

# Mesoscale Sediment Transport at Southeastern U.S. Tidal Inlets: Conceptual Model Applicable to Mixed Energy Settings

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## ABSTRACT

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Prediction of shoreline change around inlets at meso-time scales (years to decades) is the next logical step following verification of microscale models. If mesoscale simulations are a goal, a basic question is how microscale models (that simulate processes at hours to weeks) can be scaled up in time or whether macroscale geomorphic models (that qualitatively describe changes at decades to centuries) can become more quantitative. The authors propose an approach that begins with consideration of tidal inlet morphology and sediment circulation around ebb-tidal deltas. Inlets are the focus because in some barrier island settings such as the southeast U.S. coast, it appears a majority of coastal erosion problems at meso-time scales can be traced to changes in adjacent inlets. Inlet morphology and geomorphic models, typical of mixed-energy coastal plain shorelines, are reviewed to illustrate certain common sediment transport patterns. A simplified conceptual model of inlets at meso-time scale is proposed from which the problem of sediment transport may be spatially partitioned. Four primary inlet domains are considered: (A) main ebb channel where tidally generated ebb currents control sediment discharge, (B) ebb-tidal delta with a broad swash platform that is ultimately in balance between ebb-directed flows and wave- and tide-generated shoreward transport, (C) shoal-bypassing zones at the margins of the ebb-tidal delta where sediment shifts unidirectionally from the delta to the shoreline under wave-generated transport, and (D) recurved spits adjacent to the inlet which receive shoal-bypass sediments. Excess sand accumulating in Domain D becomes subject to longshore advection toward and away from the inlet. A portion nourishes the adjacent beach and the remainder recycles back to the inlet channel (Domain A), completing the inlet transport loop.

**ADDITIONAL INDEX WORDS:** *Inlet model, ebb-tidal delta, shoal bypassing, mesoscale, inlet sediment budget, waves, tidal currents.*



## INTRODUCTION

Tidal inlets control the evolution of adjacent shorelines. This is one of the basic tenets of coastal science. Evidence that inlets trap and retain mobile sediments or periodically release material to nourish adjacent shores can be found along every sedimentary coast, particularly the southeastern United States.

The need to understand tidal inlets and to establish their scales of influence is compelling. Given a range of time-and-space scales acting on the coast, there is, naturally, a spectrum of tidal inlets. This paper reviews inlet morphology characteristic of mixed energy settings such as the U.S. southeast coast and proposes a conceptual model at meso-time scales to bridge the gap between qualitative (macro-time scale) morphological models and micro-time scale numerical models.

The focus is on mixed-energy inlets as opposed to wave-dominated or tide-dominated inlets because, in our opinion, these offer more easily distinguished sand bodies and sedi-

ment-transport pathways for defining the problem. For readers interested in a more thorough review of inlet variability and physical processes, publications edited by AUBREY and WEISHAR (1988), MEHTA (1996), and DEVRIEND and STIVE (1996) offer an excellent sampling of papers.

Efforts are underway by the authors (WORK *et al.*, 1996) and other investigators (*e.g.*, DEVRIEND *et al.*, 1993; CHESHER *et al.*, 1995; ZHANG, 1996) to ultimately develop a predictive model of tidal inlet evolution at decadal time scales in mixed-energy settings such as the Georgia Embayment. The proposed conceptual model offers a rational way to partition the problem and eventually test appropriate, sediment transport algorithms within various domains of tidal inlets.

## INLET MODELS

Inlets along the southeast U.S. coast are, for the most part, associated with barrier island/lagoon shorelines. Their morphology and scale are generally related to the tidal prism accommodated by the channel(s) (O'BRIEN, 1969; JARRETT, 1976) and asymmetries in tidal flows or asymmetries in littoral sediment transport (BRUUN and GERRITSEN, 1959;

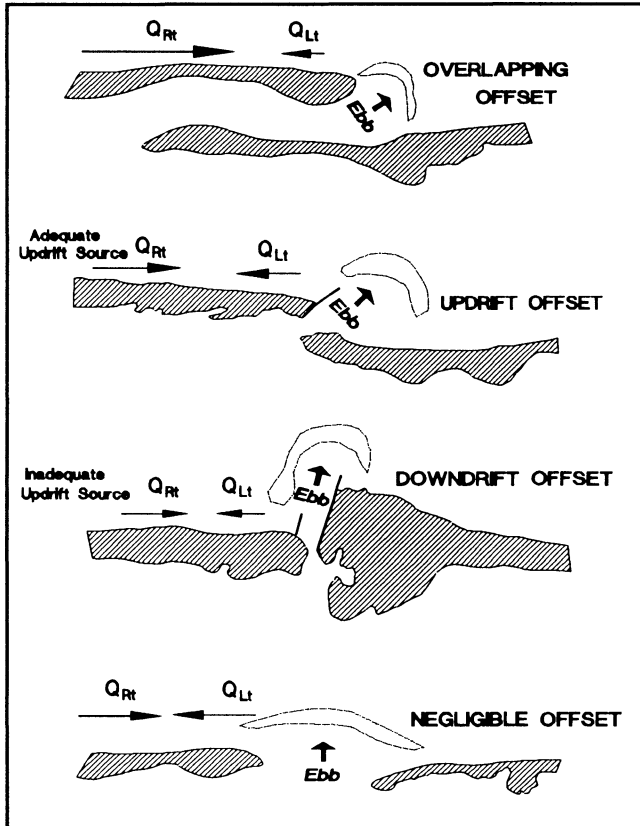


Figure 1. Four types of barrier-island offsets proposed by GALVIN (1971). (Modified from CERC, 1984)

HAYES, 1975; NUMMEDAL and HUMPHRIES, 1978; FITZGERALD, 1984). The frequency of inlets increases with tide range along coastal plain depositional shorelines (HAYES, 1979).

The regional morphology of inlets, regardless of size, has been shown to fall into four characteristic planforms: overlapping offset, updrift offset, downdrift offset, and negligible offset (GALVIN, 1971). Differences in morphology are qualitatively related to the ratio of longshore transport from one direction to the other. In wave-dominated settings, inlets with a plentiful sediment supply and predominant transport direction may develop updrift or overlapping offsets, whereby the updrift shoreline accretes seaward of the downcoast strandline, particularly if ebb-tidal deltas are small. Downdrift offsets (Figure 1) develop where the updrift source of sand is small relative to the amount of sand trapped in the ebb-tidal delta. As tide range increases and more sediment is trapped offshore, the sheltering effect of large, ebb-tidal deltas influences wave refraction. HAYES *et al.* (1970) attributed downdrift offsets in mixed-energy settings to this process, suggesting refraction around the ebb-tidal delta produces a transport reversal and accounts for the extra accumulation of sediment on the downdrift shoreline. Both wave-dominated and tide-dominated inlets can have negligible offsets and small, net longshore transport; however, the offshore extension of the ebb-tidal delta will be dramatically different, with

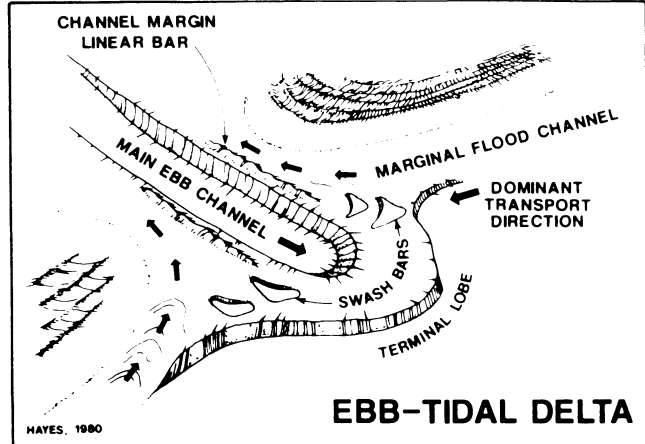


Figure 2. Typical ebb-tidal delta morphology (after HAYES, 1975). Marginal flood channels separate the channel-margin linear bars from the adjacent beaches. Morphology and bedforms indicate dominance by ebb currents, flood currents, or waves. (From HAYES, 1980)

tide-dominated inlets generally having the largest ebb-tidal deltas in the spectrum.

**Common Sediment Transport Patterns**

Studies of mixed energy tidal inlets have shown that there are certain morphologic characteristics common to most. HAYES (1975; 1980) proposed standard models for the morphology of ebb-tidal deltas (Figure 2) and flood-tidal deltas. Because they appear to exert less influence on ocean shoreline variability than ebb-tidal deltas along mixed-energy coasts, flood-tidal deltas are not considered here. Hayes' ebb-tidal delta model was developed from case studies which systematically identified net sediment transport directions from intertidal and subtidal bedforms (*e.g.*, HINE, 1975) (Figure 3)

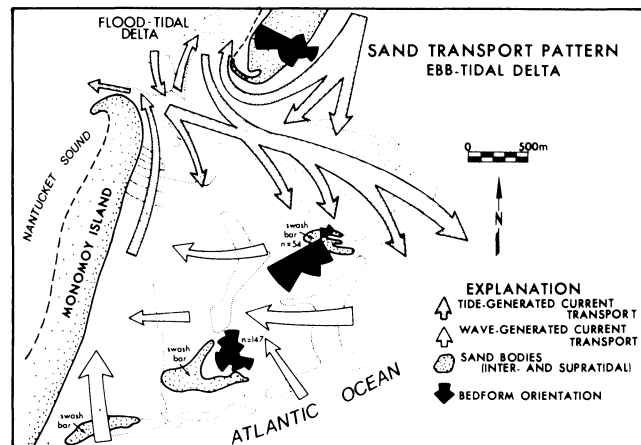


Figure 3. Net sand transport patterns of the Chatham Harbor (Massachusetts) inlet, based on studies of bedform orientation. (From HINE, 1975)

and, in some cases, measured tidal discharge over a number of tidal cycles (e.g., BOOTHROYD and HUBBARD, 1975).

The morphology and bedform patterns these inlet models describe provide useful insight on the partitioning of sediment transport around inlets. As the diagram by HINE (1975) illustrates, the channels are dominated by tidally driven currents. Shallow platform areas of the ebb-tidal delta are dominated by wave-driven currents. The principal direction of transport is further defined based on position within the ebb-tidal delta. Under normal flow conditions in moderate energy settings, the main inlet channel contains ebb-oriented bedforms owing to the dominance of the ebb discharge. Sediment supplied to the main ebb channel will be flushed seaward, fanning out and accumulating in seaward shoals as flow competency decreases. This produces a reverse gradient in bottom elevation going seaward along the channel in comparison to the positive slope of foreshore profiles away from the inlet.

The terminus of the ebb-tidal delta occurs where ebb-tidal currents diminish to the sediment transport threshold. This distance offshore is also related to incident wave energy. As waves approach the shoreline, they refract and shoal before breaking in water depths approximating the wave height. Wave-breaking over the nearly level surface of the outer bar produces translational bores that drive sediment landward in opposition to the ebb flow. The result is a characteristic lobate development of the ebb-tidal delta with swash bars forming to either side of the main ebb channel (Figure 2) and the "terminal lobe" forming where ebb-tidal currents and incident wave-generated currents balance.

The sediment transport system in tidal inlets is completed by the combination of wave-generated, longshore transport along the adjacent beaches which is usually directed toward the inlet because of sheltering effects inside the ebb-tidal delta. Where the ocean and inlet shorelines merge, a secondary channel dominated by flood currents forms. HAYES (1975) refers to this as a marginal flood channel and explains its persistence based on time-velocity asymmetry of tidal currents in the channels. If waves are present, oblique breaking toward the inlet will enhance flood-directed flow in the marginal flood channels, although the relative contribution of tide- and wave-generated flows has not been quantified.

While some inlets and their ebb-tidal deltas are bilaterally symmetric with respect to their main channel axes, most exhibit asymmetries from this ideal case. FITZGERALD *et al.* (1978) described a range of process-response (macro-time scale) models of tidal inlets, including:

- (1) Migrating inlets, which are positionally unstable and affect adjacent shorelines by the process of spit growth and direct cutting of the downdrift shoreline.
- (2) Stable inlets (throat section), which have asymmetric ebb-tidal deltas as a result of one dominant longshore-transport direction.
- (3) Stable inlets, which tend to have symmetric ebb-tidal deltas and no dominant, net longshore-transport direction.

In the third case, deltas may grow seaward during extended periods of low wave energy (*i.e.*, ebb-directed currents become relatively stronger) or collapse landward during periods of higher than normal wave energy (Figure 4). There is empir-

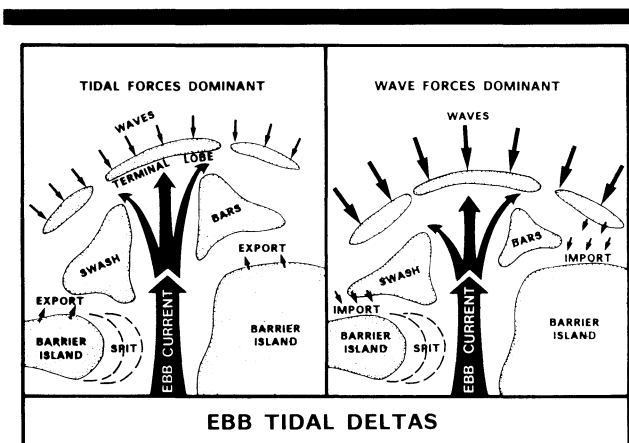


Figure 4. Yearly or seasonal variations in wave energy can modify the ebb-tidal delta, favoring contraction and import of sediment to adjacent beaches when wave energy is higher than normal, and expansion of the delta when waves are lower than normal. (From KANA, 1988)

ical evidence that this growth and decay in areal extent of ebb-tidal deltas occur around some equilibrium delta volume (WALTON and ADAMS, 1976; FITZGERALD, 1984).

### Empirical Relations

Early inlet studies related inlet formation, size, and persistence to a qualitative ratio of tidal energy to longshore transport (BRUUN and GERRITSEN, 1959). The size of inlets was shown to depend on the tidal prism available to maintain the channel (O'BRIEN, 1969). O'BRIEN and other researchers (e.g., JARRETT, 1976) developed empirical relationships between mean sea-level cross-section at the inlet throat ( $A_c$ ) and spring tidal prism ( $T_p$ ) to compare the size of inlets. These regression relationships have the general form:

$$A_c = k \cdot T_p^x, \quad (1)$$

where  $k$  is an empirical constant varying from  $7.75 \times 10^{-6}$  to  $2.833 \times 10^{-4}$  and  $x$  is a coefficient varying from 0.84 to 1.05. These ranges of values are derived independently for West Coast, Gulf Coast, and East Coast inlets (CERC, 1984), using English or metric units of  $T_p$  and  $A_c$ .

Another empirical model of tidal inlets relates to the size of ebb-tidal deltas. WALTON and ADAMS (1976) proposed a relationship between delta volume ( $\nabla$ ) and tidal prism ( $T_p$ ):

$$\nabla = 13.8 \times 10^{-5} T_p^{1.23}, \quad (2)$$

where volume is in cubic yards and  $T_p$  is given in cubic feet. WALTON and ADAMS (1976) showed U.S. ebb-tidal delta volume ranges in size over three orders of magnitude (Figure 5).

Brown (1928) noted that inlets can change significantly over short periods. For example, a single northeaster is reported to have moved upwards of 100,000 cubic yards ( $0.75 \times 10^5$  cubic meters) into Absecon Inlet, New Jersey. Moriches Inlet, New York, nearly closed as a result of littoral drift inputs during a March 1962 storm (USACE, 1963). VOGEL and KANA (1985) provide additional evidence that sediment inputs to the lagoon (*e.g.*, buildup of flood-tidal deltas) are ep-

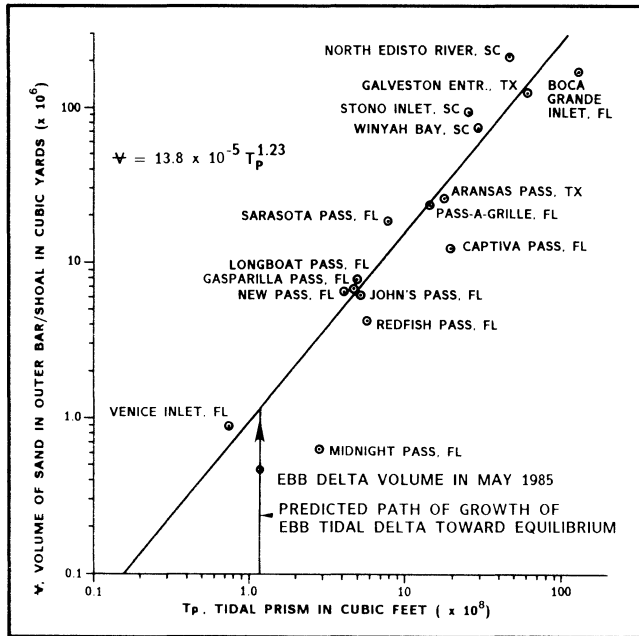


Figure 5. Regression curve of ebb-tidal delta volume versus tidal prism for mildly exposed coasts (after WALTON and ADAMS, 1976), including data and predicted delta growth at an artificially constructed inlet (Captain Sams Inlet, South Carolina). (From KANA and MASON, 1988)

isodic. They suggest that even in low-tide range settings, some inlets show a natural tendency toward ebb dominance and growth of the seaward shoals under normal tides. This becomes more evident in settings where inlets flush marsh-filled lagoons. Flow attenuation over the marsh perturbs the tide curve such that peak ebb velocities (the controlling sediment transport variable) are higher than peak flood velocities (FITZGERALD *et al.*, 1976; NUMMEDAL and HUMPHRIES, 1978). If mixed-energy inlets are, for the most part, ebb-dominant under normal flow conditions, the littoral budget will be conserved seaward of the inlet throat (VOGEL and KANA, 1985), with important implications for inlet sediment-transport modeling.

Clearly, inlets cannot export sediment indefinitely to the seaward shoals without some counteractive balance in sediment volumes. As previous studies have shown (*e.g.*, BRUUN and GERRITSEN, 1959; FITZGERALD *et al.*, 1978; SEXTON and HAYES, 1983), there are a number of mechanisms for exchange with the beach, all related to the concept of *bypassing*.

### Inlet Bypassing

Since BRUUN and GERRITSEN'S (1959) pioneering study, scientists have recognized the importance of sand bypassing across inlets. In fact, maintenance of sand flow along the coast, whether by artificial or natural bypassing, is now recognized as an essential element of coastal zone management (NRC, 1990). There remain questions regarding the exact nature of bypassing, how sediment actually crosses inlet channels, and how the rate of bypassing is controlled.

Early researchers (*e.g.*, BRUUN and GERRITSEN, 1959) suggested a major pathway was the natural bridge formed by the outer bar (terminal lobe). Littoral transport from updrift of the inlet simply continued its flow around the delta terminus until it resumed along the downdrift beach. This may be the case for small, wave-dominated inlets where the ebb-tidal delta is less prominent and continuous wave-breaking occurs from the updrift to downdrift limits of the inlet (*i.e.*, where the delta lobe merges with the foreshore). However, around larger inlets in tide-dominated settings, such channel crossover is considered unlikely. Deep, main ebb channels and ebb-tidal deltas extending several kilometers (km) offshore form a natural barrier to bypassing. So for littoral transport to cross large or deep inlets, an alternate, more circuitous route is required.

Inlet sand-circulation patterns described by HINE (1975) and FITZGERALD *et al.* (1976) provide evidence that sand bypassing is more commonly episodic. For sand to cross larger inlets, the ebb-tidal delta model suggests it must first enter the main ebb channel by way of the updrift recurved spit and marginal flood channel. Once in the main ebb channel, sand will be flushed seaward and dispersed over the swash platform. If it reaches the downdrift swash platform, it can then move shoreward under breaking waves, coalescing into a discrete sand body. Bypassing to the downdrift beach technically occurs when a portion of the swash platform (usually in the form of an isolated subaerial bar) attaches at some point along the beach downdrift of the inlet. In recognition of the episodic nature of this process (and oftentimes, discrete sand bodies involved), some researchers use the term—*shoal bypassing*.

### Shoal Bypassing

SEXTON and HAYES (1983) documented shoal bypassing at Captain Sams Inlet (South Carolina), a small inlet with a spring tidal prism of  $3 \times 10^8 \text{ m}^3$  (KANA and MASON, 1988) and a nearly attached terminal lobe of the ebb-tidal delta. At spring low tide in this setting where mean tide range is approximately 1.8 m, it is often possible to wade across the inlet over the terminal lobe (about 0.5 km offshore). SEXTON and HAYES (1983) showed that discrete, shoal-bypass events, one of which was triggered by a natural realignment of the inlet thalweg updrift of its former location after Hurricane *David* (September 1979), accounted for rapid accretion of the downdrift beach. The sand volume in one bypass amounted to over 75,000 cubic meters ( $\text{m}^3$ ) in this inlet, where the ebb-tidal delta volume is of the order  $10^6 \text{ m}^3$  (MASON, 1986).

KANA *et al.* (1985) and WILLIAMS and KANA (1987) documented two shoal-bypass events downdrift of Dewees Inlet (South Carolina), both of which involved around  $0.5 \times 10^6 \text{ m}^3$ . In this mid-sized, stable inlet ( $T_p \approx 10^7 \text{ m}^3$ ), shoal bypassing occurred near the downcoast extremity of the ebb-tidal delta approximately 1 km from the main ebb channel. Bypassing in these instances occurred at a larger scale but over a longer period than at Captain Sams Inlet with no apparent realignment of the inlet thalweg. KANA *et al.* (1983) documented a similar, large-scale shoal bypass involving  $\sim 10^6 \text{ m}^3$  between the late 1970s and early 1980s downdrift

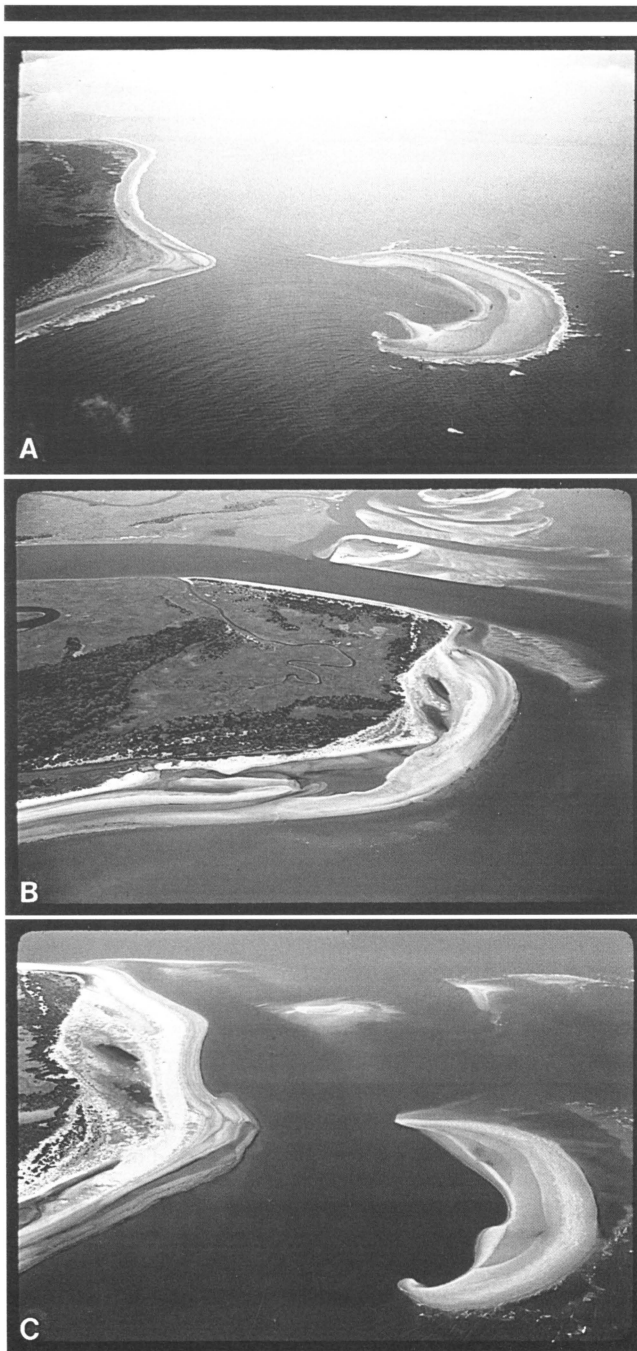


Figure 6. Shoal-bypass event involving  $\sim 10^6 \text{ m}^3$  at Stono Inlet/Kiawah Island (near Charleston, South Carolina) between 1977 (A) and 1983 (B). A successive event began around 1986 (C), culminating in attachment around 1990. Views looking north at low tide.

of Stono Inlet at the east end of Kiawah Island, South Carolina (Figure 6). Figure 7 illustrates the shoal attachment sequence for Dewees Inlet/Isle of Palms. KANA *et al.* (1985) refer to three stages, as follows:

**Stage 1—Offshore shoal “detaches”** from the swash platform or outer shoals of the inlet after coalescing as a dis-

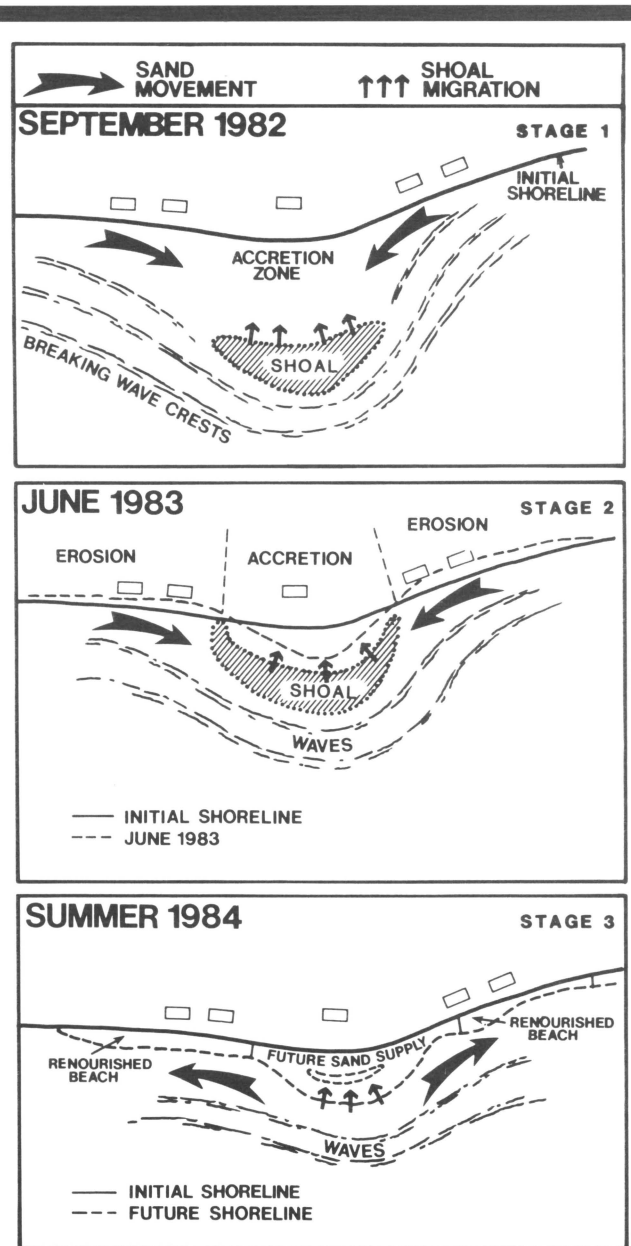


Figure 7. The three stages of shoal attachment based on a case study at Dewees Inlet/Isle of Palms (South Carolina). (After KANA *et al.*, 1985)

crete bar. This may be triggered by an excess buildup of sediment on one side of the delta and by the development of breaks in the swash platform (e.g., spillover lobes or runnels between multiple bars) which isolate the shoal from the rest of the ebb-tidal delta. Wave-breaking on the shoal begins to dominate over ebb-directed currents, driving the shoal landward. Wave refraction produces a characteristic crescent morphology with apex pointing toward shore. Oblique waves to either side of the shoal drive littoral transport from adjacent beaches into the lee of the shoal, initiating formation of a cusped spit at the shoreline.

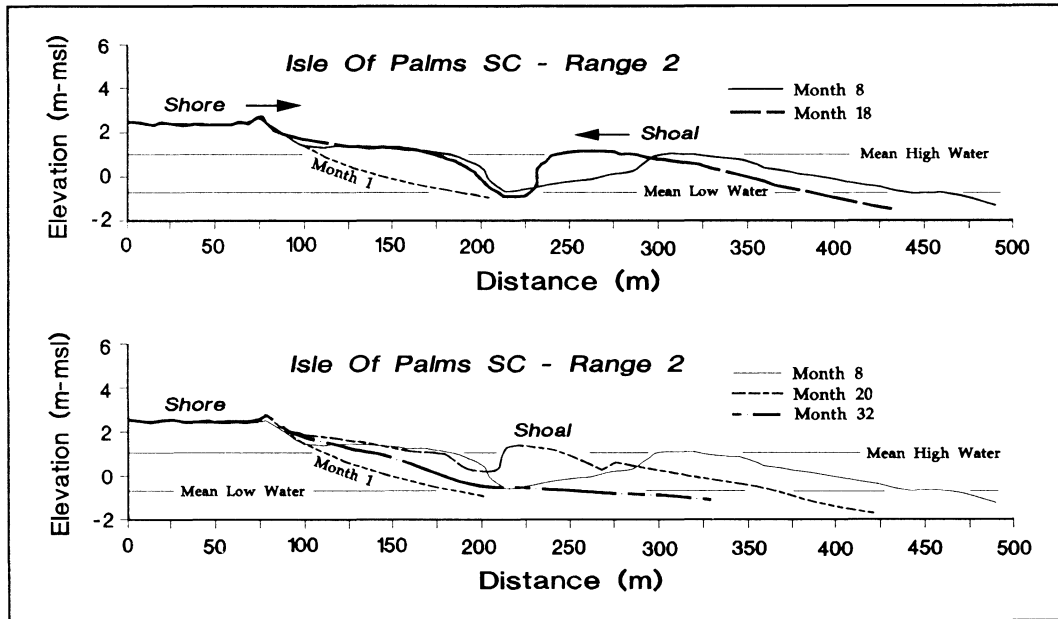


Figure 8. Wading-depth profile illustrating a shoal-bypass event at Dewees Inlet/Isle of Palms (South Carolina). During month 1 (October 1982), a shoal (not surveyed) emerged at low tide approximately 500 m offshore. During the successive three years, this  $0.5 \times 10^6 \text{ m}^3$  shoal migrated shoreward, attached at its apexes by month 8 (stage 2), then merged with the beach and spread laterally. By month 32, the net change in shoreline position was approximately 30 m seaward.

**Stage 2—Shoal attaches** to the shoreline at one or both apexes, temporarily trapping a large runnel. Waves continue to push the shoal landward and up the foreshore slope until it welds with the preattachment shoreface (Figures 8 and 9).

**Stage 3—Shoal spreading** occurs as excess sediment accumulates in a bulge that becomes bounded by the shoreline. Waves break and disperse sand in either direction away from the point of attachment. The process is complete when the shoreline straightens or when there is little variation in profile changes at and adjacent to the zone of shoal bypassing.

Observations of shoal bypassing by KANA *et al.* (1985) and others along South Carolina beaches suggest this process is common and exceedingly important. The volume of sand involved in some shoal bypasses is comparable to a large-scale nourishment project; therefore, the implications for nearby beaches are obvious.

The shoal-bypass sequence (KANA *et al.*, 1985) is further confirmed for South Carolina inlets by a project at Seabrook Island whereby Captain Sams Inlet was artificially relocated about 2 km updrift of its 1982 position. This February 1983 event (KANA, 1989) produced a forced bypass of the entire ebb-tidal delta. Four years after a new inlet was cut and the old one was closed, the abandoned ebb-tidal delta ( $>10^6 \text{ m}^3$ ) had migrated shoreward and merged with the downdrift beach, widening it by over 350 m.

Following inlet relocation, KANA and MASON (1988) developed a sediment budget for the new inlet. One goal was to

document the rate of growth of the new ebb-tidal delta. A secondary outcome of the study was the determination of the primary sediment sources accounting for growth of the new delta. Figure 10 shows an annualized sediment budget for the first two years after inlet relocation. Despite the early stages of ebb-delta growth, sediment arriving from updrift was expended in forming the updrift recurved spit (G and A in Figure 10). Erosion of the downdrift shoreline occurred as the updrift spit forced the main ebb channel downdrift. Volumetric growth of the ebb-tidal delta was accounted for by a combination of losses in the downdrift spit and erosion of the inner shoreface (volumes B and C). Shoal bypassing is also indicated along the downdrift shoreline between areas F and E (Figure 10).

The Captain Sams Inlet, 1983–1985 sediment budget demonstrated that sand bypassing even at some small inlets does not have to take the shortest route across an inlet. In this case, which may be typical for many mixed-energy inlets, sediment takes a more circuitous pathway, and transport becomes “partitioned” between wave-generated flows and tidal-generated flows. Wave-generated sand transport predominates over shoals, along the beach face, and along recurved spits at the margins of inlets (i.e., in shallow water, where wave-breaking is a dominant process). Tidal-current-generated transport predominates in the channels, is directed seaward only in the main ebb channel [or, where present, in incipient channels, sometimes termed spillover lobes (FITZGERALD, 1984)], and tends to occur in depths greater than the wave-breaking zone (KANA and MASON, 1988).

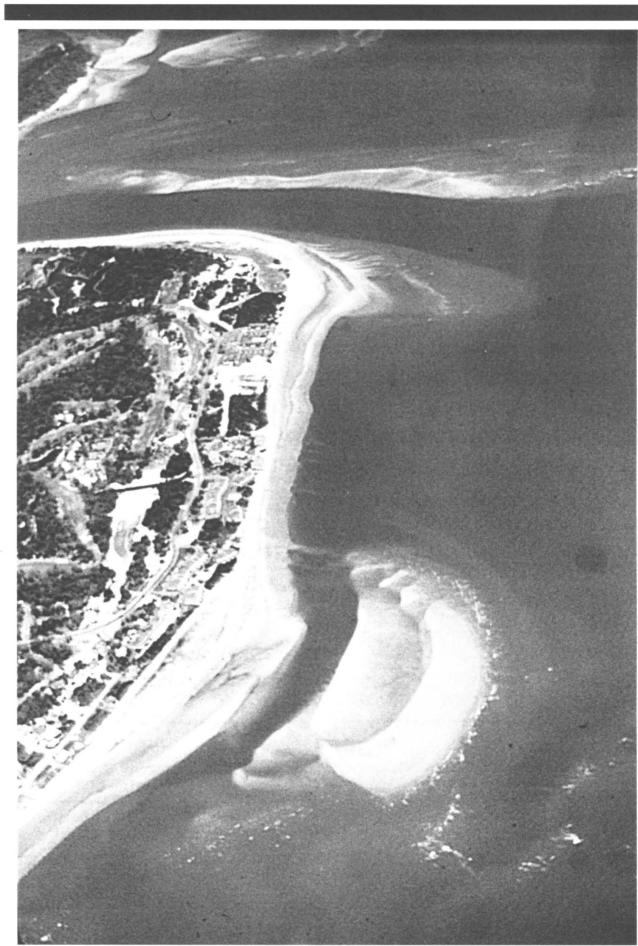


Figure 9. Shoal bypass (A) at Stage 2—Attachment adjacent to Dewees Inlet, South Carolina, at low tide around month 8 of a cycle. Range 2 referenced in Figure 8 bisects the center of the shoal.

### SIMPLIFIED CONCEPTUAL MODEL OF INLETS ON MESO-TIME SCALES

As a first step toward applying descriptive geomorphic inlet models, such as those described, to mesoscale and microscale predictive models, the authors propose a simplified conceptual model of inlets (Figure 11). This model is based on the previously referenced empirical studies and review of inlet morphology along moderate energy shorelines typical of the southeastern United States, and provides a basis for identifying the primary driving forces, transport directions, and rates for sediment movement and bathymetric change. A basic assumption is the dominance of ebb flows in the main channel which tend to flush sediments seaward. The model assumes flood tidal deltas are absent (a characteristic of most marsh-filled lagoons) and, therefore, the predominant sand bodies associated with the inlet are confined to the ocean side of the system.

Four primary inlet domains are considered:

- A— Main ebb channel.
- B— Ebb-tidal delta with broad swash platforms parti-

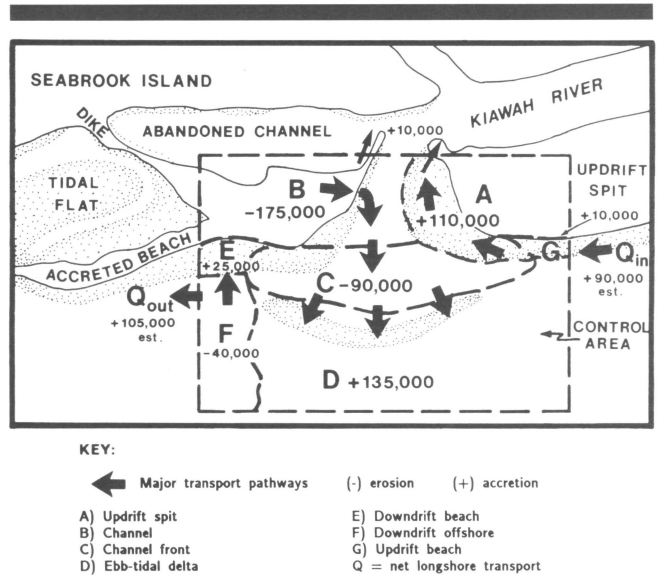


Figure 10. Annualized inlet sediment budget for March 1983 to May 1985 following construction of new Captain Sams Inlet (South Carolina). All values are in cubic meters per year ( $m^3/yr$ ). (From KANA and MASON, 1988)

tioned alongshore into left, center, and right sub-compartments.

- C— Shoal-bypassing zones at the flanks of the ebb delta.
- D— Recurved spits along the inlet margin.

**Domain A** in Figure 11 is the main ebb channel (following HAYES' 1975 terminology), or the gorge as referenced by hydraulic engineers. Flow is controlled by tides and volumetric exchange (tidal prism,  $T_p$ ), through the narrowest part of the inlet (throat, defined by  $A_c$ ), and net transport is influenced by asymmetry between the ebb and flood. Site-specific tidal

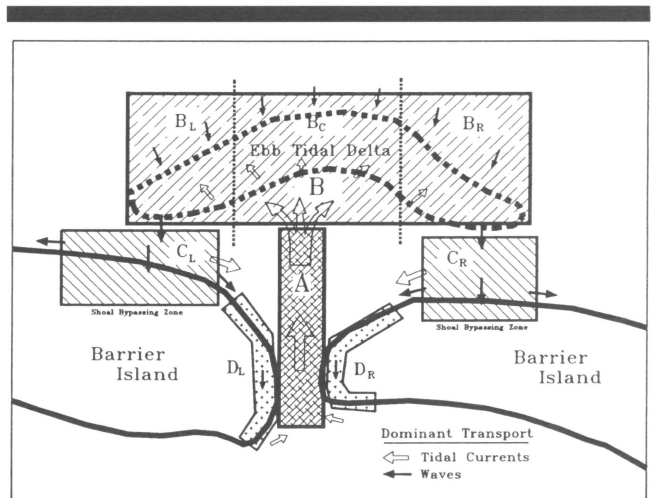


Figure 11. Simplified mesoscale (conceptual) tidal inlet model for mixed-energy tidal inlets, showing principal model domains A-D.



hydrography data from three South Carolina inlets—North Inlet (FINLEY, 1976; NUMMEDAL and HUMPHRIES, 1978), Price Inlet (FITZGERALD *et al.*, 1976), Captain Sams Inlet (MASON, 1986)—and others confirm a typical time-velocity asymmetry whereby the ebb flow is shorter in duration but higher in speed than the flood. This velocity asymmetry promotes export of sediment on the ebb. Time asymmetry also occurs in the tidal flow with peak ebb velocities occurring closer to the time of low water. This is related to increased channelization over the marsh as the tide falls (NUMMEDAL and HUMPHRIES, 1978), forcing more water into the channel. Inertial effects produce a time lag between the predicted time of low water and the actual time of slack water in the inlet throat. As FITZGERALD *et al.* (1976) report for Price Inlet, the sediment-transport potential (a power function of current speed) is more than adequate to flush introduced sediment seaward. In this case, longshore transport reaching the inlet channel is much lower than the residual ebb-transport rate. Domain A represents the beginning of the inlet sediment-transport system in the present model. Tidal hydrodynamics models form the principal basis for quantifying potential sediment transport in this domain.

**Domain B** represents the main body of the ebb-tidal delta. Others, including FINLEY (1976) and WALTON and ADAMS (1976), have defined the limits of the ebb-tidal delta as the area of excess sediment seaward of the strandline above the level of the adjacent foreshore. This definition implies the delta volume can be computed from the difference between actual bathymetry and the bathymetry that would exist if the inlet were absent and foreshore contours were straight-parallel to the coast. As sediment is flushed from Domain A to the ebb-tidal delta, tidal and wave-generated currents intersect. With the ebb discharge unconfined seaward of the throat, flow competency declines and sediment becomes dispersed in a characteristic lobate, fan-shaped deposit.

It is generally recognized the terminus of the delta is where tidally generated currents on the ebb balance with wave-generated, landward flow. With a continuous supply of sediment, the delta expands and grows higher. But as this occurs, the incidence of wave-breaking increases. As WALTON and ADAMS (1976) have shown, there tends to be some finite size limit to the ebb-tidal delta in relation to the tidal prism (Eq. 2). Observations at Price Inlet (FITZGERALD, 1984) suggest the subaerial exposure of the ebb-tidal delta changes cyclically. Incident wave energy tends to push sediments shoreward, up the foreshore slope. Presumably, this process accelerates during years of storm activity and decelerates during years with fewer storms. Ebb-directed tidal energy serves to counteract landward movement of sediment and provides a mechanism for bisecting the swash platform in the form of spillover lobes (incipient ebb channels) (FITZGERALD, 1984).

Within Domain B, variations in wave direction have the potential to shift sediment alongshore; therefore, the ebb-tidal delta can be subdivided alongshore into the left, center, and right areas as shown in Figure 11. An unstable, migrating inlet such as Captain Sams Inlet (KANA, 1989) will contain a larger part of the ebb-tidal delta in the downdrift one-third of Domain B (*i.e.*,  $B_R$ ). The extent to which the delta shoals “overextend” in the downdrift direction is related to

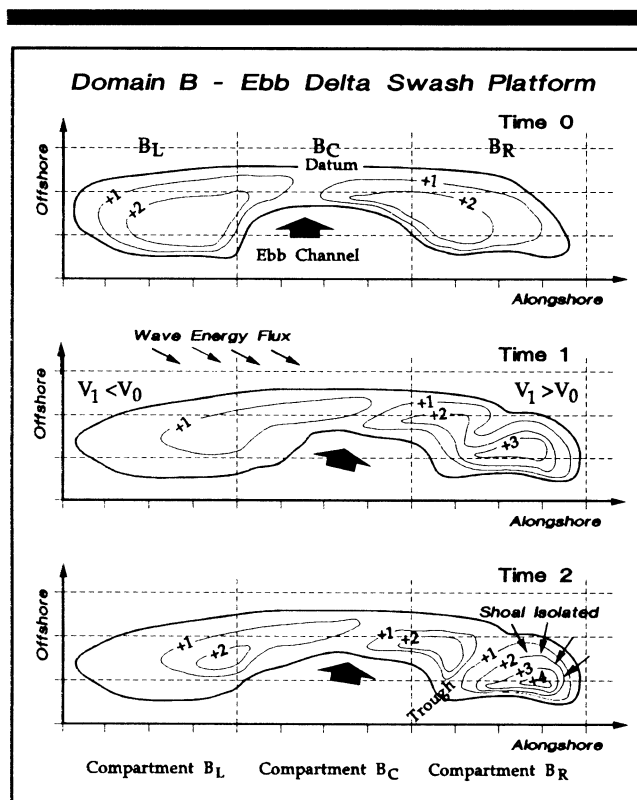


Figure 12. Sequence of ebb-tidal delta (Domain B) changes that may trigger frequent, shoal-bypass events. Initially, the delta is symmetric (Time 0) with equal volumes ( $V$ ) and similar swash platform elevations in compartments  $B_L$  and  $B_R$ . At Time 1, excess sediment has accumulated in  $B_R$  under the influence of a net longshore transport. By Time 2, multiple shoals at higher elevations develop in  $B_R$  under more frequent wave-breaking, leading to isolation of and eventual release from the delta of the highest, most remote bar. Contour units are relative.

the rate of sediment input to the updrift spit, which is driven by the longshore component of wave energy. For the case of a migrating inlet, Domain B sediments move with the channel until such time as a new inlet breaches the updrift spit. Such an event may trigger closure of the old channel, a wholesale collapse of the abandoned ebb-tidal delta, and accretion of the shoals along the downdrift shoreline. A new ebb-tidal delta will evolve at the realigned channel and grow via the introduction of sediment from Domain A.

While channel relocation to an updrift position generally presages a major shoal-bypass event, smaller frequent events (relative to the scale of an inlet's delta volume) may be common. Figure 12 illustrates how this can occur. Initially (Time 0), the swash platform of the ebb-tidal delta is symmetrical, with a near balance in sand volume and similar shoal elevations and areas to either side of the main ebb channel. With the occurrence of an event and strong waves from left to right (Time 1), some sediment shifts from compartment  $B_L$  to  $B_C$  and  $B_R$ . This decreases the shoal volume and elevation in  $B_L$  and introduces more sediment into  $B_R$  with respect to the initial condition (Figure 12, middle panel). Such events also tend to deflect the main channel in the direction of net



wave energy, possibly producing multiple breaks (incipient channels) in the outer delta. Between Times 1 and 2, Domain B begins to shift back toward its "equilibrium" configuration with the ebb channel bisecting the delta symmetrically. However, excess sand in  $B_R$  will tend to coalesce into multiple bars separated by troughs. If the bar furthest removed from the main channel moves into shallower water and gains elevation, it will experience a higher frequency of wave-breaking and enhanced wave refraction. This may trigger its release from the delta and initiate the shoal-bypass sequence.

Sediment may remain in Domain B for decades or longer, particularly if the inlet is large. The principal sediment motion can be grossly described as "sloshing," whereby a particular ebb-tidal delta volume is maintained but portions of the swash platform shift within the domain as wave direction changes, or the ratio of tidal energy on the ebb to wave plus tidal energy on the flood changes. FITZGERALD (1984) illustrates this process for Price Inlet (South Carolina) in a series of sketch maps from aerial photography spanning 40 years. In that example, the inlet channel is positionally stable, but lateral shifts in the ebb-tidal delta occur episodically and lead to bar-welding events and progradation of the adjacent beaches.

A key problem for numerical simulations is the prediction of conditions leading to gross asymmetries in sand volumes within subcompartments  $B_L$ ,  $B_C$ , and  $B_R$  in model Domain B, which may lead to rechannelization and shoal bypassing on either side of the inlet (or both sides at the same time!). Once part of the swash platform of Domain B is free of the influence of ebb-directed tidal flows, the process of shoal bypassing becomes inevitable.

**Domain C** is generally situated along the flanks of the ebb-tidal delta and refers to the specific process of shoal bypassing. Landward transport dominates and the domain culminates with attachment of shoals at the shoreline (Figures 8 and 9). In Domain C, incident wave energy greatly exceeds ebb-directed tidal energy, allowing a portion of the ebb-tidal delta to "break off" and migrate toward shore. Observations at a number of inlets suggest the onshore migration of shoals operating in Domain C can be rapid, with migration rates exceeding 15 meters per month (*cf.*, Figure 8) once a portion of the shoal becomes emergent at low tide (WILLIAMS and KANA, 1987). Wave-breaking over the shoal during sustained portions of the tidal cycle appears to be a prerequisite of shoal bypassing in Domain C. As a means of checking the validity of numerical simulations of this process at meso-time scales, the volume of sediment in a given shoal bypass will generally be a small fraction of the ebb-tidal delta volume. Figure 13 illustrates how shoal-bypass volume and period at three South Carolina inlets may be approximately related to inlet size.

**Domain D** represents the foreshore along the adjacent beaches to either side of the inlet. Serving as a topographic boundary, the existing shoreline forces sediments arriving from Domain C to shift from onshore movement to shore-parallel movement along the beach. This transport is driven principally by obliquely breaking waves, with a secondary component due to flood currents which dominate in the marginal flood channels. Empirical data from Dewees Inlet

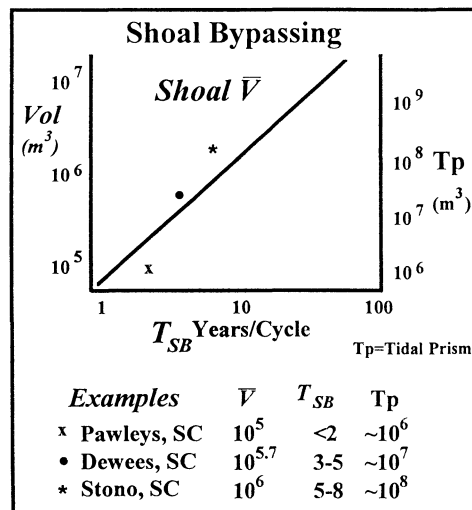


Figure 13. Approximate relationships among shoal volume, inlet tidal prism, and period of bypassing for three mixed-energy inlets in South Carolina.

(KANA *et al.*, 1985) confirm the completion of the inlet transport loop with sediment migrating along the recurved spit. CSE (1991) also documented longshore transport along the Seabrook Island margin of North Edisto Inlet in the flood (upstream) direction. Both of these cases lend support to the empirical observations that sediment transport around inlets becomes partitioned according to bathymetry (KANA and MASON, 1988). Wave-generated transport dominates along the upper bathymetric profile, with incident waves propagating obliquely along recurved spits, driving sediment up-inlet as they break. Tidal-current-generated transport dominates along the channel profile below breaker depths.

Clearly, a part of Domain D represents sediment returning to the inlet for further recycling in the inlet transport loop. The remainder shifts away from the inlet and moves down-coast in the longshore transport system. For purposes of projecting impacts on the shoreline associated with bypassing, the authors have observed that one-half the shoal volume typically will shift back toward the inlet and the other half will shift away from the inlet in mixed-energy settings like the southeast U.S. coast. This division is centered at the point of shoal attachment (apex of cusped spit formation on the receiving beach). Sediment dispersion is likely to occur at a rate that decreases with time until the shoreline change (alongshore, as measured by beach profiles) becomes uniform updrift, downdrift, and at the point of shoal attachment. When this condition occurs, a new shoreline boundary (incipient beach ridge) is formed, one in which the foreshore is displaced seaward in proportion to the sediment volume gained from the shoal bypass. If no additional sediment is added to Domain D, this area becomes a "headland" source to the adjacent beach, at least until such time as a new cycle of shoal bypassing occurs. The frequency and magnitude of shoal bypassing in Domain C and the rate of advection in Domain D ultimately control the long-term evolution of the shoreline.

Modeling sediment transport from Domain A through Domain D is an ultimate goal of studies such as the present project. However, even this simplified conceptual model involves numerous uncertainties that must be resolved before formulating a deterministic model at meso-time scales.

### SUMMARY

In summary, a conceptual model is proposed as the basis for partitioning sediment transport and morphologic changes around tidal inlets typical of southeast U.S. and other mixed-energy settings. It draws on macroscale geomorphic models and empirical studies of tidal inlet sediment dynamics. It also acknowledges the limitations of microscale predictive models when attempting meso-time scale simulations (years to decades).

Clearly, to extend the time scale of predictive models of inlet sediment dynamics, simplifying assumptions must be made. The basis of the conceptual model is a sediment transport loop around ebb-tidal deltas, whereby sediment exchanges between the delta and the beach. Four domains define the transport loop and within three of the domains, either tidal current-generated transport or wave-generated transport clearly dominates.

The transport loop is initiated as sediment enters the main ebb channel (Domain A). Ebb flows, which tend to dominate in mixed-energy inlets, shift excess sediment offshore to the ebb-tidal delta (Domain B). Domain B is subdivided along-shore into left, center, and right compartments. Incident waves interact with ebb flow to produce a gross geometry and delta volume that is in balance between tidal and wave energy. If prolonged winds and waves move parallel to the coast, delta sediments in Domain B will shift to the downdrift subcompartment, and the main ebb channel of Domain A will eventually be diverted updrift to the subcompartment where there is the least impedance to the flow. To the extent variations in wave direction can effect an imbalance between wave- and current-generated transport, onshore transport (shoal bypassing) or offshore transport (delta growth) will be favored. Domain C occurs where excess sediment in a subcompartment of the ebb-tidal delta is freed to move shoreward under incident waves.

The transport loop is completed when the shoal bypass to the adjacent shoreline is complete. As sediment moves through Domain C and attaches to the beach, high-angle salients (with respect to the pre-existing shoreline) form, such that longshore transport is directed both toward and away from the inlet. A simple, but reasonable, assumption for mixed-energy inlets is that half the volume in a shoal bypass moves downcoast and feeds the adjacent beach while the remaining half cycles back to the inlet. Transport in Domain D is principally via wave-generated currents along the fore-shore.

Domain D at the inlet terminates in spits and secondary channels flanking the main ebb channel. Excess sand accumulation in Domain D becomes subject to erosion, particularly if it tends to reduce the cross-sectional area of the inlet throat below equilibrium. Erosion and scour of the inlet

shoreline and spits of Domain D feed sediment back to Domain A.

Using this conceptual model of sediment transport around tidal inlets, the authors are testing various algorithms in an attempt to simulate some of these processes at meso-time scales.

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