UFL/COEL - 89/002

# SHORT COURSE
# ON
# PRINCIPLES AND APPLICATIONS
# OF
# BEACH NOURISHMENT

February 21, 1989

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Thomas Campbell
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FLORIDA SHORE AND BEACH PRESERVATION ASSOCIATION
DEPARTMENT OF COASTAL AND OCEANOGRAPHIC ENGINEERING,
UNIVERSITY OF FLORIDA

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## Chapter 4

# SEDIMENT STORAGE AT TIDAL INLETS

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## INTRODUCTION

Accumulation of sediment around tidal inlets has become a matter of renewed interest mainly for three reasons. The first of these is the need to estimate the shoal volumes, particularly in the ebb shoal, as a potential source of sediment for beach nourishment. Portions of the ebb shoal can be transferred to the beach provided there are no measurable adverse effects on navigation, or on the stability of the shoreline near the inlet. Such an operation, for example, has been carried out successfully at Redfish Pass, on the Gulf of Mexico coast of Florida (Olsen, 1979). A schematic example of a potential site for ebb shoal excavation and sand transfer to the downdrift beach is shown in Fig. 4.1.

The second reason is the need to assess the role of the inlet in influencing the rate of erosion of downdrift shoreline, as a result of interruption or deflection of the littoral drift. For example, the effect of construction of Port Canaveral Entrance channel, Florida, on the downdrift beach is shown in Fig. 4.2 (Dean, 1987). The beach shoreline eroded at a comparatively rapid rate over a ~ 5 km stretch immediately south of the inlet, and a beach nourishment project was consequently carried out in 1974.

Finally, an evaluation of inlet sediment accumulation is essential to account for the long term sedimentary budget of shorelines interrupted by inlets, as schematized in Fig. 4.3. The budget in this case is for the "box" volume enclosed by shore-parallel and shore-normal boundaries. $Q_1$ through $Q_8$

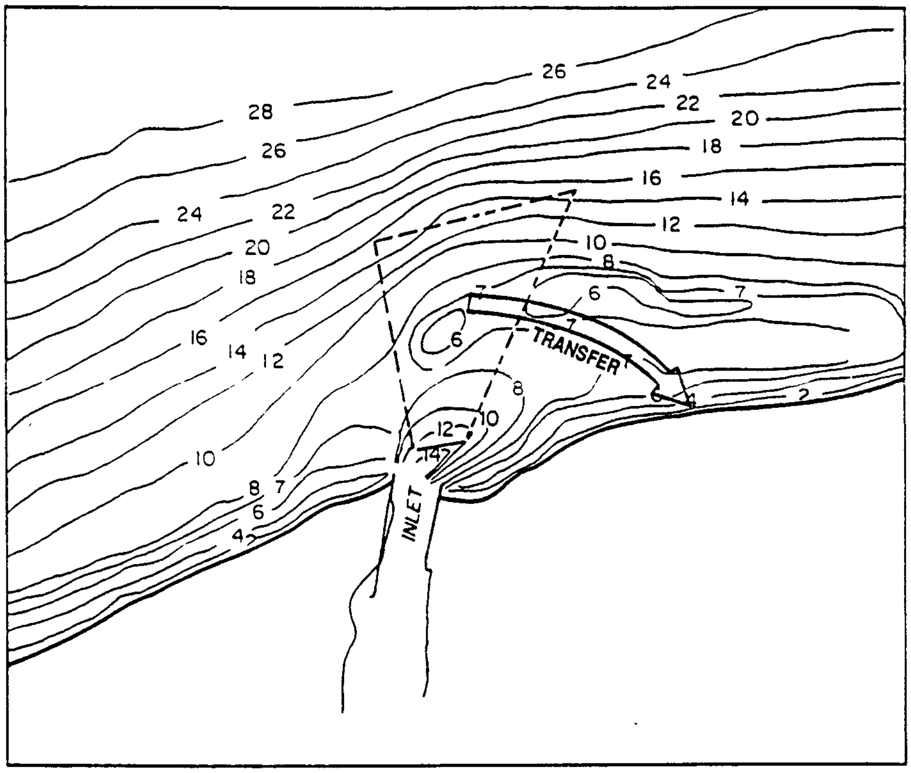

Figure 4.1. A Schematic Example of a Potential Site (Area Enclosed by Dashed Lines) for Ebb Shoal Excavation and Sand Transfer. Depth Contours are Hypothetical.

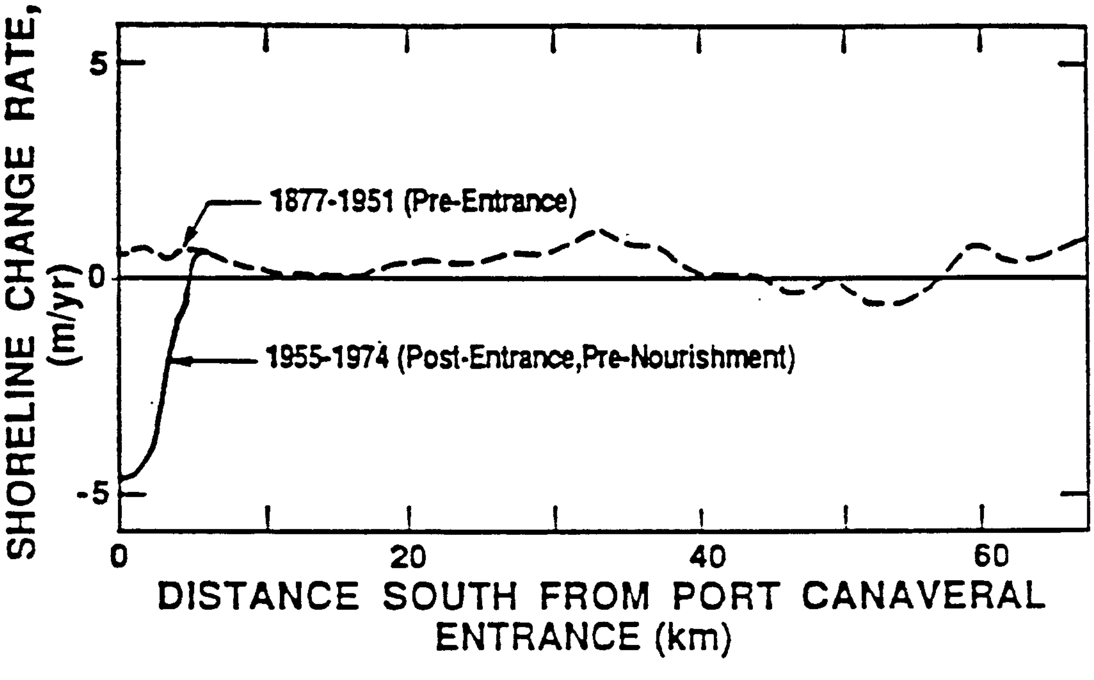

Figure 4.2. Effect of Construction of Port Canaveral Entrance, on the Atlantic Coast of Florida, on Downdrift (Southward) Shoreline (After Dean 1987).

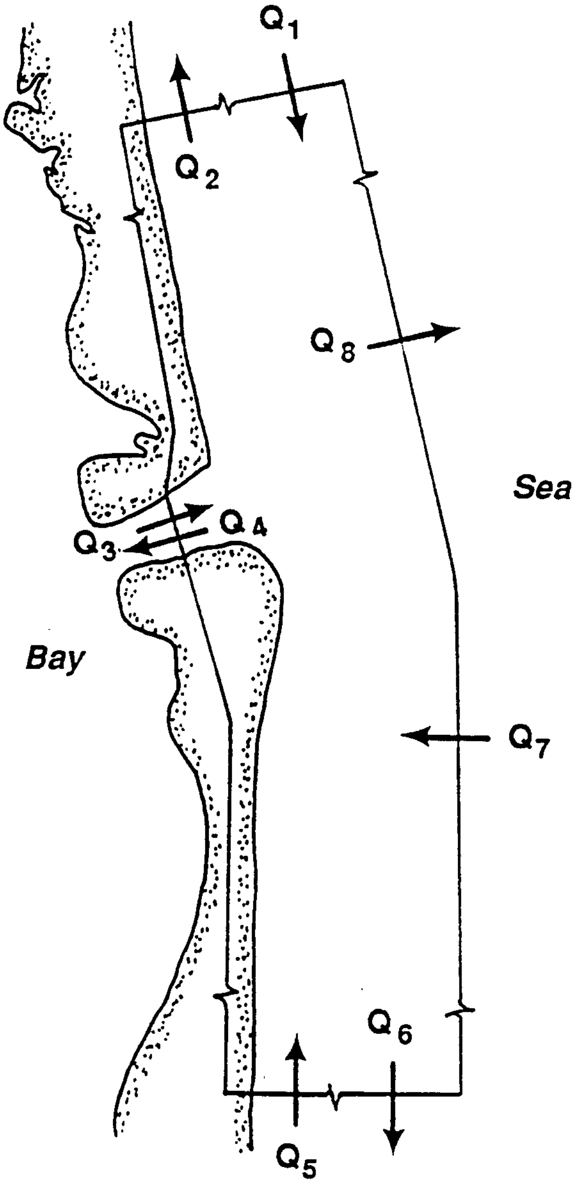

**Figure 4.3.** Box Volume Approach for Sediment Budget near a Tidal Inlet.

are volumetric rates of sediment transport across these boundaries. The algebraic sum of all the Q's equals the time-rate of change of sediment volume within the box. For an illustrative example see Jones and Mehta (1978).

In reference to these issues, quantities of particular interest are the volume of sediment presently stored in the ebb shoal, and the volume of material trapped, either as a result of training works such as jetties, or as a consequence of the opening of an artificial inlet and the growth of associated shoals. There is also the related question of volumetric erosion of the downdrift shoreline. These issues will be examined with specific reference to major inlets on the east coast of Florida together with additional examples from Georgia inlets, following some comments concerning natural and artificial sediment bypassing at sandy inlets.

## SEDIMENT BYPASSING

### Natural Bypassing

It has been well established that waves striking obliquely along the coastline cause a significant transport of sediment along the coastline in what has been called "the littoral drift system." An inlet located along such a coastline represents a discontinuity to the littoral drift system, and although the exact processes of the interaction between the inlet and the littoral drift system are not fully understood, the gross effects are; namely, accumulation of sediment in the ebb and flood shoals and a considerable sediment exchange between the inlet channel and the shoal complexes (Dean and Walton, 1975, Byrne _et al._, 1974, and FitzGerald, _et al._, 1976).

A schematic representation of the sediment transport processes at an inlet has been given by Bruun _et al._, (1978) and is shown in Fig. 4.4 (Winton and Mehta, 1981). Sediment moving down the coast in the littoral drift system

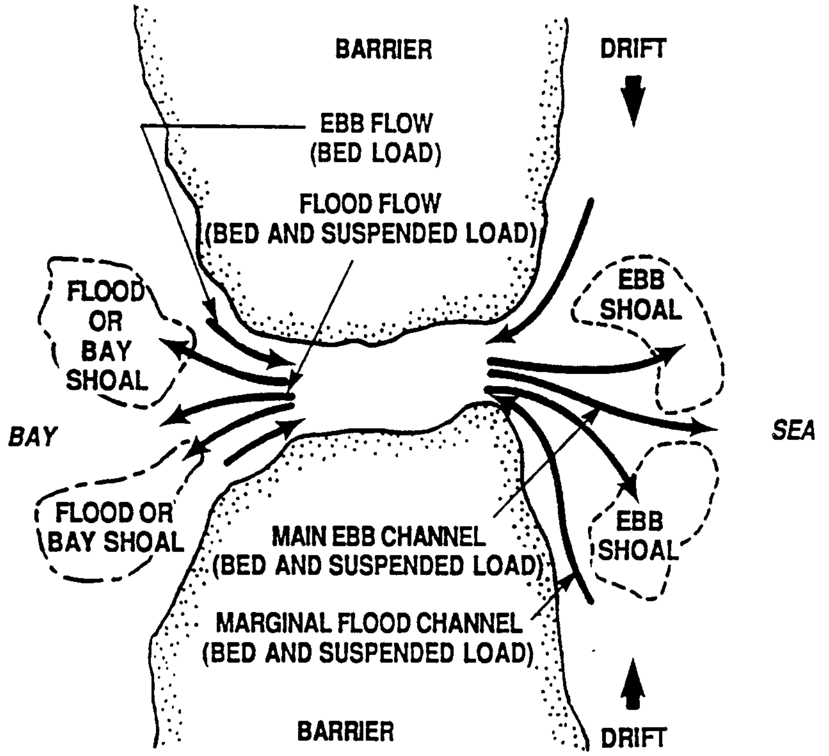

Figure 4.4. Schematic Diagram Showing Inlet Ebb/Flood Shoals and Sediment Transport (After Winton and Mehta, 1981).

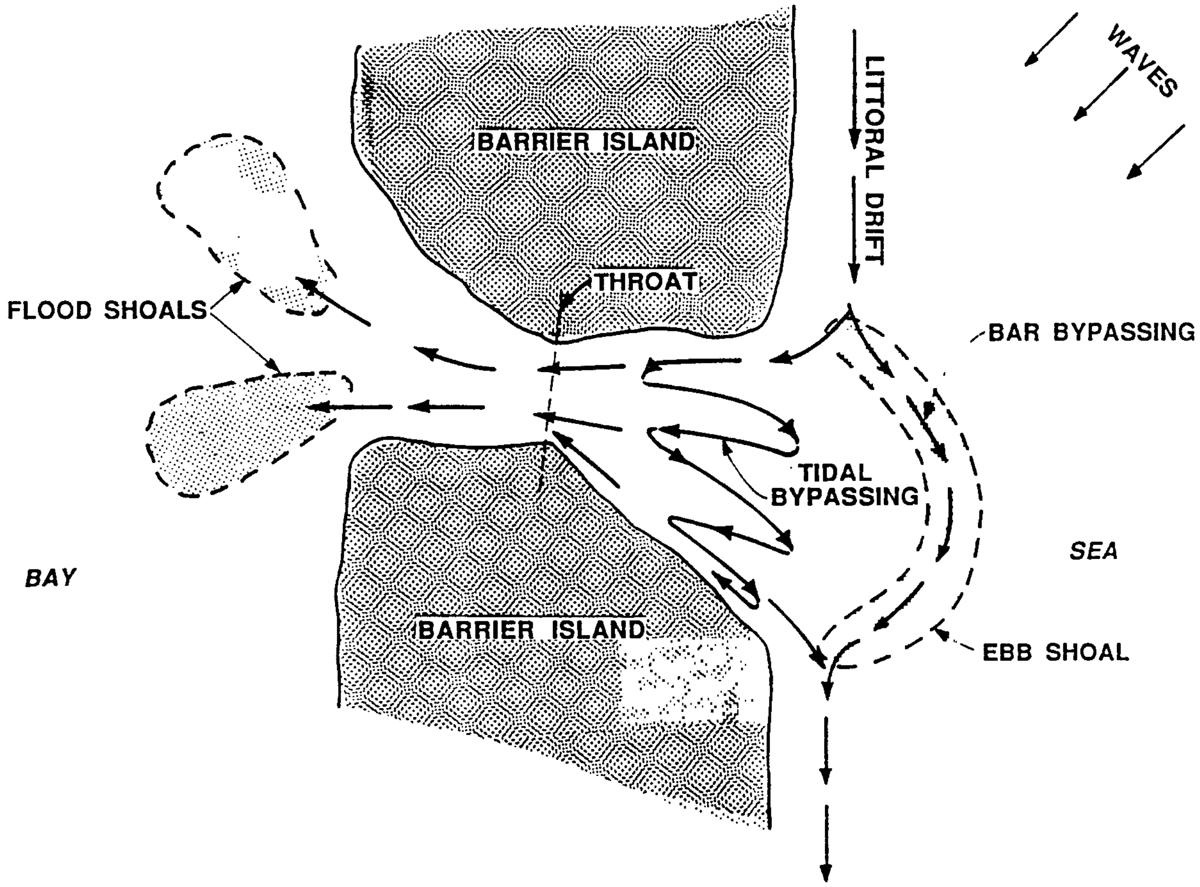

Figure 4.5a. Bar Bypassing and Tidal Flow Bypassing at an Inlet.

enters the inlet mouth mainly through the swash or marginal flood channels, and to a lesser extent over the ebb shoals. When the flow through the inlet is in the flood stage, some of the littoral drift will be carried through the inlet to the bay or flood tidal shoals, some still in suspended form and the rest as bed load. When the flow through the channel is in the ebb stage, some of the material which was transported through the channel to the bay shoals may be transported back through the channel to the ebb shoals and beyond, and "new" material (i.e. deposited from the littoral drift) will also be transported out onto the ebb shoals and/or beyond. For inlets with certain morphologic characteristics and strong ebb flow, some littoral material would be transported as bed load in deep water past the inlet, while for inlets with relatively small ebb flows subject to strong wave action at low tide, part of the material in the littoral drift may effectively bypass the inlet and not pass back and forth through the main channel.

Thus as noted by Bruun et al. (1978), there are essentially two ways by which sediment (sand) is bypassed naturally around an inlet (Fig. 4.5a). These two modes are referred to as bar bypassing - in which sand is predominantly transported from updrift to downdrift beach via the ebb shoal, and tidal flow bypassing - in which the material enters the channel and, under the combined action of tidal currents and cross-flow (alongshore current), is eventually transported downdrift. However, during this process of natural transfer, particularly in the case of tidal flow bypassing, a certain fraction of the sediment mass transported per unit time may end up in the interior, bayward of the throat section, thus forming flood shoals.

Under natural conditions, inlets generally differ in character from those modified, as for example in the case of Florida's east coast inlets prior to their modification. These natural entrances and their associated shoals approached long term equilibrium with the sand transport processes under prevailing wave and tide environment. Due to the predominant northeast direction of wave approach, the net longshore transport of sand along the shoreline is from north to south. Typically, as demonstrated by Fineren (1938), the characteristics of these inlets included a broad shallow ebb shoal or ocean bar; perhaps with a channel incised through the bar. Table 4.1 demonstrates that the bar depth was typically 1 to 2 m, much too shallow for navigational purposes. Although the channels through the bar were considerably deeper, most of them were still too shallow for modern commercial purposes. Additional serious navigational disadvantages of these natural channels were their tortuous alignments and migrational tendencies.

Table 4.1. Natural Depths in Channels and on Ebb Shoals of Florida's East Coast Inlets[a]

| Inlet | Depth on Bar (m) | Channel Depth (m) |
|---|---|---|
| Nassau Sound | 1.2 | 6.4-8.2 |
| Fort George | 1.2 | 3.4-7.9 |
| St. Augustine | 1.8 | 3.1-9.1 |
| Matanzas | Nearly blocked | 3.7-5.5 |
| Mosquito | Nearly blocked | 2.7-7.9 |
| Canaveral Bight | 1.8 to 5.5 | 9.1-12.2 |
| Indian River | Blocked | 2.1-2.4 |
| St. Lucie | 1.2 | 2.4-3.7 |
| Jupiter | Blocked | 0.9-1.5 |
| Lake Worth | 0.9 | 0.9-2.7 |
| New River | 2.4 | 3.1-4.6 |
| Hillsboro | 0.8 | 0.9-1.2 |
| Norris Cut | Not affected by sand | Shoal |
| Bear Cut | 1.2 | 2.1-5.2 |
| Cape Florida Channel | Not affected by sand | Coral reefs |

[a] Source: Fineren (1938)

When an inlet of natural origin is trained by jetties, the associated sedimentary volumes change until the bottom topography reaches a new configuration, which can be considered to be approximately in equilibrium with the prevelant currents and wave climate (Dean and Walton, 1975). Often, the net accretion in the updrift beach fillet is of the same order of magnitude as the corresponding erosion downdrift. The flood shoal may experience only minor change in shoal volume. The most dramatic effect occurs at the ebb shoal, which contains most of the stored material (Marino and Mehta, 1986).

Jetties, possibly coupled with a dredged channel, concentrate the ebb flow and cause the shoal to move seaward into deeper waters (Fig. 4.5b). Furthermore over the long term, a secular rise in mean sea level will cause the nearshore waters to become deeper. The contribution to shoal volume, if any, from sea level rise along Florida's east coast cannot be evaluated easily; however, at all the jettied inlets, training is likely to be the dominant factor. Given the same tide and offshore wave conditions, the seaward shoal at a trained inlet can store a larger quantity of impounded sediment (Figs. 4.6a,b) than prior to training. Indeed, in many cases, the impounded volume associated with the ebb shoal due to training is the only significant trapped quantity of practical significance (Marino and Mehta, 1986).

## Artificial Bypassing

Sediment transfer systems are oftentimes necessary components in an inlet improvement system for two reasons. First, the ability of a tidal inlet to naturally flush material from its channel may not be adequate to meet navigation requirements. Second, the improvement of a tidal inlet may interfere with the inlet's ability to naturally bypass materials from one side

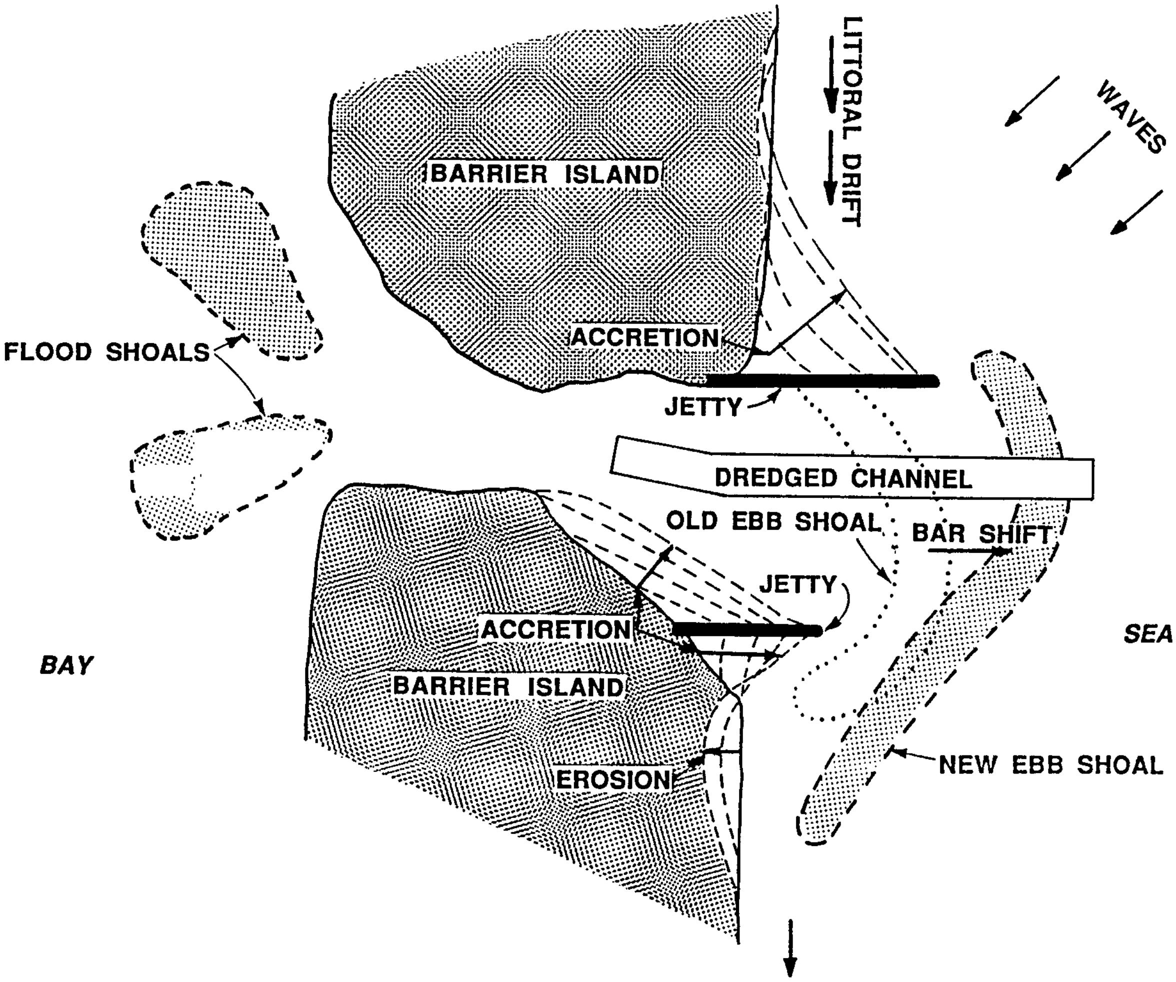

Figure 4.5b. Plan View Changes at an Inlet Due to Jetties and Dredged Channel: Shoreline Response to Modification.

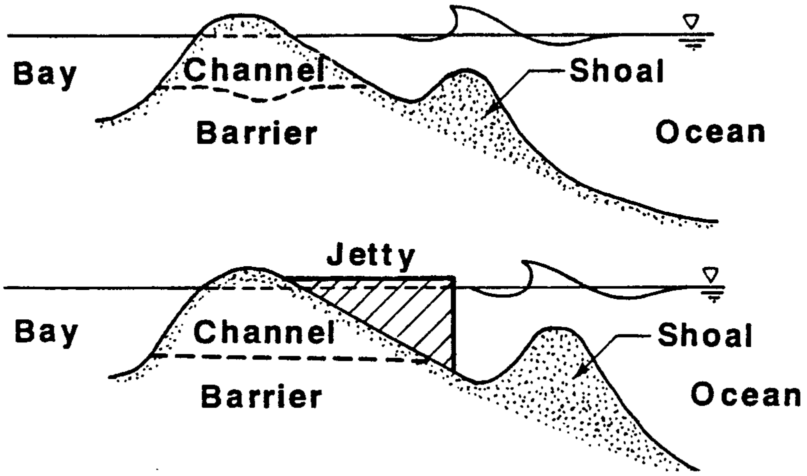

Figure 4.6. Ebb Shoal Elevation View: a) Natural Inlet, b) Trained Inlet (After Marino and Mehta, 1988).

to the other; hence, shoreline erosion is frequently intensified in the vicinity of the inlet. Figure 4.7 and Table 4.2 illustrate the locations and types of sand transfer systems in Florida. Note that more than one transfer system may be employed at an entrance; the principal method is listed first and the others are enclosed in parentheses. At Canaveral Harbor Entrance a moveable sand transfer plant designed two decades ago has not been built. Perdido Pass, Alabama has been included since it can be physiographically considered to be part of the Florida panhandle.

The transfer systems have been divided into six types as follows (Jones and Mehta, 1977):

Type I: Hydraulic dredging from the inlet, navigation channel, shoal areas or sand trap (excluding weir jetty systems).

Type II: Hydraulic dredging in the entrance vicinity from an impoundment basin adjacent to a weir jetty.

Table 4.2. Sand Transfer Systems in Florida[a]

| Entrance | Transfer System |
|---|---|
| Ponce de Leon | II (I) |
| Canaveral Harbor | IV |
| Sebastian | I |
| Jupiter | I |
| Lake Worth | III (I) |
| S. Lake Worth | III (I) |
| Boca Raton | I |
| Hillsboro | II (I) |
| Mexico Beach | VI (V) |
| East Pass | II (I) |
| Perdido Pass | II (I) |

[a] Source: Jones and Mehta (1977)

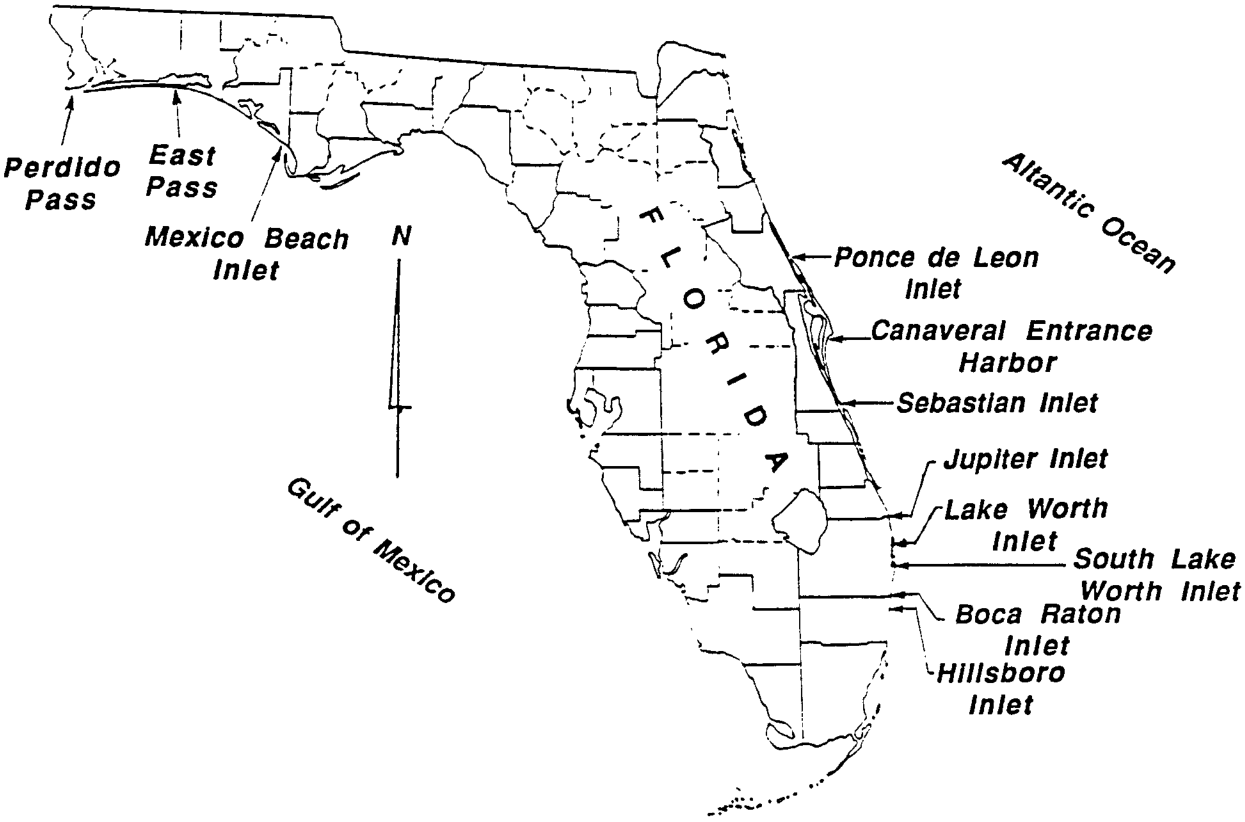

Figure 4.7. Locations of Several Sand Transfer Systems in Florida (After Jones and Mehta, 1977).

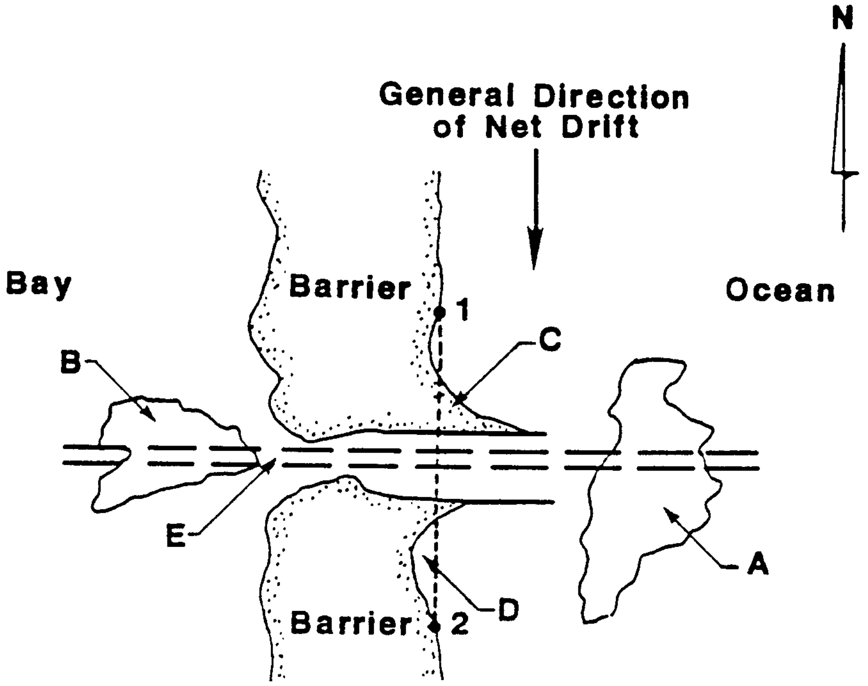

Figure 4.8. Sediment Volumes near an Inlet (After Marino and Mehta, 1988).

Type III: Fixed bypassing plant.

Type IV: Moveable bypassing plant.

Type V: Land-based transfer by dragline, truck, etc.

Type VI: Jet pump system.

The stability of a tidal entrance is generally thought to depend upon the balance between the littoral movement of sediment which tends to close the entrance, and the ability of the entrance to scour the sediment that has been deposited in the channel. If an entrance cannot maintain a stable navigation channel by its own flushing capability, then this must be supplemented by artificial means. However, merely improving an entrance and undertaking an artificial sand transfer program does not guarantee that navigable depths will always occur through the entrance. Nor is there any guarantee that beach erosion conditions on the downdrift side of the entrance will be measurably improved. These depend upon the stability of the entrance, the manner in which it naturally bypasses materials from the updrift to the downdrift side, the method of artificial transfer, and the geomorphic characteristics of the entrance. The direction of wave approach during the period when sand deposition on the downdrift beach is carried out is quite important. If this direction is such as to result in an updrift sand transport along the shoreline, then a portion of the transferred material may be transported into the channel, thus clogging it.

Observed entrance stability, based primarily on historic information for tidal entrances shown in Fig. 4.7, is cited in Table 4.3. Also included in this table are descriptions of the natural bypassing tendencies (tidal flow, intermediate between tidal flow and bar, and bar) of the entrances as determined by a method developed by Bruun (1966) using the ratio of the net

Table 4.3. Florida Inlet Stability and Bypassing Tendency[a]

| Entrance | Observed Stability | Bypassing Tendency |
|---|---|---|
| Ponce de Leon | Fair | Intermediate |
| Sebastian | Good | Tidal Flow |
| Jupiter | Poor | Bar |
| Lake Worth | Fair | Intermediate |
| S. Lake Worth | Poor | Bar |
| Boca Raton | Poor | Bar |
| Hillsboro | Fair | Bar |
| Mexico Beach | Poor | Bar |
| East Pass | Good | Intermediate |
| Perdido Pass | Fair | Intermediate |

[a] Source: Jones and Mehta (1977)

Table 4.4. Florida Inlet Bypassing Effectiveness[a]

| Entrance | Naviagation | Beach Erosion |
|---|---|---|
| Ponce de Leon | Fair | Fair |
| Sebastian | Good | Good |
| Jupiter | Fair | Fair |
| Lake Worth | Fair | Fair |
| S. Lake Worth | Fair | Fair-Poor |
| Boca Raton | Fair | Fair-Poor |
| Hillsboro | Good | Fair-Poor |
| Mexico Beach | Poor | Fair |
| East Pass | Good | Fair |
| Perdido Pass | Fair | Fair |

[a] Source: Jones and Mehta (1977)

annual littoral drift at an entrance to the maximum discharge through the inlet during spring tide conditions. At entrances where the numerator predominates, the offshore bar plays a major role in bypassing matrial. At entrances where the denominator predominates, tidal flow bypassing occurs. The ebb shoal or offshore bar in this latter case is usually limited in size and volume.

Table 4.4 gives an evaluation of the bypassing effectiveness of each entrance and its associated transfer system, as related to their combined ability, i.e. natural and artificial, to aid in maintaining navigable depths and in retarding downdrift erosion. These estimates are based upon shoreline changes on both sides of the entrance, dredging data, and discussions with individuals having local knowledge of the entrance behavior and shoreline history. As a result, these estimates are essentially subjective, but are believed to be fairly representative of actual performance. Unacceptable bypassing effectiveness for prevention of beach erosion at several inlets in Florida has led to strong recommendations for enhancing sand transfer capabilities at these inlets (Dean and O'Brien, 1987a,b).

## SEDIMENT VOLUMES NEAR AN INLET

Figure 4.8 shows a schematic of an inlet through a land barrier. This description applies, for instance, to Florida's east coast inlet down to Government Cut except Nassau Sound and Matanzas, which have no jetties or dredged channel. Significant features are the sea or ebb shoal, A; bay or flood shoal, B; updrift and downdrift beach fillets, C and D; and navigation channel, E. For convenience in describing Florida's east coast inlets, the updrift beach may be considered to be north and downdrift beach south of the inlet. Among these features, the flood shoal is typically the most poorly described area at most inlets, because it occurs in confined waters where limited bathymetric information exists. Additionally, the history of dredging or spoil deposition from the internal waterways is not documented well. The beach fillets, which define alongshore distances corresponding to the updrift and downdrift influences (up to points 1 and 2, respectively), of the inlet are difficult to identify unambiguously. The dashed line between points 1 and 2 indicates shoreline position in the absence of the inlet. Point 2 is particularly difficult to locate, with consequent limitation for the accuracy of estimates of downdrift loss of sediment over the selected time interval. At some inlets the ebb shoal distribution varies widely and shoal contours are not defined clearly.

## EVOLUTION OF EBB AND FLOOD SHOALS

Prior to evaluating the various volumes associated with an inlet, it is instructive to make reference to the manner in which ebb and flood shoals evolve at a newly cut entrance. Although each situation is obviously unique, the following examples are illustrative of probable trends.

To trace the evolution of an inlet ebb shoal, a time history of the inlet must be studied. St. Augustine Inlet, for example, has a unique history and helps in understanding evolutionary trends as well as difficulties which are typically encountered in precisely determining the shoal volume at any particular point in time.

St. Augustine Inlet was cut 4 km north of an existing inlet in 1941. Figure 4.9 depicts both the previous (1937) and recent (1985) shoreline and shoal contours. Locations I and J represent the areas through which the old, natural inlet meandered prior to the new inlet opening at location K, in 1940. The shoal contour lines delineate significant levels of sediment

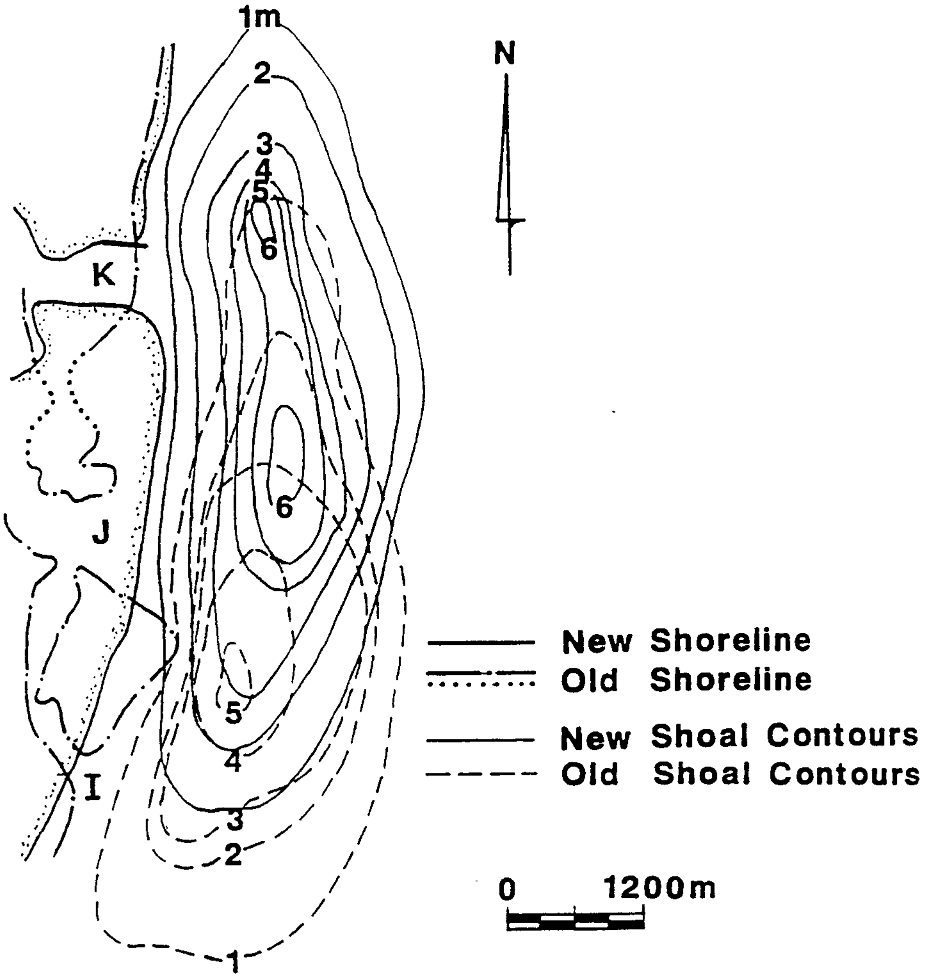

Figure 4.9. Ebb Shoal Changes at St. Augustine Inlet, Florida (After Marino and Mehta, 1987).

deposition above an "ideal" offshore profile. The ideal profile is defined as the natural offshore profile in that local area, as if the inlet were not present. It can be seen that as a result of the opening of a new inlet, the previous ebb shoal was caused to migrate. The old shoal formation moved both westward, to form what is now known as Conch Island, and northward to the new inlet. The old inlet was completely closed by sand deposition in 1957. The elongated shape of the recent shoal is believed to be due to the presence of a predominant longshore current to the south. The narrowest part of the shoal directly east of the inlet is evidence of the dredging done by sidecast dredges in the shoal area since 1940. The large bulge adjacent to the south jetty is a direct result of jetty construction in 1957. The shoreline since construction has moved eastward approximately 750 m adjacent to the jetty. This suggests jetty sand-trapping during seasonal reversals of the littoral drift.

This inlet is a mere example of the manner in which ebb shoals form and how the coastline responds to inlet formation. By constructing jetties of sufficient length to stabilize an inlet, as was done at St. Augustine, the shoals are maintained a significant distance away from the inlet. It may also be noted that dredging seems to have significantly affected the shape of the shoal. Where a channel has been dredged, the shoal is divided into two distinct lobes, rather than one large mass as is the case for example at Boca Raton Inlet, where there is no dredged channel.

Figure 4.10 presents a history of St. Lucie Inlet interior shoaling volumes (Dean and Walton, 1975). As observed this inlet shoaled rapidly in its earlier years and gradually approached a much smaller "equilibrium" shoaling rate as represented by the slope of the right-hand sides of the curves. The two curves represent shoaling over different areas considered as

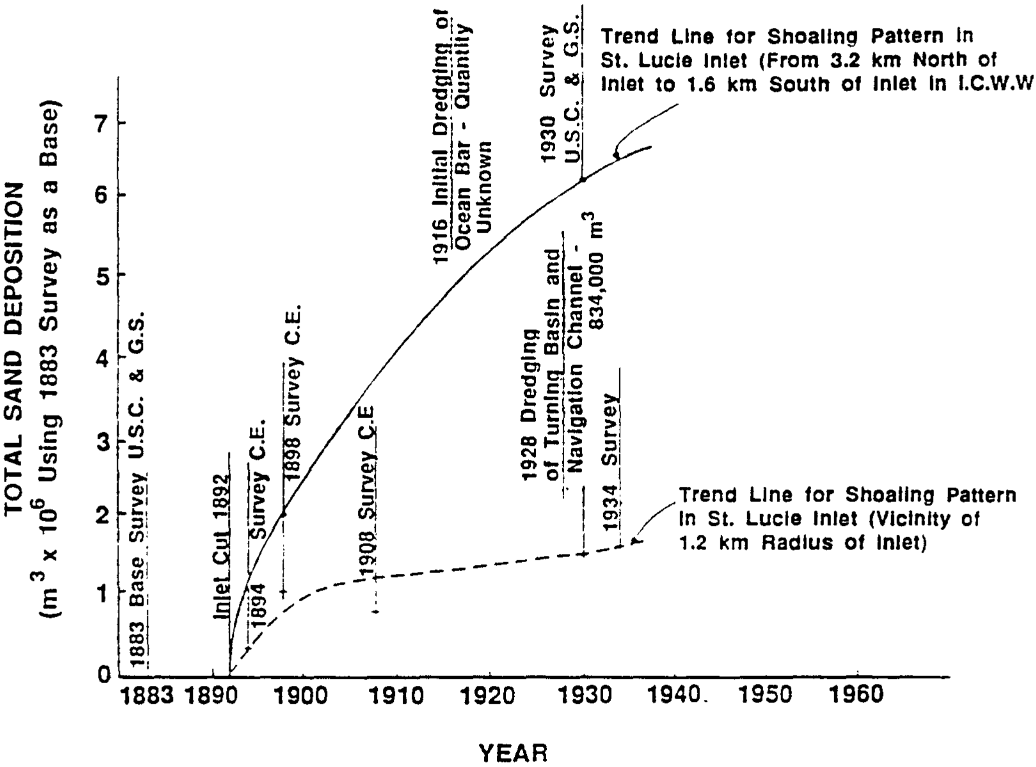

Figure 4.10. Time-History of Sediment Deposition in the Interior of St. Lucie Inlet (After Dean and Walton, 1975).

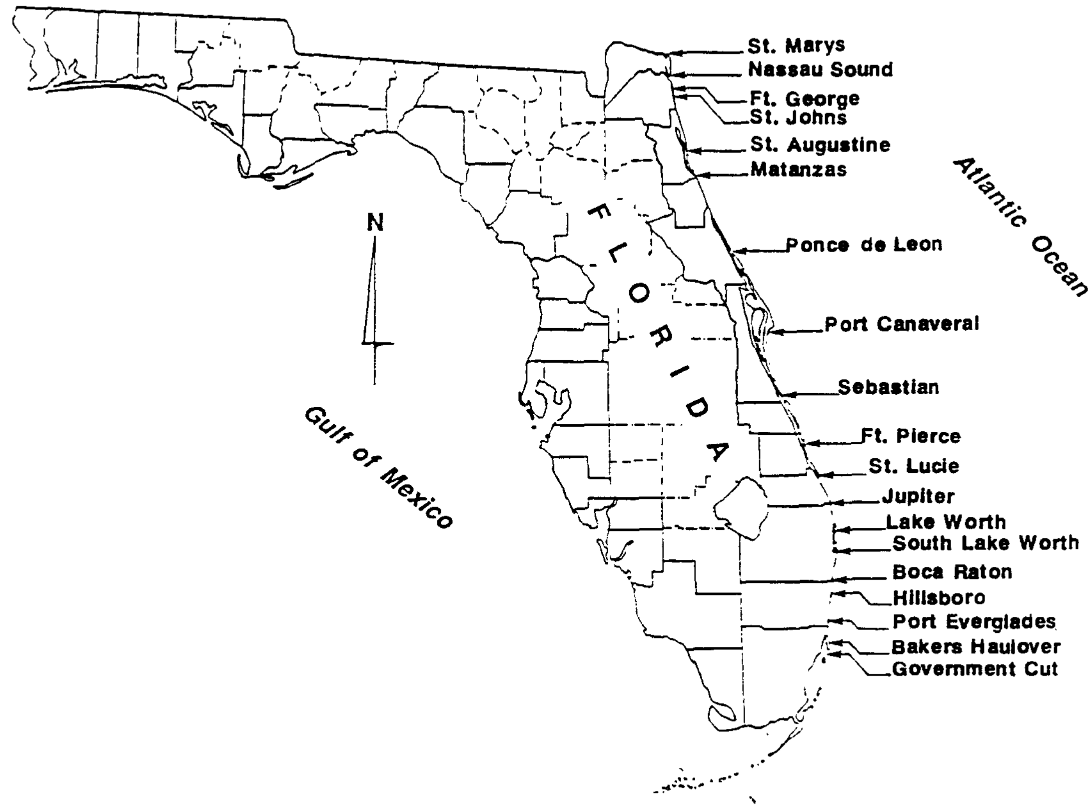

Figure 4.11. Nineteen Inlets along Florida's East Coast.

a "bay". The widely differing results are indicative of problems inherent in flood shoal calculations.

## SAND TRAPPING

### Selected Inlets and Physical Environment

Nineteen inlets along the 580 km shoreline between St. Marys Entrance at the Florida/Georgia border to Government Cut, Miami, are listed in Table 4.5 (see also Fig. 4.11). St. Johns River Entrance and Ft. George Inlet are two separate inlets. Ft. George, a small riverine entrance, occurs immediately north of St. Johns. They are characterized together by a single large ebb shoal and are therefore treated here as a single inlet system. Eleven inlets were opened artificially, although three (St. Augustine, Boca Raton and Port Everglades) have replaced inlets of natural origin in the vicinity. The remainder are known to have existed naturally since the earliest recorded history. All presently have two jetties except Nassau Sound and Matanzas. No training works occur at Nassau Sound. During 1976-77 a portion of the bay at Matanzas was closed by a dike at a location where a storm-induced breakthrough had occurred in 1964. Inlet hydraulics and sediment distribution were influenced measurably by this closure operation (Hayter and Mehta, 1979).

The tidal range and nearshore wave energy are reliable descriptors of the coastal physical environment. The semi-diurnal spring tidal range varies from 2.1 to 0.8 m (Table 4.5). A nearshore wave energy characterizing parameter can be defined as the square of the product of the wave height and the period. Annual average significant height and modal period may be selected for the present purpose (Marino, 1986). The range of wave energy parameter values are from 29.1 to 3.8 $m^2$ $sec^2$. Thus both the tidal range and the wave climate exhibit some variability along the coast, although this variability is

Table 4.5. Florida's East Coast Inlets[a]

| Inlet | Origin | Training works | Spring tidal range (m) | Wave energy parameter ($m^2sec^2$) |
|---|---|---|---|---|
| St. Marys | natural | jetties | 2.1 | 10.9 |
| Nassau Sound | natural | none | 1.9 | 10.9 |
| St. Johns/ Ft. George | natural | jetties | 1.7 | 18.3 |
| St. Augustine | opened, 1940[b] | jetties | 1.6 | 18.7 |
| Matanzas | natural | closure[c] | 1.5 | 20.6 |
| Ponce de Leon | natural | jetties | 1.3 | 26.7 |
| Port Canaveral | opened, 1950 | jetties | 1.2 | 24.0 |
| Sebastian | opened, 1948 | jetties | 0.9 | 28.7 |
| Ft. Pierce | opened, 1921 | jetties | 0.9 | 26.5 |
| St. Lucie | opened, 1892 | jetties | 1.0 | 29.1 |
| Jupiter | natural | jetties | 0.9 | 27.5 |
| Lake Worth | opened, 1917 | jetties | 0.8 | 14.6 |
| South Lake Worth | opened, 1927 | jetties | 0.8 | 15.0 |
| Boca Raton | opened, 1925[b] | jetties | 0.8 | 16.0 |
| Hillsboro | natural | jetties | 0.8 | 5.2 |
| Port Everglades | opened, 1926[b] | jetties | 0.8 | 5.2 |
| Bakers Haulover | opened, 1925 | jetties | 0.8 | 5.2 |
| Government Cut | opened, 1902 | jetties | 0.8 | 3.8 |

[a] Source: Marino (1988)
[b] Replacing a natural inlet in the vicinity; two near Port Everglades
[c] Storm breakthrough closure inside the bay by a dike

relatively minor in a global context. From the point of view of tide and waves, Florida's east coast environment has been classified as moderate (Walton and Adams, 1976; Marino, 1986).

The net littoral drift is generally from north to south, although a local reversal is suggested at some inlets. At St. Marys, the net southward drift is believed to be 420,000 $m^3$/yr, while near Government Cut it is on the order of 15,000 $m^3$/yr (Marino, 1986). While these estimates are admittedly rough, the littoral drift rate in the stretch between St. Marys and Jupiter is considerably larger than that in the stretch between Lake Worth and Government Cut. There is thus a general correlation with wave energy, which is relatively low in southern Florida due to the intervening influence of the Bahama Banks.

### Volumetric Calculation

St. Marys, St. Augustine and Lake Worth may be selected as illustrative examples. Sediment volumes have been calculated for each site by routine procedures based primarily on bathymetric information, making allowances for complicated bathymetry or lack of adequate data (Marino and Mehta, 1986). Relevant quantities listed in Table 4.6 are self-explanatory.

### Summary of Results

Three noteworthy quantities are given in Table 4.7 for all nineteen inlets. These include the most recent, available (post-training) estimate of the ebb shoal volume, the total material trapped due to training during the approximate period indicated, the corresponding change of volume downdrift and the quantity of sediment disposed at sea. The trapped volume in each case represents the sum of ebb shoal volume change, flood shoal volume change (where computed), updrift beach fillet volume change, and material disposed at sea or placed upland, but not on the beach. A positive number indicates accretion and a negative number implies erosion.

At shorelines where the littoral drift is predominantly unidirectional, the total volume of sediment trapped by the updrift beach fillet, the ebb shoal and the flood shoal must equal the volume of sediment denied downdrift.

Table 4.6. Sediment Volumes at Three Florida Inlets[a]

| | St. Marys | | St. Augustine | | Lake Worth | |
|---|---|---|---|---|---|---|
| | Quantity ($x10^{-6}m^3$) | Period (yr) | Quantity ($x10^{-6}m^3$) | Period (yr) | Quantity ($x10^{-6}m^3$) | Period (yr) |
| Ebb shoal | 89.2 | 1870 | 59.4[b] | 1924 | 0.0[c] | 1917 |
| | 95.1 | 1974 | 83.3 | 1979 | 2.9 | 1967 |
| Updrift | -1.3 | 1870-1975 | 1.1 | 1937-1970 | 4.8 | 1883-1957 |
| Downdrift | 8.8 | 1857-1957 | 5.5 | 1924-1976 | -0.7 | 1883-1957 |
| Flood shoal | -[d] | - | 0.0 | 1940 | 0.0 | 1917 |
| | -[d] | - | 0.5 | 1970 | -[d] | - |
| Deposit-sea | 9.4 | 1903-1985 | 0.0 | - | 2.1 | 1929-1985 |
| -beach | 0.3 | 1982 | 1.2 | 1940-1976 | 0.5[e] | 1929-1985 |
| -inland | 0.0 | - | 0.0 | - | 0.9 | 1970-1985 |

[a] Source: Marino and Mehta (1988)
[b] Old inlet
[c] Inlet opened in 1917
[d] Not calculated; believed to be small compared to ebb shoal
[e] Excluding 1.1 x $10^6 m^3$ bypassed from updrift to downdrift beach, 1968-1986

However, no strong correlation between trapped volume and downdrift volume change is apparent from the data in Table 4.7, although a general (but not uniform) trend of decreasing magnitudes of both quantities from north to south can be discerned. At four inlets - St. Marys, Nassau Sound, St. Augustine and Ponce de Leon - downdrift beach fillet volume showed an apparent increase. Nothwithstanding the likelihood of the effect of local reversals in the direction of littoral drift at these sites, it must be noted that the downdrift volumetric changes calculated are very approximate. Considerably lower confidence can be placed in these values than in the estimates of material trapped.

Over the indicated 99-year period, Nassau Sound trapped 6.3 x $10^6 m^3$, despite the fact that no modifications have been made at this large entrance.

Table 4.7. Florida Inlet Sediment Volumes[a]

| Inlet | Ebb Shoal $(\mathrm{x}10^{-6}\mathrm{m}^3)$ | Material trapped | | Downdrift Vol.change $(\mathrm{x}10^{-6}\mathrm{m}^3)$ | Disposed Vol.at sea $(\mathrm{x}10^{-6}\mathrm{m}^3)$ |
|---|---|---|---|---|---|
| | | Volume $(\mathrm{x}10^{-6}\mathrm{m}^3)$ | Period (yr) | | |
| St. Marys | 95.1 | 14.0 | 1857-1979 | 8.8 | 9.4 |
| Nassau Sound | 40.5 | 6.3 | 1871-1970 | 3.2 | 0.0 |
| St. Johns/ Ft. George | 131.3 | 120.9 | 1874-1978 | -23.4 | 15.7 |
| St. Augustine | 83.3 | 25.6 | 1924-1979 | 5.5 | 0.0 |
| Matanzas | 4.8 | 5.4 | 1963-1978 | -0.2 | 0.0 |
| Ponce de Leon | 17.0 | 0.7 | 1925-1974 | 1.7 | 0.0 |
| Port Canaveral | 4.3 | 13.8 | 1953-1985 | -0.8 | 7.5[b] |
| Sebastian | 0.1 | 3.2 | 1924-1976 | -0.2 | 1.4 |
| Ft. Pierce | 22.2 | 66.3 | 1882-1983 | -35.9 | 2.0 |
| St. Lucie | 16.4 | 20.3 | 1888-1984 | -34.7 | 0.0 |
| Jupiter | 0.3 | -3.0 | 1883-1978 | -2.4 | 0.0 |
| Lake Worth | 2.9 | 4.3 | 1883-1985 | -0.7 | 2.1 |
| South Lake Worth | 1.1 | 1.5 | 1927-1979 | -0.4 | 0.0 |
| Boca Raton | 0.8 | 1.3 | 1920-1981 | ~ 0.0 | 0.0 |
| Hillsboro | -0.2[c] | -1.7 | 1883-1967 | -0.5 | 0.5 |
| Port Everglades | ~ 0.0 | 6.0 | 1927-1981 | -0.5 | 2.1 |
| Bakers Haulover | 0.5 | 0.3 | 1919-1969 | -0.5 | 0.2 |
| Government Cut | ~ 0.0 | 3.5 | 1867-1978 | ~ 0.0 | 0.0 |

[a] Source: Marino and Mehta (1988)

[b] Excluding 15.9 x $10^6\mathrm{m}^3$ dredged during harbor construction and disposed at sea

[c] Negative sign is indicative of a scour hole at the site

An approximately 0.3 m relative mean sea level rise which has occurred during this period is a possible cause. Furthermore, modifications carried out at St. Marys are believed to have influenced sand distribution at Nassau Sound. At Jupiter and Hillsboro, there was actually a post-training loss of sediment, although in both cases the volume lost was small in comparison with the gains at inlets between St. Marys and St. Lucie, with the exceptions of Ponce de Leon and Sebastian.

At four inlets - St. Marys, St. Johns/Ft. George and Port Canaveral - sizeable quantities of sediment have been disposed at sea over decades. The type and quality of the disposed sediment were not investigated in this study; hence no conclusion can be drawn regarding the potential suitability of this sediment for such uses as beach replenishment. It is significant, however, that a total of 40.9 x $10^6 m^3$ have been disposed offshore. This number does not include, for example, an additional 15.9 x $10^6 m^3$ which also were deposited offshore during the construction of Port Canaveral harbor. It is not clear how much of this material was derived from upland dredging.

## EBB SHOALS

### Florida Inlets

Ebb shoals at eight out of the nineteen inlets contain a total of 405.8 x $10^6 m^3$ of sediment (Table 4.7). These eight inlets - St. Marys, Nassau Sound, St. Johns/Ft. George, St. Augustine, Ponce de Leon, Ft. Pierce and St. Lucie - thus contain nearly 97% of the ebb shoal sediment. Out of these, the five northernmost inlets - St. Marys, Nassau Sound, St. Johns/Ft. George and St. Augustine - store 350.2 x $10^6 m^3$, or 83% of the total sediment. Clearly, most of the stored sediment is found in northern Florida, with relatively small contributions from the south. Below St. Lucie there is practically negligible storage of sediment in the ebb shoals.

The observed variability in the ebb shoal volume, ranging from as high as 131.3 x $10^6 m^3$ at St. Johns/Ft. George to almost zero at Port Everglades and Government Cut, is indicative of the influences of a wide variety of physical factors that determine ebb shoal configuration and volume. Prominent among these factors are tidal range, wave climate and littoral drift, offshore bathymetry, type of sediment, inlet and bay geometries and runoff. For the east coast of Florida, tidal range, wave climate and littoral drift, and inlet and bay geometries are more important. At least in some cases however, an overriding influential factor, as one would suspect, is likely to be the holocene processes which have led to nearshore sand deposition ultimately from riverine sources. Quite simply, sand seems to be available at shorelines where it was deposited in the first place.

## Georgia Inlets

The inlets of Georgia are of particular interest since they are contiguous to those of Florida's east coast inlets, and because their ebb shoals store significant quantities of sand. In Table 4.8 nine major inlets are listed including representative spring tidal range at each inlet, the corresponding wave energy parameter, and ebb shoal volume. The tidal range places this shoreline in the mesotidal regime, as opposed to Florida's east coast which, with the exception of St. Marys area, is microtidal (Table 4.5). On the other hand, the wave energy parameter values suggest wave action similar to that along the northern part of Florida's east coast (Table 4.5), which is moderate. Overall, therefore, these nine Georgia inlets are much more tide dominated than for example Sebastian through Boca Raton.

The ebb shoal volumes, ranging from $15.1 \times 10^6$ $m^3$ to $191.0 \times 10^6$ $m^3$, are quite large, and with the exception of St. Catherines Sound are comparable to northern Florida inlets between St. Marys and St. Augustine. The sum of these volumes, $828.3 \times 10^6$ $m^3$, is double that stored in Florida east coast ebb shoals. The two southernmost inlets, St. Simons Sound and St. Andrew Sound, together account for $376.6 \times 10^6$ $m^3$ or 45% of the total.

Table 4.8. Georgia Inlet Ebb Shoal Volumes[a]

| Inlet | Spring tidal range (m) | Wave[b] energy parameter ($m^2$ $sec^2$) | Ebb shoal volume (x $10^{-6}$ $m^3$) |
|---|---|---|---|
| Nassau Sound | 2.5 | 13.7 | 86.6 |
| Ossabaw Sound | 2.6 | 17.1 | 51.3 |
| St. Catherines Sound | 2.5 | 13.3 | 15.1 |
| Sapelo Sound | 2.5 | 15.6 | 165.8 |
| Duboy Sound | 2.4 | 14.2 | 33.0 |
| Altamaha Sound | 2.3 | 14.2 | 66.7 |
| Hampton River | 2.4 | 14.2 | 33.2 |
| St. Simons Sound | 2.3 | 12.5 | 185.6 |
| St. Andrew Sound | 2.3 | 9.5 | 191.0 |

[a] Data generated by Millard Dowd, graduate student, University of Florida.

[b] Energy parameter values derived from Jensen (1983).

## Ebb Shoal and Nearshore Environment

Following the opening of a new inlet or the training of a natural inlet, the rate of growth of the ebb shoal is mainly contingent upon the rate of supply of sediment from the littoral drift. The larger the drift, the faster the rate at which the ebb shoal will develop to its new equilibrium size (Dean and Walton, 1975). It may therefore be argued that, for example, northern Florida inlets have nearly attained equilibrium, while the southern inlets have not, given the significantly lower drift in the south compared to the north. In other words, as mentioned previously the availability of sediment can be a factor influencing variations in the ebb shoal size as well as the volume of material trapped. It is, however, noteworthy that, as noted in the case of St. Lucie Inlet (Fig. 4.10), when a new inlet is dredged or a natural inlet trained, sediment trapping usually occurs rapidly initially, followed by a much slower rate of entrapment. It is believed that most of the nineteen

Florida inlets considered have passed the stage of rapid entrapment, that they are approaching equilibrium sedimentary distributions at a slow rate, and that, in most cases, the quantities (ebb shoal volume and material trapped) in Table 4.7 are close to those at equilibrium.

This hypothesis, i.e. that inlet sediment distribution is in equilibrium with the governing forces due to tides and waves, would imply that variability in littoral drift may not correlate measurably with variability in ebb shoal volumes. Without evaluating this hypothesis further, however, it is worthwhile noting some observations by assuming that one is dealing with ebb shoals of equilibrium size.

The assumption of equilibrium ebb shoal size was used by Walton and Adams (1976) to empirically relate the ebb shoal volume to the spring tidal prism, considering the prism to be the characteristic parameter representing inlet hydraulics, encompassing the effects of tidal range and inlet-bay geometry. By further assuming the variability in wave energy to be relatively small, all Florida east coast inlets were treated as being influenced by a similar wave climate. The result was a power law expression indicating the ebb shoal volume to be proportional to prism raised to the power 1.3, approximately. However, there was significant data scatter about this trend. Such scatter suggests that the ebb shoal volume may not be related uniquely to prism, and that the influence of additional parameters must be considered. One possible candidate is the inlet width-to-depth aspect ratio. The influence of this parameter is suggested by the data presented in Table 4.9. Three Florida inlets, Matanzas, Ponce de Leon and Ft. Pierce, are characterized by similar values of prism, wave energy parameter and channel throat or minimum flow area. There is a slight increase in prism from Matanzas to Ponce de Leon, and a significant decrease in the aspect ratio. The data suggest a stronger

Table 4.9. Influence of Inlet Aspect Ratio on Ebb Shoal Volume[a]

| Inlet | Spring tidal prism ($m^3$) | Wave energy parameter ($m^2$ $sec^2$) | Throat area ($m^2$) | Width/ depth | Ebb shoal volume ($m^3$) |
|---|---|---|---|---|---|
| Matanzas | $1.42 \times 10^7$ | 20.6 | 910 | 123 | $4.8 \times 10^6$ |
| Ponce de Leon | $1.63 \times 10^7$ | 26.7 | 1,170 | 75 | $1.7 \times 10^7$ |
| Ft. Pierce | $1.73 \times 10^7$ | 26.5 | 980 | 64 | $2.2 \times 10^7$ |

[a]Source: Marino and Mehta (1987)

correlation between increasing ebb shoal volume and decreasing aspect ratio, than with increasing prism.

Notwithstanding the fact that Matanzas channel is untrained while both Ponce de Leon and Ft. Pierce have jetties and dredged channels, it may be inferred from Table 4.9 that given the same tidal prism, wave energy and inlet throat area, a wide and shallow inlet will have a smaller ebb shoal than that a narrower and deeper inlet. Although depth at the channel throat is by no means uniquely related to the natural, shoal-free depths in the ebb shoal region, it is reasonable to associate a shallow throat with shallow offshore depths and a deep throat with deeper waters offshore. In the ebb shoal region, currents are relatively weak compared with those in the channel, and the prevailing bed shear stress is predominantly due to waves. The minimum flow depth over the ebb shoal is therefore determined mainly by waves (Mehta and Joshi, 1988). Any excess material that may deposit over the shoal will be carried shoreward by wave action (Walton and Adams, 1976). Consequently, all other conditions being equal, the thickness of stored ebb shoal sediment will be greater at an inlet with a small aspect ratio than at one with a larger ratio. The inlets of Table 4.8, where the sediment size is similar (~ 0.2-0.4 mm), appear to illustrate this process, although this concept requires further consideration including the role of geomorphologic factors.

The role of bed shear stress in reference to the relationship between the inlet aspect ratio and ebb shoal volume may be formalized via an illustrative example. The critical shear stress is that value of the bed shear stress that is exerted at the point of incipient grain motion. When the actual bed shear stress exceeds the critical shear stress, the bed material is put into motion.

Jonsson (1966) noted that the wave friction factor, $f_w$, is in general significantly larger than the current friction factor, $f_c$. The constitutive expressions representing the shear stress due current, $\tau_c$, and waves, $\tau_w$ are

$$\tau_c = 0.5\ \rho f_c u_c^2 \tag{1}$$

and

$$\tau_w = 0.5\ \rho f_w u_w^2 \tag{2}$$

respectively, where $\rho$ is the density of seawater, $u_c$ is the depth-mean flow velocity due to current and $u_w$ is the near-bed velocity amplitude due to waves.

For the problem at hand, it is sufficient to consider two inlets of the same cross-section, but having different width over depth aspect ratio, W/D. Let inlet 1 be 3 m deep by 400 m wide, and inlet 2 be 6 m deep by 200 m wide. Thus both inlets have a cross-sectional area of 1,200 $m^2$, but the corresponding aspect ratios are 133 and 33, respectively. It can be shown that the maximum ebb velocity through both the inlets will be the same because the flow areas, and therefore the tidal prisms, are equal (Marino and Mehta, 1987). Let us assume that the velocity, $u_c$ over the ebb shoal is as well the same in both cases, in spite of the differences in the flow depth over the bar. Let $u_c$ be 0.3 m/sec, a respresentative value. Select further, a representative wave height of 1 m and a wave period of 7 sec applicable to ebb shoals at both inlets. For current, a typical value of $4.1 \times 10^{-3}$ may be selected for $f_c$. The magnitude of $f_w$ depends on the relative bottom roughness, i.e. the maximum water particle displacement near the bed, $A_b$, divided by the bed roughness, $d_s$. $f_w$ can be estimated by using calculated Reynolds Numbers of $2.85\text{x}10^6$ and $1.33\text{x}10^6$ and corresponding $A_b/d_s$ values of 2,264 and 1,586 for inlets 1 and 2, respectively (Marino, 1986). The $f_w$ values are estimated to be $8.0\text{x}10^{-3}$ and $9.0\text{x}10^{-3}$ for inlets 1 and 2, respectively.

The current shear stress, $\tau_c$, and wave shear stress, $\tau_w$, are obtained for the two inlets as follows:

Table 4.10. Bottom Shear Stress Calculation

| Inlet | D (m) | $\tau_c$ (N/m$^2$) | $\tau_w$ (N/m$^2$) |
|---|---|---|---|
| 1 | 3 | 0.18 | 3.23 |
| 2 | 6 | 0.18 | 1.62 |

It is observed that in the case of both inlets, the wave shear stress is dominant. Hence the precise selection of the magnitude of $u_c$ for the inlets is not a matter of critical importance, so long as reasonable values are selected. Since the wave shear stress is twice as much in the shallower inlet, it follows that the critical shear stress will be exceeded there more often than in the deeper inlet. As the sand is put into motion, it is moved by the longshore current and wave forces back towards the shore. This movement of sand, therefore, occurs more significantly in shallower inlets than in deeper inlets, allowing the shoals of deeper inlets to grow to greater volumes than those of shallow inlets. This reasoning is in agreement with the conclusion of Walton and Adams (1976), who state that more material is stored in the shoals of low wave energy coasts than in high wave energy coasts. This is because there is more energy available to drive the sand back to shore in high energy environment after being deposited as a shoal.

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