Assessing the Impact of Tidal Inlets on Adjacent Barrier Island Shorelines

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ABSTRACT

We investigated barrier island tidal inlet sand sharing systems along the United States' mid-Atlantic coast to determine the impact of tidal inlets on adjacent shorelines. We used two reaches in our analyses with different natural (unstructured) settings: the wave-dominated Outer Banks of North Carolina and the mixed-energy, tide-dominated Virginia barrier islands. Three criteria were used to delineate inlet domination and inlet influence on the adjacent barrier shorelines based on the spatial distribution of shoreline rate-of-change values: (1) the cessation of abrupt changes, i.e., the reduction in variability in the rates of change along-the-shore; (2) a change in the sign of the rate value from erosion to accretion or vice versa; and (3) a change in the increasing or decreasing trends in rate values. The maximum distances of inlet influence extend to 6.8 km updrift and 5.4 km downdrift of inlets along the Virginia barrier islands and 6.1 km and 13.0 km for the updrift and downdrift inlet shorelines along the Outer Banks barriers. Additionally, shoreline changes can be dominated by inlet processes to a maximum distance of 4.3 km. These results support previous conclusions that sand bypassing processes exert greater influence on mixed-energy, short barrier island shorelines than on the wave-dominated, long, linear barrier island shorelines.

ADDITIONAL INDEX WORDS: Shoreline rate-of-change, erosion, navigational entrance, inlet influence, inlet domination, wave-dominated, tide-dominated, tidal prism, impact zone, shoreline stabilization.

INTRODUCTION AND OBJECTIVES

Two long-standing questions with regard to tidal inlets and adjacent shorelines are, "what is the relationship between the shoreline changes and the driving forces that produce the changes, and what are the magnitudes and spatial extent of the changes?" In the past, the answers to these questions have mainly come from conceptual models or (one- or quasi-two-dimensional) numerical models (e.g., Berek and Dean, 1982; Larson et al., 1987; Fitzgerald, 1988; Douglas and Dean, 1989; Hanson and Kraus, 1989; Work and Dean, 1990; Dean and Work, 1993).

The U.S. Army Corps of Engineers' (COE) plan to stabilize Oregon Inlet, North Carolina for navigation purposes exemplifies the practical need for understanding inlet-related shoreline changes. Accurate assessments of inlet influences on adjacent barrier shorelines are necessary to design sand bypassing systems and to assess potential ecological impact zones (e.g., Finkl, 1994). The COE plans call for two rock jetties extending 2 km seaward of the barriers, and a navigational channel maintained at a depth of 5 to 6 m extending from the backbarrier through the ebbtidal delta. A report submitted to the Secretary of the Interior and the Assistant Secretary of the Army discussed the need to mitigate erosion and environmental impacts on the adjacent beach and dune system following jetty emplacement (U.S. Department of Interior and U.S. Army Corps of Engineers, 1991). A joint scientific and engineering committee suggested, based on a qualitative assessment, that the adjacent barrier islands would be altered by the jetties significantly to a distance of 4.8 km (3 mi), that measurable and permanent changes probably would occur in a second zone 4.8 to 9.6 km (3 to 6 mi) north and south of the stabilized inlet, and that subtle, but important environmental changes would occur in a third zone to distances up to 16 km (10 mi) from the inlet (Figure 1).

In a case study designed to show that an analytical solution can be used to predict shoreline change downdrift of a tidal inlet or littoral barrier, Douglas and Dean (1989) used the sign change from erosion to accretion in the along-the-shore
Figure 1. Oblique aerial photograph of Oregon Inlet and Pea Island, North Carolina (view to south). Numbers correspond to distances south of Oregon Inlet and represent a zone of inlet domination and the maximum extent of inlet influence (see Table 1). Note the coincidence of these zones with marked changes in shoreline orientation. Location shown in Figure 2.
rate-of-change values as a criterion to show, for three Florida tidal inlets, maximum shoreline erosion extended to 10.7 km. In all cases, shoreline erosion had decreased with increasing distance from the inlet. In some localities, downdrift shoreline erosion had been severe, approaching 40 m/yr along some of the barriers such as Jupiter Island. In addition, this study discussed the complexity of processes and responses associated with tidal inlets and the limitations involved in determining cause and effect relationships in the vicinity of tidal inlets.

Work and Dean (1990) and Dean and Work (1993) applied an analytical even/odd method to evaluate both the impact of inlet stabilization projects on adjacent shorelines along the Florida coast and the factors affecting shoreline changes. While the method decomposes shoreline change away from an inlet into antisymmetric (odd) and symmetric (even) components, the approximate limit of inlet influence is identified when the updrift and downdrift shoreline changes equal zero (i.e., no erosion or accretion). For the inlets examined along the east Florida coast, shoreline impacts determined by this method ranged from 3.0 km to 7.6 km. A limitation of this method involves the assumption that the shoreline trends (components) must be symmetric or antisymmetric about the inlet (Douglas and Walther, 1994). Consequently, the even/odd analysis does not explicitly account for greater distances of downdrift inlet erosion common among many coasts (Douglas and Walther, 1994).

In this paper, we use shoreline change data and newly developed criteria to delineate the magnitude and spatial extent of shoreline changes that occur along barrier islands in two different, natural physical settings (i.e., unstructured inlets and inlet shorelines). We then discuss the processes responsible for inlet-related shoreline changes, and relate those processes to observed shoreline changes.

STUDY AREA AND PHYSICAL SETTING

We selected two reaches in different settings along the United States' east coast to examine spatial and temporal shoreline changes that occur adjacent to tidal inlets (Figure 2). Along the 90 km long, northeast-southwest trending Virginia barrier island chain, we investigated shoreline changes along five islands and four inlets. To the south, we selected a subsection of the Outer Banks of North Carolina, extending more than 80 km to the northeast and approximately 50 km to the west-southwest of Cape Hatteras (Figure 2).

Mixed energy, tide-dominated morphology, transgressive stratigraphy, and fine sand-sized sediment characterize the Virginia barrier island chain (Finkelstein, 1988). The mean tidal range is 1.3 m and the mean annual wave height is 0.55
m. Mixed energy coasts consist of short barrier islands and numerous tidal inlets (HAYES, 1979). The barrier islands located within the Virginia coast retreat along pre-Holocene interfluves while the inlets occupy the former paleochannels (HALSEY, 1979; shidel et al., 1984). As a result of the antecedent topography, the inlets in this region do not migrate appreciably.

In contrast, wave-dominated morphology, transgressive stratigraphy, and an abundance of sand-sized sediment characterize the Outer Banks of North Carolina (MOSLOW and HERON, 1979; INMAN and DOLAN, 1989). The mean tidal range is 0.6-0.9 m and the mean annual wave height is 0.69 m. Wave-dominated regimes consist of long, linear barrier islands and relatively few, highly dynamic, ephemeral tidal inlets (HAYES, 1979).

CONCEPTUAL MODELS OF INLET-INFLUENCED SHORELINE CHANGES

Mixed-energy sand bypassing systems can display updrift and downdrift inlet shoreline migration reversals related to ebb-tidal delta growth-decay cycles. Exceptions occur where inlet migration and spit breaching processes predominate. Over the long-term, however, the accretory portion of an island adjacent to an inlet can be expected to have a pronounced peak in the spatial distribution of the shoreline rate-of-change values (Figure 3A). The peak represents the highest rates of accretion, corresponds to the swash bar attachment point, and possibly reveals the even component of the even/odd analysis (FITZGERALD et al., 1984; WORK and DEAN, 1990; DEAN and WORK, 1993). The size of the inlet relative to the size of the barrier, the position of the main ebb channel, the asymmetry of the ebb-tidal delta, and the wave climate determine the location(s) and the spatial extent of swash bar attachment (e.g., shoreline accretion) (FITZGERALD and HAYES, 1980; FITZGERALD, 1988). The direction and magnitude of this general pattern can be altered by episodic storms or changes in larger spatial- and temporal-scale processes such as sea-level rise (GRANT, 1992). In general, the magnitude of downdrift inlet accretion can be expected to decrease away from the inlet as the energy associated with tidal inlets decreases, or the impact of wave sheltering by ebb-tidal delta associated sand shoals decreases (Figure 3A).

Along wave-dominated coasts, inlet migration can be expected to result in updrift inlet accretion due to barrier elongation (sediment storage) and downdrift inlet erosion due to sediment starvation or flow constriction along the downdrift barrier (Figure 3B). The spatial distribution of shoreline rate-of-change values often resembles an exponential function similar to the odd component of the even/odd analysis (Figure 3B; WORK and DEAN, 1990; DEAN and WORK, 1993).

CRITERIA FOR DETERMINING THE IMPACT OF TIDAL INLETS ON ADJACENT BARRIER SHORELINES

We used spatial patterns in shoreline rate-of-change values at 50 m spacings to delineate shoreline migration trends in the vicinity of the inlets. The data used for the Virginia barriers spanned the period 1949 to 1989 and consisted of nine aerial photographs; the data used for the Outer Banks spanned the period 1945 to 1986 and consisted of 11 sets of aerial photographs. These data, used in concert with the 50 m along-the-shore spacing of rate-of-change values, provided the rich temporal and spatial record needed for a detailed investigation of shoreline responses. We used the method of least squares (linear regression) in order to incorporate all of the temporal shoreline data in the rate of change calculations (DOLAN et al., 1991; FENSTER et al., 1993).

Three criteria were used to identify the spatial extent of inlet processes on the adjacent barriers (the symbols below correspond to those shown in Figures 3, 6, 7, and 8):

\( \forall \) (1) the cessation of abrupt changes in the rates of change along-the-shore and the reduction in variability of along-the-shore values. The rate-of-change values were deemed no longer abrupt when (a) the difference in rate values between adjacent transects over a 500 m reach did not increase or decrease by more than 0.3 m/yr (Figure 4A); (b) the difference in rate values between adjacent transects over a 500 m reach did not increase or decrease by more than 0.2 m/yr (Figure 4A); (c) the standard deviation of a subset of along-the-shore values (eliminating the transect(s) nearest the inlet each iteration) was minimized (Figure 4B); and (d) the slope of a regression line drawn through a subset of along-the-shore values (eliminating the transect(s) nearest the inlet each iteration) most closely equaled zero (Figure 4C);

\( \times \) (2) a change in the sign of the rate value from
erosion to accretion or vice versa up to a maximum four changes (to account for spatial and temporal variability associated with swash bar attachment); and

(3) a change from less erosional to more erosional or more erosional to less erosional OR a change from less accretionary to more accretionary or more accretionary to less accretionary.

In almost all cases, criterion (1) produced the maximum distances of inlet influence. As a result, we used this distance as the cutoff point for the maximum spatial extent of inlet influence on shoreline migration. Finally, it should be noted that the influence of an individual storm or a collection of storms on shoreline movement cannot be detected explicitly using these types of data and criteria, except to the extent to which the
RESULTS: SHORELINE TRENDS ADJACENT TO TIDAL INLETS

Using the criteria listed above, the distances of inlet influence along the updrift and downdrift portion of each island are listed in Table 1 and the average and maximum distances are plotted in Figure 5A–C and Figure 5D–F, respectively for the Virginia barrier islands, the Outer Banks, and all islands combined. The maximum distance of inlet influence for the updrift northern ends of the Virginia barrier islands (downdrift inlet shorelines) ranges from 1.5 (criterion 1; Cedar Island) km to 5.4 km (criterion 1; Hog Island) (Table 1; Figure 5D). The maximum distance of inlet influence for the downdrift southern ends (updrift inlet shorelines) ranges from 0.7 km (criterion 2; Metomkin Island) to 6.8 km (criterion 1; Parramore Island) (Table 1; Figure 5E). Minimum influence for both the downdrift and updrift ends approaches 0.3 km. The maximum range of inlet influence along the Outer Banks shorelines is ≈13.0 km on the downdrift northern ends (criteria 1 and 2; Pea Island) and ≈6.1 km on the combination of storms controls long-term shoreline migration (FENSTER and DOLAN, 1994).
Table 1. Range of influence (distance along the shore) that tidal inlets exert on selected barrier island shorelines according to three criteria listed in text (n/a = criterion not applicable).

<table>
<thead>
<tr>
<th>Island</th>
<th>South End (km)</th>
<th>North End (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virginia Barrier Island Chain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metomkin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>1.4, 8.8</td>
<td>n/a</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>0.7 (+ to −)</td>
<td></td>
</tr>
<tr>
<td>Criterion #3</td>
<td>0.8, 1.1, 2.3, 2.9, 3.9, 4.2</td>
<td></td>
</tr>
<tr>
<td>Cedar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>2.5, 2.6, 3.1</td>
<td>1.3, 1.4, 1.5</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>2.5 (+ to −)</td>
<td>n/a</td>
</tr>
<tr>
<td>Criterion #3</td>
<td>0.3, 0.5, 2.0, 2.9</td>
<td>0.6, 0.9, 2.7</td>
</tr>
<tr>
<td>Parramore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>1.5, 3.1, 5.8, 5.9, 6.8</td>
<td>1.6, 1.9, 2.2</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>n/a</td>
<td>0.3 (− to +), 1.2 (+ to −), 1.3 (− to +), 1.7 (+ to −)</td>
</tr>
<tr>
<td>Criterion #3</td>
<td>0.4, 2.0, 2.7, 3.2</td>
<td>1.2, 1.3, 1.6, 2.0</td>
</tr>
<tr>
<td>Hog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>0.6, 2.7</td>
<td>2.0, 3.4, 4.7, 5.4</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>2.5 (+ to −), 3.4 (− to +)</td>
<td>3.8, 3.9</td>
</tr>
<tr>
<td>Criterion #3</td>
<td>0.8, 2.5</td>
<td>0.5, 1.9, 2.9, 3.1, 3.9, 4.3</td>
</tr>
<tr>
<td>Cobb</td>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td>4.2 (+ to −)</td>
<td></td>
</tr>
<tr>
<td>Criterion #3</td>
<td>0.5, 0.7, 1.2, 1.5, 2.0</td>
<td></td>
</tr>
<tr>
<td>Outer Banks, North Carolina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bodie</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>1.6, 2.9, 3.0, 4.2</td>
<td>no north end (spit)</td>
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<tr>
<td>Criterion #2</td>
<td>2.0 (+ to −)</td>
<td></td>
</tr>
<tr>
<td>Criterion #3</td>
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<td></td>
</tr>
<tr>
<td>Pea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>Cape Hatteras</td>
<td>1.0, 1.3, 1.7, 6.7, 13.0</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>13.0 (− to +)</td>
<td></td>
</tr>
<tr>
<td>Criterion #3</td>
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<td></td>
</tr>
<tr>
<td>Hatteras</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion #1</td>
<td>0.2, 1.8, 2.0, 3.4, 4.9, 6.1</td>
<td>Cape Hatteras</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>0.4 (+ to −), 2.4 (− to +), 5.2 (+ to −)</td>
<td></td>
</tr>
<tr>
<td>Criterion #3</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Ocracoke</td>
<td></td>
<td></td>
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<tr>
<td>Criterion #1</td>
<td>not included in analysis</td>
<td>1.0, 2.2, 2.4, 9.8</td>
</tr>
<tr>
<td>Criterion #2</td>
<td>2.0 (+ to −), 10.0 (− to +)</td>
<td></td>
</tr>
<tr>
<td>Criterion #3</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

updrift inlet southern ends (criterion 1; Hatteras Island) (Table 1; Figures 5D and E).

Along the Virginia barrier islands, the spatial distribution of the rate of change values shows the expected accretion peak associated with sand bypassing and swash bar attachment at the north end of Cobb Island, Hog Island, and to a lesser extent, Metomkin Island and Parramore Island, but not on Cedar Island (Figures 6 and 7). The farthest extent of accretion on the downdrift inlet shoreline occurs ≈4.2 km on Cobb Island downdrift of Great Machipongo Inlet, ≈3.9 km on Hog Island downdrift of Quinby Inlet, ≈1.7 km on Parramore Island downdrift of Wachapreague Inlet, and ≈0.8 to 1.2 km on Metomkin Island downdrift of Gargathy Inlet (Table 1; Figures 6 and 7).
Figure 5. Extent of inlet influence using the average (A–C) and maximum (D–E) values of all criteria. The north (updrift inlet) impact distances shown in A and D, south (downdrift inlet) impact distances shown in B and E, and both updrift and downdrift inlet impact distances shown in C and F. Criteria 1, 2, and 3 are described in the text. Note the large range of inlet influence distances within and among the criteria with a maximum range from 4.3 to 13.0 km depending on the criterion selected.

In terms of rate of change magnitudes, the "peak(s)" of maximum accretion rates on the downdrift inlet shorelines occur ≈0.5, 1.2, and 2.0 km on Cobb Island, ≈1.9 and 3.1 km on Hog Island, and ≈1.3 km on Parramore Island. These peaks produce a step-like or undulatory pattern in the spatial distribution of rate-of-change values. The maximum erosion rate on Cedar Island occurs ≈0.9 km downdrift of Metomkin Inlet. Erosion becomes the predominant trend ≈4.2 km south of Great Machipongo Inlet on Cobb Island, ≈1.7 km south of Wachapreague Inlet on Par-
ramore Island, and 1.2 km south of Gargathy Inlet on Metomkin Inlet. Hog Island is primarily accretionary and Cedar Island and Parramore Island are primarily erosional.

Updrift inlet shoreline trends include decreasing accretion away from the inlet along Hog Island to a distance of \( \approx 2.5 \) km north of Great Machipongo Inlet, on Cedar Island to a distance of \( \approx 2.5 \) km north of Wachapreague Inlet, and on Metomkin Island to a distance of \( \approx 0.7 \) km north of Metomkin Inlet. Erosion predominates on the south end of Parramore Island (and almost all of Parramore Island) and Cobb Island. The spatial distribution of rate-of-change values on the updrift inlet shorelines resembles an increasing or decreasing exponential function (see Hog Island, Cedar Island, Bodie Island, and Hatteras Island in Figures 6, 7, and 8).

Along the Outer Banks, downdrift inlet accretion is present only on the northeast end of Ocracoke Island. This contrasts with downdrift inlet trends found along the majority of Virginia barrier islands. High erosion rates occur along the north end of Pea Island downdrift of Oregon Inlet (Figure 8). Maximum erosion occurs 0.5 km downdrift of Oregon Inlet and abrupt changes in the rate values cease 1.0–1.7 km. This change corresponds with a distinct change in shoreline orientation (Figure 1). Recent profiling by the U.S. Army Corps of Engineers on Pea Island shows a transition in profile shape at a similar position (Miller, personal communication). The spatial

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Figure 6. Spatial distribution of shoreline rate-of-change values on islands adjacent to Metomkin Inlet and Wachapreague Inlet. Notice the alternating high accretion and erosion rates on the south end of Metomkin Island and Cedar Island, the high erosion rates on the north end of Cedar Island, and the minor accretion rates on the north end of Parramore Island. Further south, Parramore Island is dominated completely by erosion. Symbols correspond to criteria for determining the impact of tidal inlets on adjacent barrier shorelines: \( \text{\textasteriskcentered} \) criterion 1; \( \times \) criterion 2; \( \circ \) criterion 3 (see text for discussion); \( - \) indicates erosion, + indicates accretion.
standard deviation is minimized 6.7 km downdrift of the inlet and the maximum extent of inlet influence extends to 13.0 km (Figure 1). The updrift inlet shorelines are accretionary up to 0.4 km north of Hatteras Inlet on Hatteras Island and up to ≈2.0 km north of Oregon Inlet on Bodie Island. Along Hatteras Island, erosion and accretion trends alternate along-the-shore with accretion rates occurring ≈2.4 km north of Hatteras Inlet and erosion rates occurring ≈5.2 km to the north of Hatteras Inlet on Hatteras Island. Erosion becomes the predominant trend ≈2.0 km north of Oregon Inlet on Bodie Island.

Each criterion used to delineate inlet influence yielded different results. In general, Criterion (1), the reduction in variability of along-the-shore rate values, delineated the greatest ranges and distances of inlet influence (Figure 5). Excluding the north ends of Pea Island and Ocracoke Island, Criterion (2) produced intermediate distances of inlet influence (≤5.2 km). Criterion (3), a change in the increasing or decreasing trends in rate change values, revealed the least extent of inlet influence (≤4.3 km). These differences in characterizing inlet influence on adjacent barriers indicate that shorelines can be dominated by inlet processes to distances up to 4.3 km and influenced by inlet processes to distances of 13.0 km.

DISCUSSION

The degree to which tidal inlets influence adjacent barrier shorelines is a function of the sizes...
and number of inlets, and long- and short-term changes in the sediment budget (FITZGERALD, 1988). The number of inlets and their sizes are controlled by the tidal prism which, in turn, is controlled by the size of the backbarrier bay and the tidal range. Areas of high tidal energy relative to wave energy necessitate larger sized or a greater number of tidal inlets to facilitate the larger volume of water flowing into and out of the backbarrier. In theory, as the tidal prism increases along a barrier coast, the ebb-tidal delta will increase in size (volume and geometry) and will, in turn, exert an increasingly greater influence on a barrier's sediment budget and shoreline behavior (WALTON and ADAMS, 1976; NUMMEDAL and FISCHER, 1978; FITZGERALD, 1988).

Additional processes that contribute to barrier sediment losses and shoreline erosion in the vicinity of inlets include washover events during storms, shoreface retreat, inlet migration, and/or a net reduction in the longshore sediment flux due to sediment deposition in sinks such as tidal channels, tidal deltas, tidal creeks, or the marsh surface (FITZGERALD, 1988; ÖRTEL, 1988). Sediment gains primarily result from spit growth and barrier extension on updrift inlet barriers, and/or sediment bypassing and bar welding processes on downdrift inlet barriers.

General patterns emerged from our analysis, however, the results demonstrate that the shorelines adjacent to each inlet are characterized by unique temporal histories. Therefore, we com-
Impact of Inlets on Shorelines

Table 2. Physical and hydrographic attributes of tidal inlets used in this study, n/a = data not available. Data sources include NOAA (1994a) and NOAA (1994b). Tidal prism calculated according to Jarrett (1976).

<table>
<thead>
<tr>
<th>Inlet Name</th>
<th>Min. Width (m)</th>
<th>Depth (m)</th>
<th>Width/Depth Ratio</th>
<th>Max. Flood (m/sec)</th>
<th>Max. Ebb (m/sec)</th>
<th>Mean Spring Tidal Range (m)</th>
<th>Mean Ebb Tidal Range (m)</th>
<th>Mean Wave Height (m)</th>
<th>Cross-sectional Area (m²)</th>
<th>Tidal Prism (×10³ m³)</th>
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<tbody>
<tr>
<td>Virginia Barrier Island Chain</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Metompkin</td>
<td>2073</td>
<td>2.7</td>
<td>768</td>
<td>n/a</td>
<td>n/a</td>
<td>1.2</td>
<td>1.3</td>
<td>0.58</td>
<td>5,352</td>
<td>2.57</td>
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<td>Wachapreague</td>
<td>582</td>
<td>18.0</td>
<td>32</td>
<td>n/a</td>
<td>n/a</td>
<td>1.3</td>
<td>1.4</td>
<td>0.60</td>
<td>10,002</td>
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<td>Quinby</td>
<td>1,262</td>
<td>23.2</td>
<td>59</td>
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<td>n/a</td>
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<td>1.4</td>
<td>0.62</td>
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<td>5.63</td>
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<td>Great Machipongo</td>
<td>772</td>
<td>10.7</td>
<td>72</td>
<td>n/a</td>
<td>n/a</td>
<td>1.3</td>
<td>1.4</td>
<td>0.59</td>
<td>7,900</td>
<td>3.69</td>
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<tr>
<td>Outer Banks, North Carolina</td>
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<td></td>
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<td></td>
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<tr>
<td>Oregon</td>
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<td>Hatteras</td>
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<td>100</td>
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<td>1.0</td>
<td>0.9</td>
<td>1.3</td>
<td>0.69</td>
<td>5,928</td>
<td>2.82</td>
</tr>
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</table>

Compiled information on the attributes of each inlet to compare the morphologic and hydrologic aspects of each to shoreline responses (Table 2). The North Carolina inlets are shallower than those of the Virginia barriers, but the cross-sectional profiles (widths) have changed substantially through time. The width of Hatteras Inlet, for example, has ranged from 2,300 in May, 1990, to 550 m in November, 1993. The Virginia inlets have smaller width/depth ratios (the depths are greater relative to the depths of the North Carolina inlets) except for the anomalous Metompkin Inlet. Hydrographic charts and aerial photographs reveal that Metompkin Inlet is part of an ephemeral inlet system which has opened and closed at various locations along the island numerous times over the past century.

In an effort to relate inlet morphology and hydraulics directly to shoreline responses along adjacent barriers, we examined the relationship between tidal prism and the minimum, average, and maximum extent of inlet influence on the adjacent barriers. We calculated tidal prism according to Jarrett's (1976) cubature method for natural Atlantic coast inlets using numerically integrated cross-sectional areas (Table 2). Our analysis failed to demonstrate a statistically significant relationship between tidal prism and the minimum, average, and maximum spatial extent of inlet influence for each of the criteria (Figure 9A). One exception was Criterion 1 from the downdrift inlet Virginia barrier islands (Figure 9B). To achieve a relationship, however, we eliminated Cobb Island and Metompkin Island from the analysis based on the determination that the Virginia barriers exhibit distinctive patterns of behavior in which Cobb Island belongs to a southern group; Cedar, Parramore, and Hog Islands belong to a central group, and Metompkin Island belongs to a northern group (Stottlemeyer, 1977).

Several factors may contribute to the lack of a significant relationship between tidal prism and shoreline response. First, the size of the ebb tidal delta may correspond more closely with parameters other than tidal prism such as width/depth ratios (Marino and Mehta, 1988). Our results, using Criteria 1 and 2, tend to corroborate this hypothesis with high correlations observed between the width/depth ratio and the spatial extent of inlet influence (Figure 10). These results substantiate the claim that a direct correlation may exist between the magnitude of the odd component of the even/odd analysis (the impact) and inlet size (Dean and Work, 1993). Additionally, the complexities of individual sand sharing systems, such as variations in geologic, bathymetric, and morphologic settings, and the relative magnitudes and sources of energy, may obscure the shoreline response signal produced by tidal prism (Dean, 1988). Finally, we cannot discount the fact that additional data would improve the statistical confidence needed to determine process-response relationships. For this reason, we are currently expanding our analysis to include all U.S. east coast inlets.

Substantial shoreline changes can occur without a net long-term change in the sediment budget for a mixed energy barrier island, i.e., a sand sharing system does not receive sediment from nor transport sediment to other systems (Oertel, 1988). This is a common occurrence along the Virginia barrier islands where sediment budgets have been hypothesized to be maintained primarily by "rollover" processes and not by sedi-
ment exchange between tidal inlets and inlet associated shoals (Oertel, 1988). In this model, sediments moved by longshore currents are not considered part of the overall barrier sediment prism, but variations in this “drift” can be responsible for short-term shoreline accretion or erosion trends. Thus, shoreline changes near Virginia barrier island inlets occur as a result of alterations in the sediment budget caused by washover processes and sediment bypassing around ebb-tidal deltas. Along the wave-dominated Outer Banks, inlets have a strong control on island sediment budgets and adjacent shoreline behavior due to inlet migration processes and active sediment bypassing.

Our analysis of the along-the-shore rate-of-change trends demonstrates the links among tidal inlet processes, sizes, geometries, sediment budgets and the magnitude and direction of the shoreline trends. Downdrift inlet shoreline accretion predominates in mixed-energy environments where stable inlet bypassing processes occur. In addition, a general pattern emerged showing up-
drift inlet shoreline accretion and downdrift inlet erosion in wave-dominated settings where updrift inlet spit extension and downdrift inlet migration are the dominant processes.

A comparison of the shoreline rates of change adjacent to Oregon Inlet and a geomorphic analysis of the region indicates that the spatial distribution of updrift inlet shoreline rate-of-change values is associated with barrier (spit) extension and the downdrift inlet shoreline is eroding in response to inlet migration. Inlet migration is enhanced by the relatively shallow depths in the inlet throat. Since the inlet moves parallel to the shore, the trapping rate of the ebb- and flood-tide delta cannot attain a state of dynamic equilibrium. Thus, the trapping rate of the inlet shoals remains relatively effective and sediment is removed from the southerly directed long-term sand transport system (Everts and Gibson, 1983; Inman and Dolan, 1989). Along the Outer Banks, the impact of bypassing processes on shoreline response is less extensive than those found in mixed-energy regimes due to the smaller sizes of the ebb-tide deltas relative to island length and a decrease in tidal energy.

Conversely, the trends along Cobb Island, Hog Island, Metomkin Island, and Parramore Island indicate that sediment bypassing exerts a major control on shoreline dynamics. The inlets are predominantly stable as a result of the incision of the main ebb channels into Pleistocene fluvial paleochannels with semi-consolidated banks (Byrne et al., 1976). However, it should be noted that short-term updrift barrier extension or preferential accretion on the updrift portion of the ebb-tidal delta can lead to the re-location of the main ebb channel and development of spillover channels. The step-like or undulatory pattern of increasing and decreasing accretion rates on the north ends of Metomkin, Parramore, Hog, and Cobb Islands is most likely due to ebb-channel shifting and downdrift displacement of the swash bar attachment position through time (Figures 6 and 7).

Barrier island shorelines, located adjacent to a tidal inlet, can display different trends although residing in a similar hydrographic regime. The fact that each island possesses a unique shoreline signature adjacent to its inlet emphasizes the advantages of a complete process-response analysis of individual island-inlet sand sharing systems for management purposes. For example, the north end of Cedar Island adjacent to Metomkin Inlet is predominantly erosional, the north end of Parramore adjacent to Wachapreague Inlet shows slight accretion, and the north end of Hog Island adjacent to Quinby Inlet displays an increase, decrease, and increase in the along-the-shore rates of change. The processes potentially responsible for these trends are discussed below.

**North End of Cedar Island Adjacent to Metomkin Inlet**

Metomkin Inlet is presently a flood-dominated inlet choked with extensive flood-tide deposits. This situation, in conjunction with a hydrodynamic change in the northern ephemeral inlets from flood-dominance to ebb-dominance, may eventually lead to the stabilization of northern inlets, the closing of Metomkin Inlet, and the annexing of South Metomkin Island by Cedar Island. Erosion of the north end of Cedar Island probably is due to the cessation of bypassing processes as the energy transport capacity of Metomkin Inlet diminishes and to the lack of available sediment (little to no ebb shoals). In addition, the presence of flood-tide shoals indicates that bypassing has been incomplete for a period of time.

**North End of Parramore Island Adjacent to Wachapreague Inlet**

To the north of Parramore Island, Wachapreague Inlet is a relatively stable, ebb-dominated inlet with well-developed, extensive ebb-tidal delta deposits and very little to no flood-tide delta. The position and development of the ebb-tidal delta have remained relatively unchanged for 120 years (Byrne et al., 1976). Flood tide currents are restricted to the south side of the inlet, while ebb tide currents flow on the north side and to the northeast (Byrne et al., 1976). Several stable inlet “islands” are located within and around the inlet. One mechanism of an inlet island’s formation envisions a transport reversal on the downdrift barrier causing an asymmetry of the flood- and ebb-tide currents, the deflection of channels, and the stranding of ebb shoals. Although the inlet’s position has migrated to the south at a rate of 1 m/yr over the past century (Byrne et al., 1976), spit growth and accretion at the southern end of Cedar Island and accretion at the north end of Parramore Island point to stable inlet processes as the mechanism of sediment inlet bypassing. However, the amount of sediment transported to the north end of Parramore apparently is negligible com-
pared with the amount of sediment lost due to overwash processes and longshore removal (as evidenced by an island-wide erosion trend).

**North End of Hog Island Adjacent to Quinby Inlet**

To the south of Parramore Island and north of Hog Island, Quinby Inlet is formed by the merging of three tidal creeks and appears to be less stable than Wachapreague Inlet. Comparison of an 1852 NOS T-sheet with more recent aerial photographs shows that the inlet has migrated to the south and subsequently stabilized. In 1852 the inlet throat was positioned to the north adjacent to Parramore Island and discharged to the northeast. By 1955, the channel had shifted nearly 90° to the southeast and stabilized. Extension of the active spit at the southern end of Parramore Island and/or preferential deposition of sand on the updrift portion of the ebb-tide delta and a temporary sand loss due to the transport of sediment from the sound end of Parramore Island to the inlet’s flood- and ebb-tidal deltas may have been responsible for the downdrift deflection of the ebb channel and migration of the inlet. In addition, accretion along the northern two-thirds of Hog Island is due to bar-welding associated with inlet sediment bypassing processes such as ebb-tidal delta breaching. A shift in the inlet channel position to the south, in concert with a seaward extension of the inlet throat, have resulted in a greater downdrift extent of accretion to Hog Island and the sheltering of the north end of Hog Island from direct wave attack. The change in shape on Hog Island from a southern bulbous shaped island to a northern drumstick shaped island (counterclockwise rotation) is most likely due to removal of sand from storage on the southern end of Parramore Island and from the abandoned ebb-tidal delta (Oertel, 1988). By 1934, the northern abandoned portion of the ebb-tidal delta was eroded and incorporated into the longshore sediment transport system or to the inlet shoals resulting in high accretion rates along Hog Island.

Over the short- and long-term, shoreline movement adjacent to inlets can be highly non-linear (Fitzgerald, 1984; Nordstrom, 1987). For example, patterns of erosion and deposition along South Carolina barrier shorelines are controlled by cycles of ebb-tide delta growth and decay (15–20% change in volume) which last from 4 to 7 years (Fitzgerald, 1984). During this stage of ebb-tidal delta growth, large intertidal bars form on both sides of the main ebb channel and little sediment bypasses the inlet and delta system. The delta diminishes in size as the bar complexes migrate onshore and attach to the beach. An additional 7- to 42-year cycle resulting from changes in the orientation in the main ebb channel has been shown to produce an offset configuration (Fitzgerald, 1984).

The occasion for short-term changes to occur in long-term trends documents the advantages to using a mathematical non-linear historical shoreline modeling method, such as the Minimum Description Length (MDL) approach (Fenster et al., 1993), to assist in shoreline management. Such an approach, used in concert with a complete investigation of a time history of an inlet’s hydrological processes, morphological attributes, and sediment budget can aid in our understanding of inlet-island sand sharing systems. For example, preliminary results from the MDL analysis along Hog Island show that the highly accretionary north end of the island experienced an erosional period c. 1949, 1976, 1978, and 1982 in various places along the 1.2 km reach adjacent to Quinby Inlet. These shoreline trend reversals provide evidence for 6-, 10-, 12-, and 39-year changes in ebb-tidal delta growth-decay cycles, channel configuration, and/or channel morphology.

**CONCLUSIONS**

The spatial impact of tidal inlets on the patterns of shoreline change along the wave-dominated North Carolina coast extends to a maximum distance of 13.0 km and to 6.1 km along the mixed-energy, tide-dominated Virginia barrier islands. However, a significant degree of variability in the spatial range of inlet influence exists. Criterion one, the cessation of abrupt changes in the rates of change along-the-shore and the reduction in variability of along-the-shore rate values, revealed the greatest degree of inlet-related shoreline impact (<6.1 km). Criterion two, a change in the sign of the rate value from erosion to accretion or vice versa, showed the next greatest degree of shoreline impact (except for two “anomalous” locations along the north ends of Outer Banks barriers) (<5.2 km). Criterion three, a change in the increasing or decreasing trends in rate change values provided the most conservative estimate of the spatial impact due to inlets (<4.3 km). Therefore, we suggest that a barrier zone in which inlet-related processes dominate shoreline trends can
extend to distances of up to 4 to 5 km from an inlet and a zone in which inlet-related processes influence shoreline trends can extend to distances of up to 6 to 13 km.

The process-response patterns observed along the Virginia barrier islands are expected to be similar to those found in other tide-dominated, mixed-energy environments such as northern Massachusetts, South Carolina, and Georgia. In addition, those patterns observed along the Outer Banks may be similar to those found in other microtidal, wave-dominated settings such as the east and west coasts of Florida.

The downdrift inlet shorelines (northern ends of barrier islands) showed the greatest range in the spatial extent of along-the-shore rate-of-change values (influence) due to inlet processes. From a management perspective, the problem areas (erosional) appear to be associated with barriers which are located downdrift of actively migrating tidal inlets (e.g., Pea Island), inlets in which the throat is temporarily pinned adjacent to the downdrift barrier (e.g., Cedar Island), updift of ephemeral inlets (e.g., Metomkin Island), or where bypassing is poor to non-existent. Relatively “safe” areas (accretionary) occur along barriers which are located downdrift of stable inlets (Hog Island), although high temporal variability can be expected. Areas located along updift recurved spits may show accretionary trends, but can be highly susceptible to storm washover due to their lower elevations.

Shorter islands, such as those commonly found in mixed-energy environments, experience a greater spatial impact of the shoreline due to inlet-related changes than longer islands. This is due primarily to the sizes of the tidal inlet and tidal deltas relative to the length of the island, the low inlet width/depth ratios, and the greater tidal ranges.

The methods and results from this study represent a first attempt to examine the shoreline changes that result from inlet-related processes. Presently, we are employing a variety of quantitative methods including non-linear robust regression analyses, principal component analysis, and stochastic process modeling to identify inlet related shoreline changes. Preliminary results using the coefficient of determination as a spatial outlier detection technique show that, along the 66 km reach south of Oregon Inlet on Pea Island, the rate-of-change values greater than 1, 2, 3, and 4 standard deviations from the mean occur to distances of 6.0 km, 1.5 km, 0.7 km, 0.4 km, respectively. In addition, we are examining the role of coastal storms on modifying inlet morphodynamics and adjacent barrier island shoreline changes.

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LITERATURE CITED


