Journal of Coastal Research	17	2	280–291	West Palm Beach, Florida	Spring 2001

Shoal Bypassing in Mixed Energy Inlets: Geomorphic Variables and Empirical Predictions for Nine South Carolina Inlets

Daniel J. Gaudiano† **and Timothy W. Kana**‡

†Department of Geological Sciences
University of South Carolina
Columbia SC 29208, U.S.A.
dgaudiano@aol.com

‡Department of Geological Sciences
University of South Carolina
Columbia SC 29208, U.S.A.
and
Coastal Science & Engineering LLC
PO Box 8056
Columbia SC 29202, U.S.A.
t_kana@coastalscience.com

ABSTRACT

GAUDIANO, D.J. and KANA, T.W., 2001. Shoal Bypassing in Mixed Energy Inlets: Geomorphic Variables and Empiricial Predictions for Nine South Carolina Inlets. *Journal of Coastal Research*, 17(2), 280–291. West Palm Beach (Florida), ISSN 0749-0208.

In mixed energy settings, tidal inlets undergo an episodic process known as shoal bypassing, whereby discrete bars are released from the ebb-tidal delta and migrate onshore. Such events can transport large volumes of sand, in the form of landward-migrating shoals, to adjacent beaches. Nine tidal inlets in South Carolina were analyzed to determine if there are predictable relationships among the volume of sand in the ebb-tidal deltas and in the individual bypassing shoals, the time interval between bypassing events, and the tidal prism. Historical photographs spanning up to 58 years yielded 221 discrete shoals at various stages of bypassing for the analysis. Building on earlier work by KANA (1995), mean shoal-bypassing event time intervals and the mean bypassing shoal volumes were found to be related to tidal prism. Larger inlets underwent shoal-bypassing events less frequently than smaller inlets, but produced larger bypassing shoal volumes. The relationship between average event interval and tidal prism was based on the equation, I = 0.046Tp + 4.56, where I is the average shoal-bypassing event interval (years) and Tp is the tidal prism (10^6 m^3). The relationship between average shoal volume and tidal prism was based on the equation, S = 6.42Tp + 113.4, where S is the average bypassing shoal volume (10^3 m^3). Both relationships are statistically significant. Bypassing shoals represented, on average, small volumetric percentages (0.6% to 6.6%) of their respective ebb-tidal delta volumes, yet in mesotidal, moderate wave energy settings such as South Carolina, shoal bypassing can be the single most important process contributing to a locally accreting beach.

ADDITIONAL INDEX WORDS: *Beach accretion, inlet change, shoals, shoal bypassing, shoreline change, tidal inlets.*

INTRODUCTION

Ebb-tidal deltas in mixed-energy settings exhibit shoals (or swash bars) which periodically migrate to adjacent beaches, thus causing rapid, localized accretion (Figure 1). This is particularly common along coastal plain shorelines with moderate tide range and frequent inlets (*e.g.,* barrier islands of the German East Friesian Islands (NUMMEDAL and PENLAND, 1981), New England (FITZGERALD, 1982), Virginia (RICE *et al.*, 1976), and the Copper River Delta in the Gulf of Alaska (HAYES, 1976). This process is sometimes referred to as "shoal bypassing" (SEXTON, 1981; SEXTON and HAYES, 1983), since the act of bypassing occurs episodically rather than continuously as implied by traditional inlet models (BRUUN and GERRITSEN, 1959). The goal of this study was to produce and analyze quantitative data for certain variables associated with shoal bypassing. The variables considered were total ebb-tidal delta volume, event frequency, bypassing shoal volume, and tidal prism. The data, from nine South Carolina inlets, were used to test the qualitative relationship suggested by KANA (1995) which relates tidal prism to both the frequency of shoal-bypassing events and the bypassing shoal volume.

Shoal bypassing is a natural form of beach nourishment. In some cases, upward of 10^6 cubic meters (m^3) may cycle back to the beach in a single event as a shoal breaks away from an inlet and migrates onshore (KANA *et al.*, 1985). While it has been recognized for some time that inlet deltas and shoreline evolution are related and may undergo systematic cycling of sediments (DEAN and WALTON, 1975; OERTEL, 1977), relatively little is known about the frequency and magnitude of discrete shoal-bypass events.

The South Carolina coast is a mixed-energy setting with spring tide ranges of ~2.5 m, average incident wave heights around 0.5 m, and beaches dominated by fine sand (~0.22 mm mean diameter) (HAYES, 1977). For most tidal inlets in

99065 received 18 August 1999; accepted in revision 8 August 2000.

Figure 1. Oblique aerial photographic sequence of a shoal-bypassing event at Dewees Inlet and Isle of Palms (South Carolina). Between 1996 and 1998, a shoal (seaward of the reference arrow) detached from Dewees Inlet's ebb-tidal delta (a), migrated landward (b), and attached to Isle of Palms (c). [From GAUDIANO, 1998]

South Carolina, the ebb-tide cycle is shorter than the flood, causing ebb-tidal currents to be faster than the flood (NUMMEDAL and HUMPHRIES, 1978). This time-velocity asymmetry, combined with moderate to low wave energy, helps to form large ebb-tidal deltas (HAYES, 1980). The ebb-tidal deltas, in turn, affect the energy of incoming waves, a critical factor controlling coastline morphology in mixed energy settings (HAYES, 1979). Ebb-tidal deltas owe their existence to the interaction of tidal currents and waves with the littoral sediment supply. Similar to other mixed-energy settings, a slight increase in tide range or a decrease in wave height will tend to promote seaward growth of ebb-tidal deltas; a decrease in tide range or an increase in wave heights tends to shift the delta landward and spread it in the longshore direction (HUBBARD, 1977). Over time, a state of quasi-equilibrium develops between the tidal currents building the ebb-tidal delta and incident waves forcing the delta sands landward, such that the scale of the delta is related to these primary driving forces (WALTON and ADAMS, 1976).

O'BRIEN (1931) demonstrated that an inlet's cross-section is proportional to tidal prism and will be maintained if littoral transport from the adjacent shorelines does not overwhelm the channel. Clearly, if such equilibrium in cross-sectional area and delta volume is to persist in the presence of littoral inputs, some quantity of sand must be released from the inlet. In some settings, the excess sand will form spits and flood tidal delta deposits for all intents taken out of the active system. However, in settings with marsh-filled lagoons, velocity asymmetry produces net seaward transport through the inlet, forcing littoral inputs toward the ebb-tidal delta.

KANA *et al.* (1999) describe the circuitous path such littoral inputs often take. As sediment leaves the confines of the inlet throat during the ebb tide, it disperses radially and settles on the delta. Flow segregation over the ebb-tidal delta (FITZGERALD *et al.*, 1976; HAYES, 1980) further defines low velocity zones where sediment will settle and build swash platforms. Given sufficient time for vertical accretion, inlet shoals may become subaerial during portions of the tidal cycle, particularly in higher tide range settings. Shoal growth further segregates tidal flows and makes the shoal increasingly subject to wave-generated currents. Where waves dominate, net sediment transport is generally directed toward the inlet throat. Where wave-generated currents are weaker, ebb-tidal currents dominate and account for seaward expansion of the delta. (See KANA *et al.* 1999; Figure 4.)

Shoal bypassing is the process whereby discrete swash bars are pushed shoreward by waves. A key question for researchers is—what triggers such releases of sand? One mechanism is channel realignment.

HUBBARD (1977) described the effect of inlet realignment and shoal bypassing as a three-step process (Figure 2). Stage one involves seaward, ebb-tidal delta growth. Stage two portrays channel over-extension in the direction of dominant longshore transport. In this position, the channel is less hydraulically efficient and will eventually divert its flow to a more direct and efficient route through a spillover lobe. The process may be gradual (taking 6–12 months) or can occur catastrophically during a single storm. In stage three, the downdrift swash bar becomes partially isolated from the main flows through the inlet, and wave-generated currents begin to control its movement. Breaking waves drive the shoal landward, gradually filling the abandoned channel in the lee of the shoal. Eventually, the bar welds onto the beach face (HUBBARD, 1977; FITZGERALD, 1988). Spit breaching and bar migration fall under the more general classification of "bar bypassing" (BRUUN and GERRITSEN, 1959). This process involves sediment, in the form of a migrating bar, moving past or bypassing an inlet.

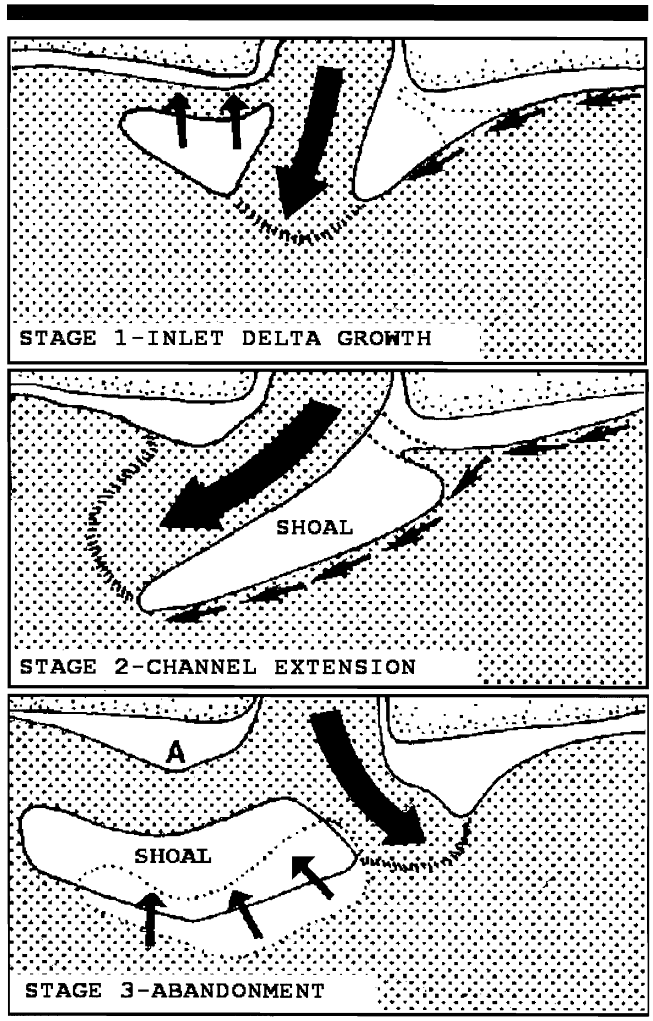

Figure 2. Simplified model of a bar bypass (after HUBBARD, 1977). Stage 1— initial ebb-tidal delta growth. Stage 2—continued growth, delta over-extends in the downdrift direction. Stage 3—delta break forming a new updrift channel, the abandoned shoal migrates shoreward.

Recent studies in mixed-energy settings (*e.g.,* KANA and MASON, 1988; KANA *et al.*, 1999) depicted shoal bypassing to be episodic rather than the semicontinuous process BRUUN and GERRITSEN (1959) had depicted. KANA *et al.* (1985) followed a large shoal (0.5×10^6 m^3) from its detachment from the margin of the Dewees Inlet ebb-tidal delta to its downdrift attachment at Isle of Palms, South Carolina. This and other similar bypassing events served as the basis for a geomorphic model depicting the final three stages of a shoal-attachment event. (See KANA *et al.*, 1999; Figure 13.) Stage one depicts an offshore bar, which has become isolated from the rest of the swash platform near the downcoast limits of the ebb-tidal delta (Figure 1a). During stage two, the shoal migrates landward and begins to attach to the beach face (Figure 1b). The migrating shoal is often crescent-shaped in this stage, with its ends reaching shore first while the central area remains further offshore. Beach erosion typically occurs adjacent to both sides of the shoal, and accretion continues directly in its lee. This third and final stage of attachment involves alongshore spreading of the shoal in either direction from the point of attachment (Figure 1c). Typically, a bulge in the shoreline persists where the shoal attaches. This bulge in the shoreline planform eventually flattens out as waves erode the protuberance. Significantly, shoal attachment introduces a new sediment supply to the beach system (KANA *et al.*, 1985).

Later investigations considered the quantitative geomorphic and hydraulic relationships of shoal bypassing. KANA (1995) predicted a direct relationship between the cycling frequency (event interval), the volume of the migrating shoals, and inlet tidal prisms. Larger inlets were shown to bypass larger volumes of sand, but less frequently than smaller inlets. Approximations were produced for only three inlets and were not derived from direct measurements. The goal of the present study was to produce and analyze quantitative data for the variables associated with shoal bypassing and to test KANA's (1995) general relationships.

METHODS

The South Carolina study area included nine inlets Pawleys (a), Midway (b), Captain Sams (c), Capers (d), Breach (e), Price (f), North (g), Dewees (h), and Stono Inlets (i) (Figure 3). An aerial photography record (ranging from 53 to 58 years) for each inlet was compiled and analyzed to identify and catalog shoal-bypassing events in progress or recently completed events. Vertical aerial photographs were digitized into a computer-mapping program (AutoCAD™) using common roads, bridges, and tidal creek intersections for scale and orientation. Oblique photos were used only to determine if a bypassing event was evident and not for shoal volume analysis. Shoreline morphologic features (such as enclosed cat-eye-shaped ponds and crescent- or mushroom-shaped sand bulges close to the inlet) were used to identify past events. Swash bars and migrating shoals were digitized from the waterline, while the shoreline was digitized from the wet-sand/dry-sand boundary. The three-stage model proposed by KANA *et al.* (1985) was applied in this study to categorize whether a particular event was in Stage 1 (bar emergence offshore), Stage 2 (bar migration and attachment), or Stage 3 (longshore spreading after attachment).

The average event interval was defined and calculated as the average number of years between observed shoal-bypassing events. An interval 'began' when a new event was first observed, regardless of the stage. The number of years between the first appearance of an event and the next observation of a new event was the event interval. For example, if a shoal-bypassing event was observed in 1949 and the next event observed was in 1957, the event interval would be eight years. Mean event intervals and their standard deviations were calculated for each inlet.

The aerial photography records are not the same for any of the inlets. The inlet with the best coverage (Dewees Inlet) has 46 percent of the years covered, while the average for all the inlets is 38 percent. The gaps are inevitable with aerial photography that was not taken annually. The standard deviations provide a measure of the uncertainty of the means. Because of the gaps in photography, these mean values are probably overestimates of the actual average event intervals.

The digital-mapping program was used to calculate the area of the migrating or attaching shoals. Multiplying the shoal area by an estimated thickness (3 m*) produced the volume of migrating sand based on only the exposed area of the shoal. *[*Note: The assumed thickness of 3 m for this setting was based on surveyed shoals at Isle of Palms (KANA et al., 1985) and Seabrook Island (KANA and MASON, 1988). Obviously, shoal thickness is site specific and will vary depending on the local tide range, inshore depths over which the shoal migrates, and subaerial exposure of the shoal.]* This technique placed unrealistic vertical sides on the shoals, which vastly underestimated the true volume of the shoal by ignoring the sloping underwater portion. The underestimation was confirmed through comparison with surveyed shoal volumes. For example, a bypassing shoal at Dewees Inlet (1982–1984) was documented by KANA *et al.* (1985) to have a volume of 500,000 m^3 while the above-outlined approach produced a volume of 214,000 m^3. To account for this 'missing' volume (57 percent), a scaling factor was derived (Figure 4) to relate the underestimated volume based solely on the exposed area and 3-m thickness to an estimated total volume based on sides with varying slopes. To determine the total volume, sides sloping at 1:10, 1:15 and 1:20 were added to square shapes (a square was used for geometric simplicity). These varying slopes were used for three of the sides, while a 1:5 slope was applied to the landward-facing side of the shoal based on surveyed shoal geometries for this setting. The scaling factor was calculated based on each shoal's specific exposed area. Because the 1:20 slope most closely represented the three sides of a shoal on the central South Carolina coast (based on representative profiles), the 1:20 equation was used in the shoal-volume scaling factor:

$$S_F = 3.5A_{EX}^{-0.22} \quad (1)$$

where S_F is the scaling factor and A_{EX} is the exposed shoal area. This correcting equation was applied to the shoal volumes that were previously calculated based on vertical sides to attain more realistic shoal-volume values. It is important to note that as shoal areas become extremely large ($\gtrsim 300 \times 10^3$ m^2), the scaling factor drops below one and would then decrease shoal volumes. This is due to the shape of the power curve and does not represent reality. Therefore, in cases where A_{EX} was $\gtrsim 300 \times 10^3$ m^2, F_s was not applied. This was the case for only four of the total 221 analyzed shoals. Standard deviations of mean shoal volumes were calculated for each inlet.

Estimated average annual contributions from ebb-tidal deltas to adjacent beaches were determined for each inlet. Dividing the corrected mean bypassing shoal volume by the mean event interval produced the local annual sediment transport inputs (m^3/yr).

Channel Cross-Sections and Tidal Prisms

Inlet-throat cross-sectional areas and tidal prisms were directly measured at seven of the nine inlets. The cross-sectional areas were computed to a standard survey datum, Na-

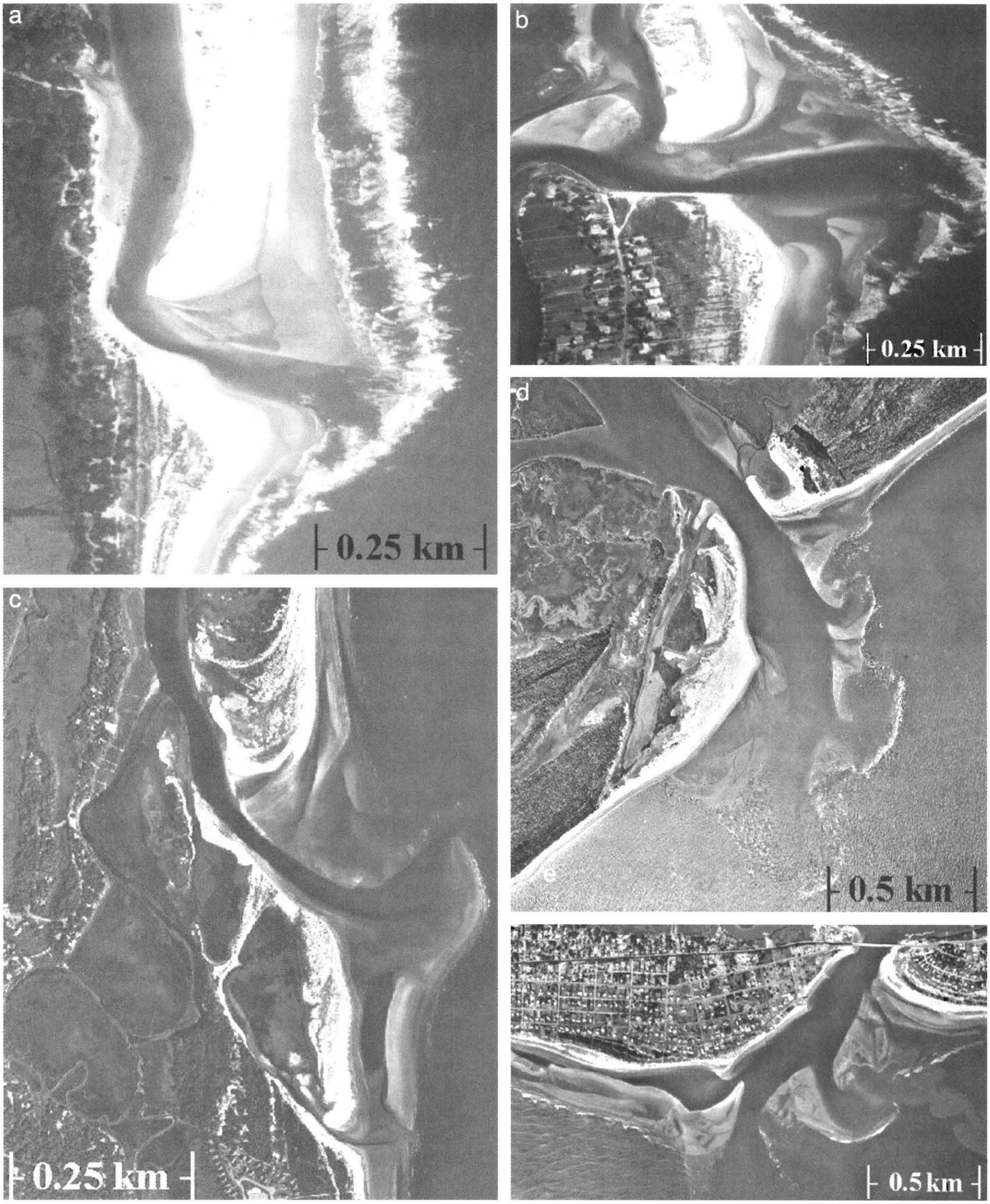

Figure 3. The study area included nine mesotidal inlets in South Carolina (a) Pawleys Inlet (1997), (b) Midway Inlet (1997), (c) Captain Sams Inlet (1992), (d) Capers Inlet (1957), (e) Breach Inlet (1982), (f) Price Inlet (1973), (g) North Inlet (1983), (h) Dewees Inlet (1987), (i) Stono Inlet (1979). Scales are approximate. [Representative photos by U.S. Department of Agriculture, Salt Lake City, Utah]

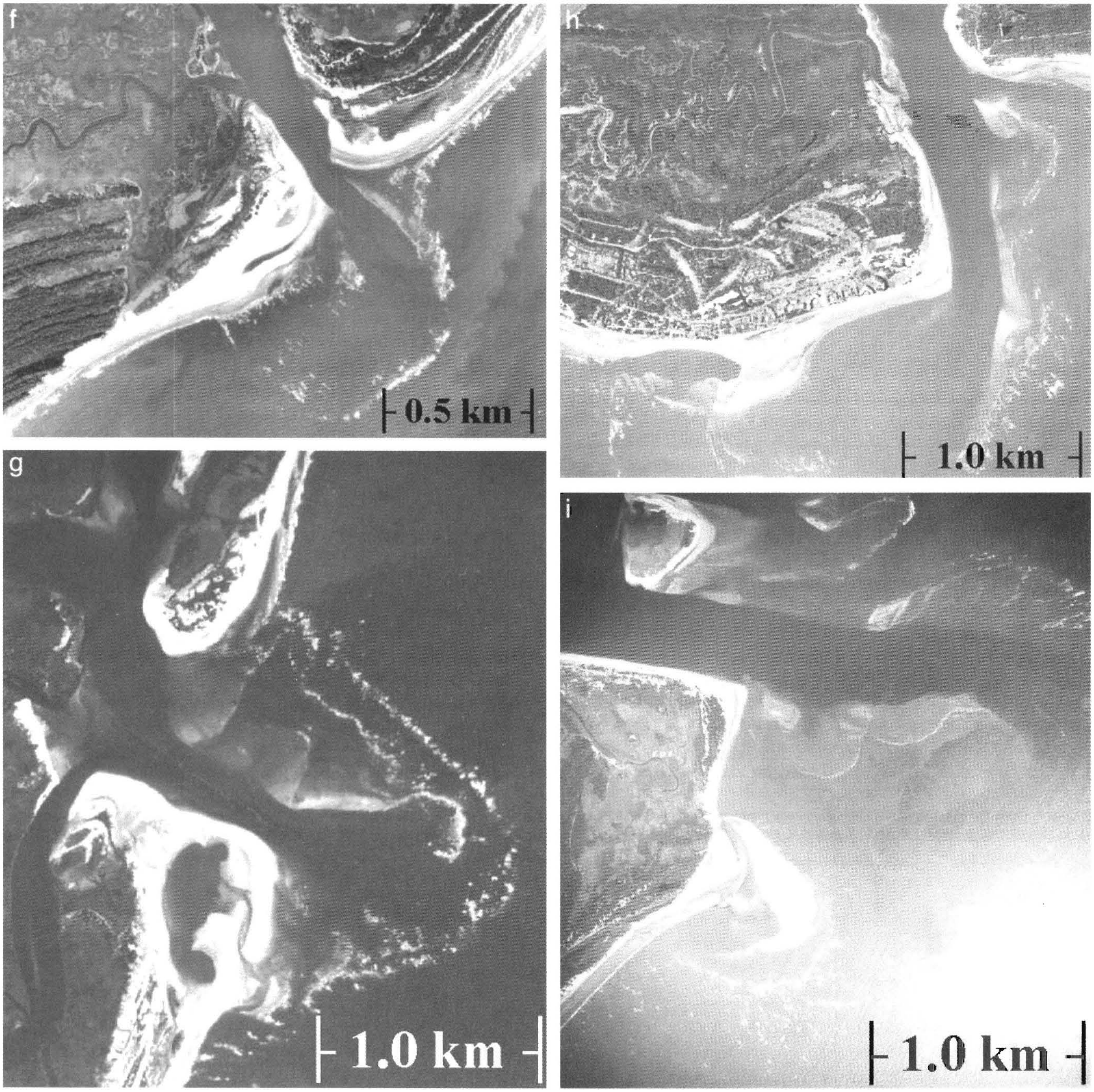

Figure 3. Continued.

tional Geodetic Vertical Datum (NGVD), which approximates mean sea level. North Inlet was previously studied by NUMMEDAL and HUMPHRIES (1978), and thus was omitted from the field survey portion of this study. Stono Inlet was also excluded, because its multiple channels and mid-channel shoals were too treacherous for the available boats and current-measurement equipment. Therefore, the tidal prism was based on channel cross-sections derived from a bathymetric map and tidal currents estimated based on the currents measured at Breach and Dewees Inlets. A 5-m shallow-draft motorboat was used to access and work in the remaining inlets. Field data were collected from August 1997 to January 1998.

Tidal prisms were determined using the method detailed by MASON (1986) [after KJERFVE *et al.* (1981)]. Current velocities for five of the inlets were measured with a Sontek *Stand-Alone* Acoustic Doppler Profiler, while a Marsh-McBirney *Model 2000 Flo-Mate* electromagnetic flowmeter was used for the remaining two inlets (Midway and Pawleys). In-

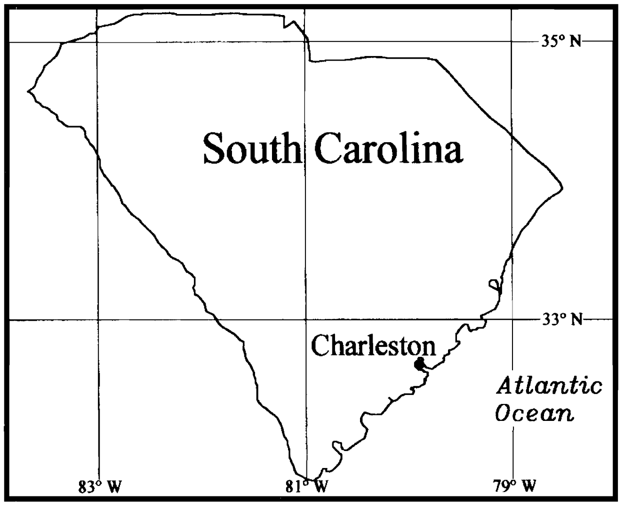

Figure 3. Continued.

cremental increases in tidal prism were plotted against tide stage to derive an empirical relationship between the two, which allowed for an estimation of the tidal prism for tidal ranges not directly observed. The inlet-specific, mean spring tide height (NOAA, 1998) was then entered into the equation to determine the spring-tide tidal prism for each inlet.

An analysis at Captain Sams Inlet by SEXTON (1981) showed that the measured spring tidal prisms differed by a maximum of 18 percent (based on three flood prisms during spring tides). NUMMEDAL and HUMPHRIES (1978) showed at North Inlet that the measured spring tidal prisms differed by a maximum of 17 percent (based on six spring-flood tidal prisms). An error of ±20 percent was assumed for the measured tidal prisms in this study.

Ebb-Tidal Delta Volumes

Ebb-tidal delta volumes were calculated using DEAN and WALTON's (1975) comparative bathymetry technique. Comparisons were made between control volumes for the existing delta bathymetries and the "no delta" bathymetries. The possible human error in these calculations can be on the order of 30 percent, but typically range from 5 to 15 percent (MEHTA et al., 1996).

RESULTS AND DISCUSSION

The measured and computed inlet parameters (averages and standard deviations) for each of the nine inlets in the study are given in Table 1. The primary variables (cross-sectional area, tidal prism, and delta volume) span two orders of magnitude with Pawleys Inlet the smallest and Stono Inlet the largest. This range is considered representative of the majority of tidal inlets in mixed-energy settings.

Figure 5 shows a direct relationship between the average shoal-bypassing event interval and tidal prism, which supports one-half of the relationship suggested by KANA (1995). Larger inlets undergo shoal-bypassing events less frequently than smaller inlets based on the equation:

$$I = 0.046Tp + 4.56 \tag{2}$$

where I is the shoal-bypassing event interval in years and Tp is the tidal prism in 10^6 m^3. There is a good deal of scatter in the graph, resulting in a modest coefficient of determination, $r^2 = 0.73$. In addition, the data set has a p-value of 3.18×10^{-3}, meaning the relationship between event interval and tidal prism is statistically significant (defined as $p<0.05$)

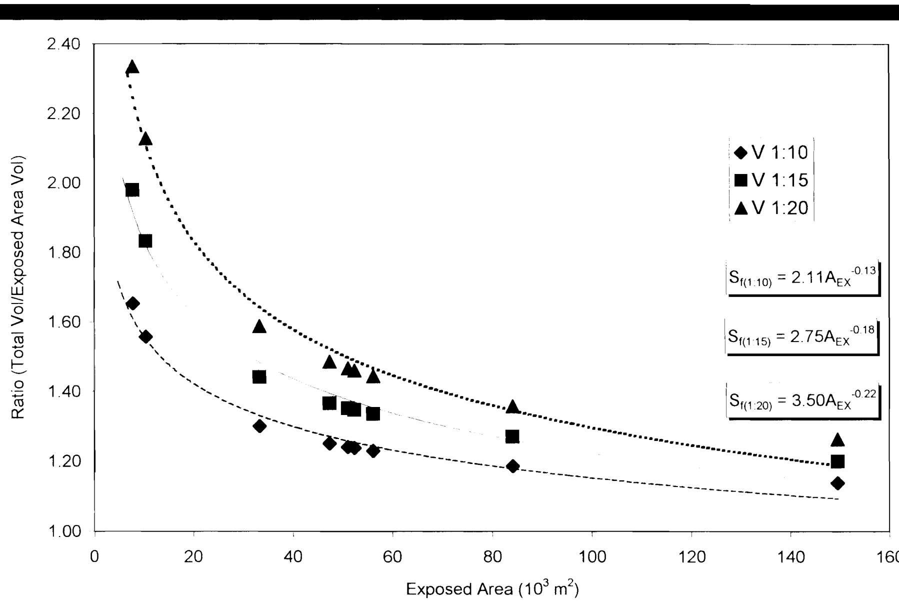

Figure 4. Relationship between subaerial-exposed area (A_{EX}) and total shoal volume. Scaling factor S_F was derived from the 1:20 governing equation. The S_F was used to calculate each shoal's specific volumetric correction, based on its exposed area.

Table 1. *Summary data of the variables associated with shoal bypassing for the nine investigated tidal inlets. (± indicates standard deviation for respective parameters, except Tp.) Tidal prism estimated error is Tp ± 20 percent. Total number of shoals analyzed is denoted by (n). Mean annual contributions are defined as the new contributions to the littoral sediment budget along the adjacent beach due to landward migrating shoals.*

Inlet	Cross-sectional Area (m^2)	Tidal Prism (10^6 m^3)	Ebb-Delta Volume (10^6 m^3)	Mean Bypassing Shoal Volume (10^3 m^3)(n)	Mean Shoal Percentage of Ebb Delta	Mean Event Interval (years)	Mean Annual Contributions (10^3 m^3/yr)
Pawleys	42	0.66 ± 0.13	0.9	61 ± 45 (23)	6.61 ± 4.87	4.1 ± 2.6	15
Midway	168	1.96 ± 0.39	2.0	50 ± 27 (22)	2.51 ± 1.34	4.3 ± 2.7	12
Captain Sams	231	2.29 ± 0.46	3.8	155 ± 90 (20)	4.08 ± 2.36	4.5 ± 3.1	35
Capers	906	5.81 ± 1.16	6.9	208 ± 173 (22)	3.02 ± 2.51	5.6 ± 3.4	37
Breach	948	12.8 ± 2.57	6.8	199 ± 156 (19)	2.93 ± 2.30	5.0 ± 3.8	40
Price	894	13.8 ± 2.75	6.1	219 ± 137 (43)	3.59 ± 2.25	4.3 ± 1.6	51
North	1475	14.9 ± 2.99	10.6	225 ± 188 (21)	2.12 ± 1.77	5.8 ± 3.7	39
Dewees	3506	24.6 ± 4.92	15.7	315 ± 285 (27)	2.01 ± 1.82	6.6 ± 2.1	48
Stono	5600	70 ± 14	95.6	561 ± 356 (24)	0.59 ± 0.37	7.6 ± 2.8	74

(MOORE and MCCABE, 1993). This equation is based on a trend line that includes Stono Inlet which, because of its large size, may exhibit a disproportionate amount of control on the data set. Therefore, Figure 5 presents a second trend line that excludes Stono Inlet. The second line has a slope 1.8 times that of the line that includes Stono Inlet.

The variability in Figure 5 may be due to temporal variations in wave energy and sediment transport rates, differences in ebb-tidal delta trapping rates, or the presence of man-made stabilization structures along the downcoast margin of some inlets (*e.g.*, Breach and Midway Inlets). The observed variation for individual inlets may be due to gaps in the aerial photography record or from the natural variability of the inlets and ebb deltas. Added to these factors is the problem of varying subaerial exposure of the shoals according to the particular stage of the tide. It is possible during low wave conditions and high tide for shoals to be hidden, given the high turbidity levels along the study coast. When waves are nonbreaking, characteristic shoal signatures will be absent on the aerial photography.

Larger inlets have a better ability to transport sand away from the main channel because of their greater carrying capacity. This large carrying capacity associated with volumetrically large tidal flows can flush sand further out onto the ebb-tidal delta where water depths are greater. This slows the formation of intertidal swash bars that can constrict and clog the channel. A hydraulically efficient channel is less likely to shift, thereby causing a shoal-bypassing event. Conversely, smaller inlets have smaller tidal prisms with much lower carrying capacities. A low carrying capacity leads to deposition of sediment close to the throat section of the channel in shallow water.

Wave-generated sediment transport increases dramatically under breaking waves compared to nonbreaking waves. This

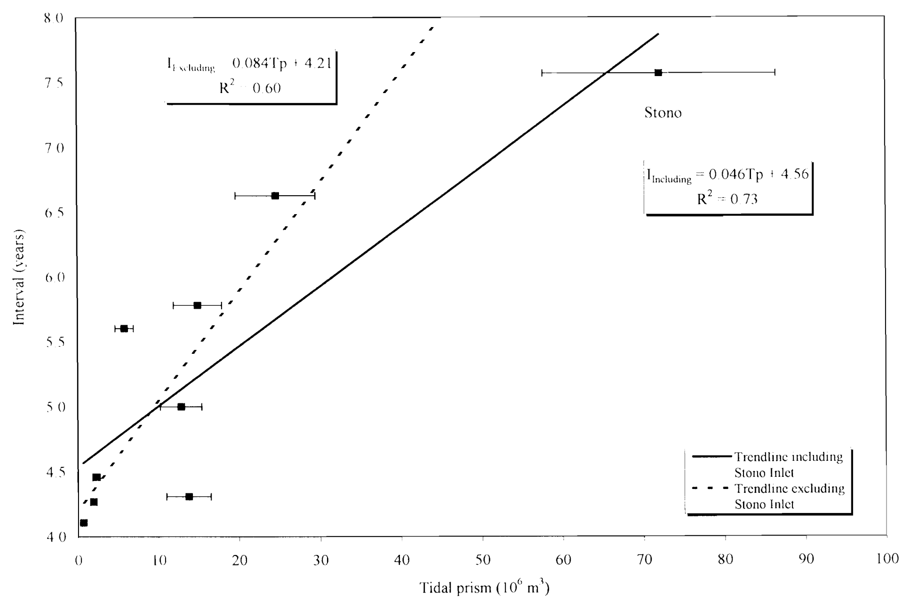

Figure 5. Average shoal-bypassing event interval as a function of tidal prism. The solid line incorporates all of the inlets, while the dashed line excludes Stono Inlet which may be an outlier.

becomes an important factor for shoal bypassing in mesotidal settings. A higher proportion of the ebb-tidal delta in a small inlet is likely to be subject to wetting and drying as the tide elevation changes. This exposes most of the delta to wave breaking and landward-directed sediment transport during some portion of the tidal cycle. In contrast, larger inlets will have more of their delta submerged during all tide stages and a proportionately lesser area subject to wave breaking.

In mesotidal settings, small inlets often exhibit huge differences between low-tide and high-tide throat cross-sections (NUMMEDAL and HUMPHRIES, 1978). This has the effect of inhibiting inlet closure even if a large part of the delta volume is deposited close to the throat. In fact, in the smallest inlets, it is often difficult to distinguish where swash bars of the ebb-tidal delta end and ridge-and-runnel systems along the low-tide beach begin. *[Note: They can be quantitatively distinguished by systematically measuring alongshore profile volumes.]*

The interval between bypassing events is also conceptually related to the net longshore sediment transport rate. Where there is a strong direction of littoral transport, more sediment accumulates on the updrift swash platform. This forces a downcoast deflection of the inlet channel and prevents sediment from reaching the downcoast side of the inlet where the primary shoal bypassing occurs. Inlets with low net sediment transport are likely to experience shoal bypassing on either side of the inlet and at somewhat more frequent rates, but probably lower shoal volumes.

During shoal-bypassing events, once the old channel is abandoned or a portion of the swash platform breaks free of the major tidal flows, the migration of the abandoned swash bar(s) begins. The rate of migration depends on a number of factors. First, larger ebb-tidal deltas have a wave-sheltering effect on the swash bars, slowing their landward migration. Second, shoals associated with large ebb-tidal deltas begin their migration further offshore, giving them a greater distance to travel before they reach the upper shoreface. Finally, the larger migrating shoals have a greater volume and mass to be moved by waves. Because the energy of a wave is proportional to the height of the wave squared and that energy has a finite carrying capacity, a larger bar would require more wave energy to force it onshore. By this reasoning, under constant wave heights and equal distances to travel, larger shoals would take more time to migrate onshore than smaller shoals. Therefore, larger wave heights would decrease the amount of time required to move shoals onshore and vice versa.

Ebb-Tidal Delta Volumes

Figure 6 shows the empirical relationship of delta volume versus tidal prism for mildly exposed coasts as determined by WALTON and ADAMS (1976). The volume bound in the ebb-tidal delta is related to the tidal prism based on the equation:

$$V = 13.8 \times 10^{-5}\,Tp^{1.23} \qquad (3)$$

where V = ebb-tidal delta volume in 10^6 cubic yards and Tp = tidal prism in 10^8 cubic feet. English units were used for continuity with the original figure. All of the nine inlets from this study fall slightly above Walton and Adams's line of best fit. The reasons for the consistent disparities are uncertain, but may reflect the greater tide range of South Carolina (allowing larger deltas to form in this setting) compared to the suite of East and Gulf Coast deltas analyzed by WALTON and ADAMS (1976).

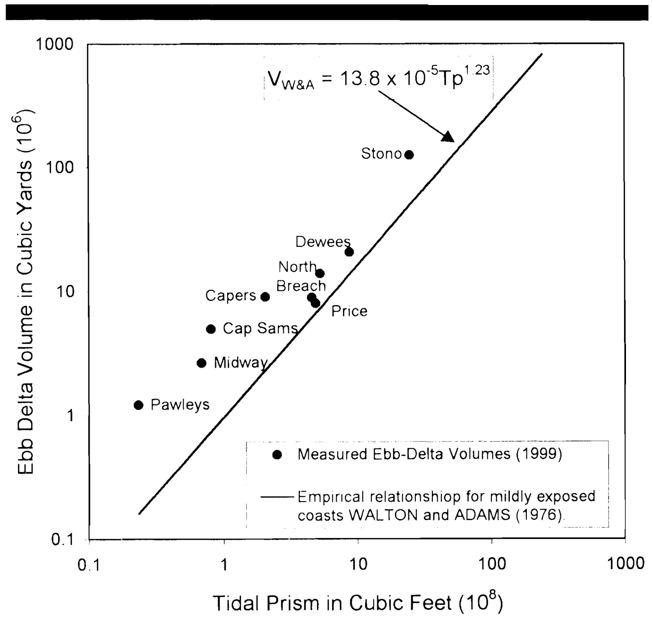

Figure 6. Tidal prism-outer bar storage relationship for mildly exposed coasts (WALTON and ADAMS, 1976) and specific values for present study. The axes and regression equation are in English units, consistent with the original (1976) figure. [Note: multiply cubic feet by 0.0283, and cubic yards by 0.7646 to obtain cubic meters.]

Shoal Volumes

The analyzed aerial photographs captured one moment in time, but were generally used to represent an entire year. The tide stages were not known for any of the photos and are not taken into account. Because of this, the potential existed for a shoal-bypassing event to be missed because the migrating shoal may have been covered by a high tide.

Shoal volumes correlated well with tidal prism. Figure 7 shows the direct linear relationship between average shoal volumes and tidal prism. The empirical equation is:

$$S = 6.42Tp + 113.4 \qquad (4)$$

where S is the average bypassing-shoal volume in thousands of cubic meters and Tp is tidal prism in millions of cubic meters. The coefficient of determination is high ($r^2 = 0.91$), and the trend has a statistically significant p-value of 5.4×10^{-5}. This relationship also makes intuitive sense, because larger inlets possess large deltas, which can undergo bigger volumetric (but similar percentage) changes.

Shoal-Bypassing Characteristics and Magnitudes

The observed shoal-bypassing events were found consistent with the inlet-change mechanisms proposed by FITZGERALD

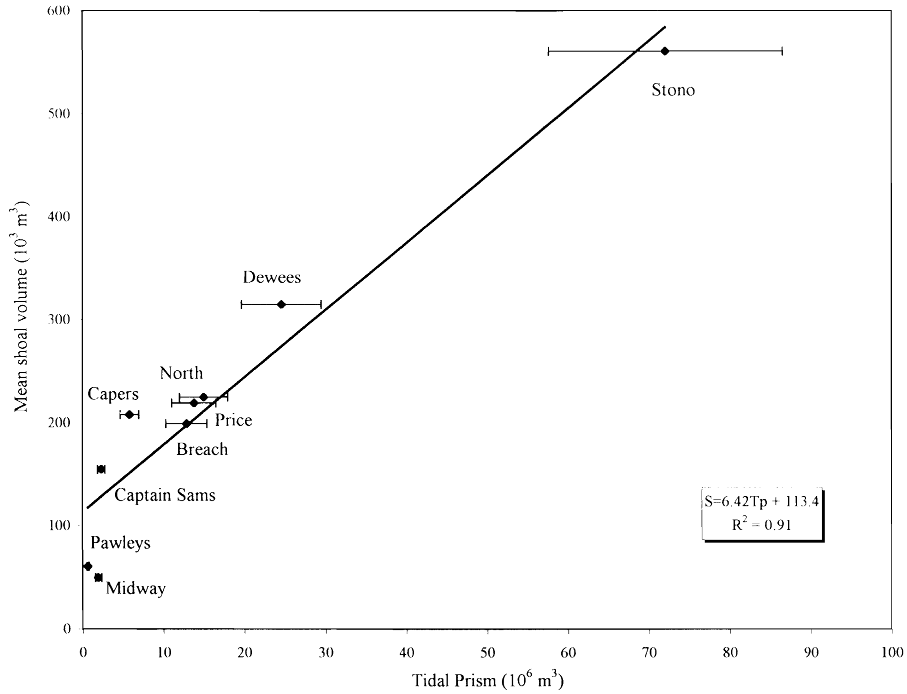

Figure 7. Empirical relationship between mean bypassing-shoal volume and tidal prism for nine South Carolina inlets.

et al. (1978). Each of the three mechanisms (inlet migration and spit breaching, periodic landward migration of swash bars at stable inlets, and ebb-tidal delta breaching) were observed. Also consistent with FITZGERALD (1988), some inlets exhibited more than one characteristic method. For example, Captain Sams Inlet undergoes a major spit breaching after 30–60 years of southerly inlet migration (HAYES, 1977), but in the interim, ebb-tidal delta swash bars migrate landward (usually downdrift to Seabrook Island) during smaller-scale, shoal-bypassing events (SEXTON and HAYES, 1983). Pawleys Inlet underwent a similar process, releasing most of its migrating shoals downdrift to Debidue Island. In contrast, Breach Inlet (stabilized along its downdrift throat section) periodically had a major channel shift in its ebb-tidal delta, which resulted in large-scale, shoal-bypassing events (Figure 8). In between these major events, smaller shoals broke off from the delta, migrated downdrift, and attached to the northeast end of Sullivans Island.

Price Inlet bypassed shoals consistent with the stable inlet model of FITZGERALD *et al.* (1978). The shoals that migrated landward toward Capers Island (to the south) and Bulls Island (to the north) began their migrations relatively close to the shoreline. In contrast, Dewees Inlet bypassed shoals that began their migration further offshore, taking a longer period of time to move onshore. This was due to the different sizes and shapes of ebb-tidal deltas. Price Inlet's ebb-tidal delta was not as large and did not extend as far seaward as Dewees Inlet's. This allowed the Price Inlet shoals to begin their landward migration closer to the shoreline than the shoals migrating from Dewees' ebb-tidal delta.

Both Dewees and Stono Inlets underwent large-scale, ebb-tidal delta breaching, releasing large volumes (averaging 315,000 m^3 and 561,000 m^3 respectively) of sand to northern sections of their adjacent, downdrift barrier islands—Isle of Palms and Kiawah Island. Due to the size of bypassing shoals, these events had a dramatic accretional effect on the northern areas of both these islands. For example, the northeast end of Kiawah Island has prograded over 1300 m in the past century because of this process (HAYES, 1977).

Each inlet is able to bypass shoals because their associated ebb-tidal deltas contain large volumes of sediment. The deltas contain and provide the sand that naturally nourishes the beaches adjacent to the inlets. As FITZGERALD *et al.* (1978) have described, the deltas can be thought of as large sand reservoirs, periodically releasing sediment in the form of migrating shoals. Comparing the enormous volumes of sand trapped in the ebb-tidal deltas to the relatively small volume of sand contained in the bypassing shoals (see Table 1) reveals that only small fractions of the entire ebb delta are transferred to shore during bypassing events. The mean volume percentages are similarly low for each inlet, ranging from 0.59$\pm$0.37 percent (Stono Inlet) to 6.61$\pm$4.87 percent (Pawleys Inlet). Values of the extremes ranged from a low of 0.2 percent (Stono Inlet) to a high of 22.6 percent (Pawleys Inlet). Even with these relatively small contributions from the ebb-tidal deltas, shoal bypassing can be the single most important process contributing to a locally accreting beach.

Synthesizing these new relationships between the bypassing shoal volumes and bypassing-event intervals provides the estimated volumetric contribution for specific tidal inlets. For example, the north end of Pawleys Island can expect a shoal bypass of 50 $\times$ 10^3 m^3 $\pm$ 27 $\times$ 10^3 m^3 from Midway Inlet's

Figure 8. Vertical aerial photograph of a 1982 channel shift in Breach Inlet's ebb-tidal delta. Prior to the shift, tidal currents flowed through channel (A). After the change, a more efficient path (B) carries most of the flow. The change triggered a shoal-bypass event, promoting onshore migration of the abandoned shoal (C).

ebb-tidal delta every 4.27±2.72 years. This produces a mean-annual transport rate of 12×10^3 m^3/yr from Midway's ebb-tidal delta to the adjacent beaches of Pawleys Island. It is likely that these types of results may apply to many of the inlets along mixed energy coasts. However, care should be taken with such application because site-specific characteristics undoubtedly affect the relationships at each inlet. As previously stated, a mixed-energy environment and an ample sediment supply are necessary to provide the needed potential for wave-generated currents and tidal currents to allow shoal bypassing to occur.

SUMMARY AND CONCLUSIONS

This paper quantifies some of the factors (tidal prism, shoal volume, event interval and ebb-delta volume) governing shoal-bypassing events occurring over a 53–58 year period at nine South Carolina tidal inlets. Shoal bypassing is a volumetrically small event with respect to the volume trapped in ebb-tidal deltas. Yet these events can be the single most important process supplying sand to adjacent beaches. Qualitative and conceptual models of shoal bypassing were statistically validated by quantitative data collected and analyzed in the present study. As predicted by KANA (1995), both the mean interval of shoal-bypassing events and bypassing-shoal volumes depend on the tidal prism. Smallest inlets in the study area underwent shoal-bypassing events almost twice as frequently as the largest inlets. Due to gaps in the aerial photography record, the range of event intervals (~4–8 years) probably underestimates the true event frequency, particularly for smaller inlets.

The study also revealed a direct-linear relationship between average shoal volume and tidal prism. Although quantitatively related, tidal prism cannot be the sole factor controlling the periodicity and magnitude of shoal-bypassing events. Without an adequate sediment supply, ebb-tidal deltas would not reach the unstable configuration needed to induce an event, and shoal bypassing would not take place. However, enough data have been analyzed to conclude that tidal prism does have some level of control over the shoal-bypassing process. Based on the available data, it is impossible to say exactly what that level is.

In an era when beach erosion is considered inevitable, shoal-bypassing events have kept numerous beach areas adjacent to tidal inlets in South Carolina healthy and accreting. This reminds us that the coast can prograde where sediment supply overwhelms inundation from sea-level rise. These types of inlet processes must be understood on a quantitative level so coastal towns, homeowners, and management agencies can anticipate and accommodate the natural range of shoreline changes associated with shoal-bypassing events.

ACKNOWLEDGMENTS

Funding for this study was provided by the US Geological Survey and the South Carolina Sea Grant Consortium under Grants R/CP-10 (Mesoscale Modeling of Sediment Transport and Morphologic Changes at Tidal Inlets, Timothy W. Kana and Earl J. Hayter, principal investigators) and RGS-1e4 (South Carolina Coastal Erosion Study, Leslie R. Sautter, principal investigator). We would like to acknowledge Dr. Leonard Gardner and Dr. Christopher Kendall (Department of Geologic Sciences, University of South Carolina) for their technical support. We are indebted to Philip McKee, Jamie MacMahan, and Lisha Chase for providing field assistance. Coastal Science & Engineering, Inc., provided aerial photographs, boats, and survey equipment. Diana Sangster contributed her editing expertise. We would also like to acknowledge the University of South Carolina Thomas Cooper Library, the South Carolina Department of Land Resources, and South Carolina Department of Health and Environmental Control's Office of Ocean and Coastal Resources Management in Charleston for providing aerial photographs. Two anonymous reviewers are thanked for their helpful comments.

LITERATURE CITED

BRUUN, P. and GERRITSEN, F., 1959. Natural bypassing of sand at coastal inlets. *Journal of Waterways and Harbor Div.,* (ASCE, New York), 84(WW4), 75–107.

DEAN, R.G. and WALTON, T.L., 1975. Sediment transport processes in the vicinity of inlets with special reference to sand trapping. *In: Estuarine Research Conference,* Vol. 2, CRONIN, L.E. (ed.), New York: Academic, 129–149.

FITZGERALD, D.M., 1982. Sediment bypassing at mixed energy tidal inlets. *Proc. of Eighteenth Coastal Engineering Conference* (ASCE, Cape Town South Africa), pp.1094–1118.

FITZGERALD, D.M., 1988. Shoreline erosional-depositional processes associated with tidal inlets. *In:* AUBREY, D.G. and WEISHAR, L. (eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets, Lecture Notes on Coastal and Estuarine Studies,* 29. New York: Springer-Verlag, pp. 186–225.

FITZGERALD, D.M.; NUMMEDAL, D., and KANA, T.W., 1976. Sand circulation patterns of Price Inlet, South Carolina. *Proc. 15th Coastal Engineering Conf.* (ASCE, New York), pp. 1868–1880.

FITZGERALD, D.M.; HUBBARD, D.K., and NUMMEDAL, D., 1978. Shoreline changes associated with tidal inlets along the South Carolina coast. *Proceedings Coastal Zone '78* (ASCE, New York), pp. 1973–1994.

GAUDIANO, D.J., 1998. Shoal bypassing in South Carolina tidal inlets: geomorphic variables and empirical predictions for nine inlets. *Technical Report,* Dept. Geol., Univ. South Carolina, Columbia, 182p.

HAYES, M.O., 1976. Geomorphology of Southern coast of Alaska. *Proc. of the Fifteenth Coastal Engineering Conf.* (ASCE, Honolulu), pp.1992–2008.

HAYES, M.O., 1977. Development of Kiawah Island, South Carolina. *Proceedings Coastal Sediments '77* (ASCE, New York), pp. 828–847.

HAYES, M.O., 1979. Barrier island morphology as a function of tidal and wave regime. *In:* LEATHERMAN, S. (ed.), *Barrier Islands,* New York: Academic, pp. 1–26.

HAYES, M.O., 1980. General morphology and sediment patterns in tidal inlets. *Sedimentary Geology,* 26, 139–156.

HUBBARD, D.K., 1977. Variations in tidal inlet processes and morphology in the Georgia embayment. *Technical Report No. 14-CRD,* Coastal Research Div., Dept. Geol., Univ. of South Carolina, Columbia, 79p.

KANA, T.W., 1995. Signatures of coastal change at mesoscales. *Coastal Dynamics '95, Proceedings of the International Conference on Coastal Research in Terms of Large Scale Experiments.* New York: ASCE, pp. 987–997.

KANA, T.W. and MASON, J.E., 1988. Evolution of an ebb-tidal delta after an inlet relocation. *In:* D.G. AUBREY and L. WEISHAR, (eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets, Lecture Notes on Coastal and Estuarine Studies,* 29. New York: Springer-Verlag, pp. 382–411.

KANA, T.W.; HAYTER, E.J., and WORK, P.A., 1999. Mesoscale sediment transport at southeastern U.S. tidal inlets: conceptual model applicable to mixed energy settings. *Journal of Coastal Research,* 15(2), 303–313.

KANA, T.W.; WILLIAMS, M.L., and STEVENS, D., 1985. Managing shoreline changes in the presence of nearshore shoal migration and attachment. *Proceedings Coastal Zone '85* (ASCE, New York), pp. 1277–1294.

KJERFVE, B.; STEVENSON, L.H.; PROEHL, J.A.; CHRZANOWSKI, T.H., and KITCHENS, W.M., 1981. Estimation of material fluxes in an estuarine cross-section: a critical analysis of spatial measurement density and errors. *Limnology Oceanography,* 26, 325–335.

MASON, J.E., 1986. Morphologic evolution of a relocated tidal inlet: Captain Sams Inlet, South Carolina. *Technical Report,* Department of Geology, University of South Carolina, Columbia, 149p.

MEHTA, A.J.; DOMBROWSKI, M.R., and DEVINE, P.T., 1996. Role of waves in inlet ebb delta growth and some research needs related to site selections for delta mining. *Journal of Coastal Research, Special Issue 23,* 121–136.

MOORE, D.S. and MCCABE, G.P., 1993. *Introduction to the Practice of Statistics.* Second Edition, New York: Freeman, 854p.

NOAA, 1998. *Tide Tables: High and Low Water Predictions, East Coast of North and South America Including Greenland.* U.S. Department of Commerce, NOAA, National Ocean Service.

NUMMEDAL, D. and HUMPHRIES, S.M., 1978. Hydraulics and dynamics of North Inlet, South Carolina, 1975–1976. *General Investigation of Tidal Inlets (GITI) Rept. No. 16,* Coastal Eng. Res. Center, U.S. Army Corps of Engineers, Ft. Belvoir, VA, 214p.

NUMMEDAL, D. and PENLAND, S., 1981. Sediment dispersal in Norderney Seegat, West Germany. *Proc. of National Meeting on Holocene Marine Sedimentation in the North Sea Basin.* International Assoc. of Sedimentologists Spec. Pub. 5, Texel Netherlands, pp. 187–210.

O'BRIEN, M.P., 1931. Estuary tidal prisms related to entrance areas. *Civil Engineering,* 1(8), pp. 738–739.

OERTEL, G.F., 1977. Geomorphic cycles in ebb deltas and related patterns of shore erosion and accretion. *Journal of Sedimentary Petrology,* 47, 1121–1131.

RICE, T., NIEDORODA, A., and PRATT, A., 1976. Coastal processes and geology, Virginia barrier islands. *In: Virginia Coast Reserve Study. Ecosystem Description.* Arlington, VA. The Nature Conservancy, pp. 109–382.

SEXTON, W.J., 1981. Natural Bar Bypassing of Sand at Captain Sams Inlet, South Carolina. Unpublished MS thesis, Dept. Geol., Univ. South Carolina, 148p.

SEXTON, W.J. and HAYES, M.O., 1983. Natural bar bypassing of sand at a tidal inlet. *Proceedings 18th Coastal Engineering Conference* (ASCE, New York), pp. 1479–1495.

WALTON, T.L., JR. and ADAMS, W.D., 1976. Capacity of inlet outer bars to store sand. *Proceedings 15th Conference Coastal Engineering* (ASCE, New York), pp. 1919–1937.