but erosion can not easily proceed in this hard indurated limestone.

Finally, there are concerns that engineering solutions to the beach erosion problem will degrade the coastal environment. Some concerns are based on previous blunders that are no longer tolerated. No attempt to protect the coast from erosion also results in a shore that is different from todays. It thus seems that some sort of protective effort is required for these developed shores. That there is some sort of ecological impact of sand bypassing and beach replenishment is a foregone conclusion (HOLDERMAN, 1992). Questions should now focus on comprehending which impacts are minor, moderate, or severe and which ones are short-term or have long lasting undesirable effects.

Enhanced sand bypassing (COE, 1991) is essential to periodic beach replenishment. The engineering community is commended for emphasizing new techniques to accomplish this goal. If better sand management is not achieved, it probably will be due to bickering among political antagonists, parties with local self-serving vested interests, or environmentalists with extremely conservative views that favor "no human interference" with natural systems. The reality is that the Florida coast has suffered massive interference by inlets and no one is prepared to go back to the *status quo* of 100 years ago. Progress must be made to solve the on-going "sand wars," or continued beach replenishment may not remain a viable option along Florida coasts.

## CONCLUSION

The prominent role of jettied inlets in the beach erosion problem requires increased understanding of how stabilized navigational entrances affect nearshore processes that in turn re-direct longshore sand flow into inlets or offshore. Attempts to enhance sand bypassing around navigational entrances via fixed pumping stations, weir jetties and inlet dredges have historical precedence in southeast Florida. New and innovative techniques, such as jet pumps, seabed fluidizers, or shallow-draft hopper dredgers with over-the-bow pump-out capabilities, may supplement these tried and true methods by making use of sand in the littoral drift system that does not naturally end up on beaches immediately downdrift from inlets.

Whatever erosion-control technique is applied, it is abundantly clear that the sand management strategy must reflect sensitivity to environmental concerns. Public awareness of the fragile nature of marine environments and their important role in the whole ecological system is becoming increasingly acute, as evidenced by recent laws that protect mangroves, sea turtles and manatees. The stage, upon which all of this is played out, is the coastal geological framework which itself is susceptible to change, mainly by the combined effects of jettied navigational entrances, offshore sediment transport, and rising relative sea level. Although historical coastal barriers, spits and bars, were destroyed by inlet cutting near the turn of the century, the present developed shoreline must be protected as long as possible so that coastal infrastructures remain viable. New strategies for enhanced sand bypassing and beach replenishment will thus pre-empt techniques that are now inefficient, outmoded, or environmentally unacceptable.

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