## CHAPTER 70

# PROCESS-RESPONSE MODELS FOR DEPOSITIONAL SHORELINES: THE GERMAN AND THE GEORGIA BIGHTS

by


Dag Nummedal
Department of Geology
Louisiana State University
Baton Rouge, Louisiana
70803, USA

and

Ian A. Fischer
Mobil Oil Corporation
1001 Howard Avenue
New Orleans, Louisiana
70113, USA



## ABSTRACT

Sediment dispersal patterns in tidal inlets within the German and the Georgia Bights are found to be controlled by three major environmental factors: (1) the tide range, (2) the nearshore wave energy, and (3) the geometry of the back-barrier bay. Both embayments chosen for study are characterized by high wave energies and low tide ranges on their flanks, and low wave energies and high tide ranges in their centers. The spatial variability in inlet morphology, therefore, contains information on the relative role of tides and waves in inlet sediment dispersal. The paper concludes by proposing a simple model for inlet morphologies for successively greater relative role of tidal currents in the sediment dispersal.


## INTRODUCTION

Investigations of process-response characteristics of tidal inlets along the southeast coast of the United States (Bruun, 1966; Finley, 1976; FitzGerald et al, 1976; Hubbard et al, 1977; Nummedal et al, 1977) have demonstrated that the geometry of the inlet entrance and the associated sand schoals depends upon three major environmental factors: (1) the tide range, (2) the nearshore wave energy, and (3) the bathymetry of the back-barrier bay.

The relative magnitudes of factors 1 and 2 control to a large extent the inlet stability. Inlets along the Georgia coast, which has high tide range and low wave energy, are much more stable than those along North Carolina's Outer Banks where the wave energy is high and the tide range relatively low. These observations support, in a qualitative sense, Bruun's (1966) stability criterion which is based on the ratio between the tidal prism and the longshore sediment transport rate.

The third factor listed above, the bathymetry of the bay, controls the degree of velocity asymmetry through the inlet gorge (Nummedal and Humphries, 1978). The bays in the southeastern United States are typically filled with intertidal salt marsh (Spartina alterniflora being the dominant grass species), leaving only about 20 per cent of the total bay area as open water (tidal creeks). The consequent large variation in water surface area during the tidal cycle tends to develop strongly ebb-dominant flow in such a bay-inlet system. The peak ebb current and the consequent seaward-directed sediment transport, far exceed that moving landward during flood. In cases where the back-barrier bay is essentially all open water (as in the lagoons behind the Outer Banks of North Carolina) there is no such tendency for ebb dominance.

In order to determine the response of the tidal inlets to the three controlling factors one must examine coastal segments within which all factors undergo significant changes in magnitude according to a well-known geographic pattern. The coastal segments chosen for this investigation were the southeast coast of the United States from Cape Hatteras to Cape Canaveral (Fig. 1) and the northwest coast of Europe from the Netherlands to the west coast of the Jutland peninsula in Denmark (Fig. 2). For short, the first region will be referred to as the Georgia Bight, the second one as the German Bight.

## TIDE RANGE

Along the east coast of the United States the open coast tide range is primarily a function of shoaling of the tidal wave across the continental shelf. Therefore, the wider the shelf, in the direction of advance of the tidal wave, the larger the tide range (Redfield, 1958; Silvester, 1972). Figure 3 (from Nummedal et al, 1977), shows the regional tide range variation along the U.S. east coast as well as the accompanying variation in shelf width. The tide range dependency on shelf width can clearly be seen.

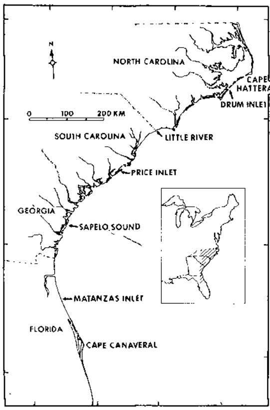


Fig. 1. Location map of the Georgia Bight.

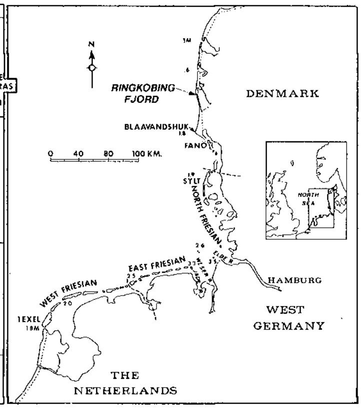


Fig. 2. Location map of the German Bight.

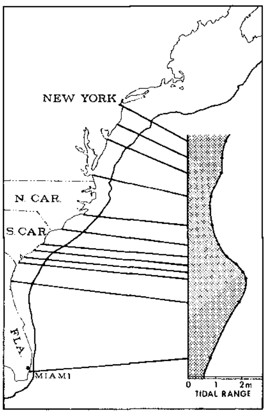


Fig. 3. Mean tide range along the east coast of the United States. Data from: National Oceanic and Atmospheric Administration, 1978.

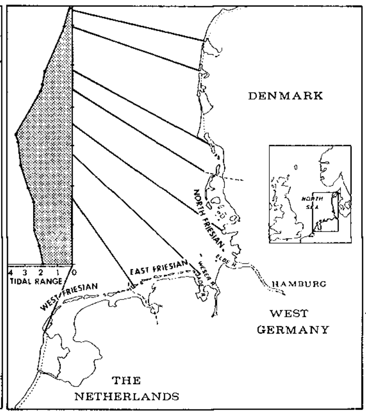


Fig. 4. Mean tide range along the shores of the German Bight. Data from Deutschen Hydrographischen Institut, 1978.

In the North Sea, the entire region is essentially a continental shelf. The variation in open-coast tide range within the German Bight, therefore, is largely controlled by the amphidromic system. Classical models of the $M_2$ tide within the North Sea (Defant, 1958), demonstrate the existence of a counter-clockwise rotation of the tidal wave in the North Sea around an amphidromic point between Jutland and the east coast of England. Iso-range lines are nearly concentric around this point. Therefore, the central part of the German Bight which is further away from the amphidromic point than is the northwest Netherlands or the coast of Jutland, has the larger tide range. The tide range variability within the coastal segment of interest in this study is plotted in figure 4.

By comparing figures 3 and 4 it is evident that both the Georgia and the German Bights are characterized by low tide range at their flanks and high tide range in the center. Mean tide range in the center of the Georgia Bight exceeds 2 meters; in the center of the German Bight it exceeds 3.5 meters.

## WAVE ENERGY

Evaluations of the regional variability in nearshore wave climate is presently impossible because reliable wave records are very scattered and typically of too short duration to be of much use in long-range sedimentation studies. In order to derive a consistent picture of wave energy variability, therefore, it was decided to utilize the Summary of Synoptic Meteorological Observations (SSMO - data) published by the U.S. Naval Weather Service Command (1974, 1975). Wave energy flux distributions within pre-established data squares were calculated by a procedure outlined in Nummedal and Stephen (1978). In this same article the authors have also discussed in some detail the assumptions and problems associated with the utilization of SSMO-data in studies of coastal sedimentation dynamics. Results of the wave energy flux calculations for data squares off the southeast coast of the United States and in the North Sea are summarized in figures 5 and 6, and tables 1 and 2.

The deep water energy flux shows a distinct southward decrease along the U.S. east coast from a total onshore flux at Cape Hatteras of $7.7 \cdot 10^3$ Watts/m to $4.6 \cdot 10^3$ Watts/m at Jacksonville. In spite of this deep water trend, however, the mean annual breaker height in northeast Florida exceeds that of the central part of the Georgia Bight (58 cm at

Daytona Beach versus 12 cm at St. Simon Island; Coastal Engineering Research Center, 1975) probably because of the steeper inner shelf profile off the Florida coast (Nummedal et al, 1977).

Table 1. Deep water wave energy flux values for the southeast U.S. SSMO data squares. Energy flux in units of $10^3$ Watts/meter.

| Data Square Direction | Cape Hatteras | Charleston | Jacksonville | Miami |
|---|---|---|---|---|
| N | 4.8 | 3.2 | 4.2 | 1.9 |
| NE | 3.3 | 3.5 | 2.2 | 2.2 |
| E | 1.3 | 1.9 | 1.3 | 2.4 |
| SE | 1.2 | 1.3 | 1.1 | 1.2 |
| S | 1.9 | 2.2 | 1.8 | .8 |
| SW | 2.8 | 2.5 | 1.6 | .8 |
| W | 3.0 | 3.2 | 1.9 | .7 |
| NW | 2.7 | 2.6 | 3.2 | 1.3 |

Table 2. Wave energy flux values for SSMO data squares along the margins of the North Sea. Energy flux in units of $10^3$ Watts/meter.

| Data Square Direction | Edinburg | Grimsby | Rhine Delta | Bremer-haven | Esb-jerg | Stavan-ger |
|---|---|---|---|---|---|---|
| N | 2.1 | 1.5 | .8 | .7 | 2.1 | 5.1 |
| NE | .5 | 1.5 | .7 | .3 | 1.0 | 1.4 |
| E | 3.3 | 1.5 | .5 | .8 | 1.8 | 4.5 |
| SE | 3.4 | .8 | .3 | .3 | 1.0 | 7.8 |
| S | 1.8 | 2.1 | .7 | .5 | 2.3 | 3.8 |
| SW | 1.7 | 2.8 | 2.1 | 1.5 | 5.0 | 5.4 |
| W | 3.0 | 2.3 | 1.9 | 2.9 | 5.5 | 9.8 |
| NW | 3.3 | 2.7 | 1.4 | 2.4 | 6.3 | 11.8 |

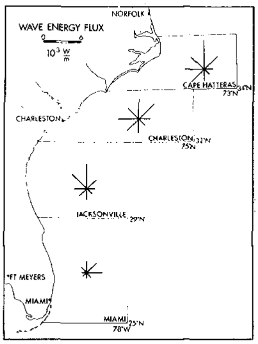


Fig. 5. Wave energy flux distribution off the southeast coast of the U.S.

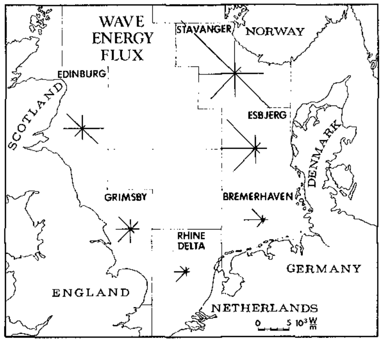


Fig. 6. Wave energy flux distribution along the margins of the North Sea.

Along the southeast coast of the North Sea one also finds a distinct southward decrease in total wave energy flux. This is thought to reflect a combination of a decrease in storm frequency as well as westerly fetch in the same direction. Total onshore wave energy flux in the Esbjerg data square (Fig. 6) is about $17 \cdot 10^3$ Watts/m, compared to $7 \cdot 10^3$ Watts/m along the North Friesian Islands and only $3.5 \cdot 10^3$ Watts/m along the East Friesian Islands.

By combining the information presented on the wave energy and tide range variations one can derive a generalized pattern of wave and tide dominance along the shores of these two bights (Fig. 7). The flanks have high wave energy and low tide range. They are wave dominated. Further towards the center the two factors will both be of major importance; therefore, this will be a zone of mixed energy. In the center of both bights the tidal currents clearly control the sedimentation patterns. These areas are tide dominated.

## INLET MORPHOLOGY

Both the Georgia and the German Bights show distinct and similar trends in inlet morphologic changes as one progresses from the flanks toward the centers. These changes provide unambiguous evidence regarding the relative role of tidal and wave induced sediment dispersal in the total inlet circulation pattern. This paragraph will review the characteristics of inlet morphology, moving from the wave dominated embayment flanks to increasing tidal dominance at the embayment centers.

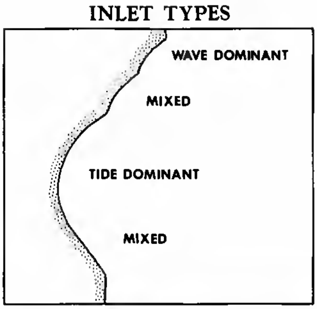


Fig. 7. Generalized distribution of wave and tide dominance along an embayment coast

Fig. 8. Oblique air photo of Drum Inlet, North Carolina. Photo, May 1977, courtesy of Albert C. Hine.

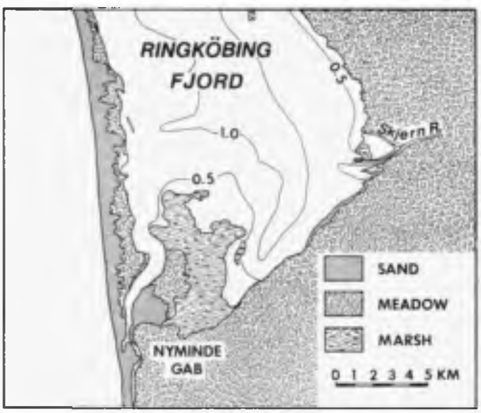


Fig. 9. Map of the southern part of Ringkobing Fjord, including the old flood-tidal delta at Nyminde Gab. Depth contours in meters.

Inlets along the wave dominated coastal segments of both bights are typified by Drum Inlet, North Carolina, at the northern flank of the Georgia Bight (Figs. 1 and 8). Although the Drum Inlet flood-tidal delta was developed over a very short time immediately after the inlet was artificially opened in 1972 its morphology is typical of the much larger deltas behind Ocracoke, Hatteras and Oregon inlets as well. Today, the Drum Inlet flood-tidal delta is rather inactive (Hubbard, 1977).

Within the German Bight the wave dominated barrier-lagoon coast is restricted to the west coast of Jutland. Furthermore, all these lagoons now have artificially cut and maintained entrances. However, it is clear from old maps and the present lagoon morphology that the natural entrance to Ringköbing Fjord was associated with a large flood-tidal delta, the remains of which are clearly recognizeable at Nyminde Gab (Figure 9).

The morphology of an inlet at a wave dominated coast is summarized in frame 1, figure 10.

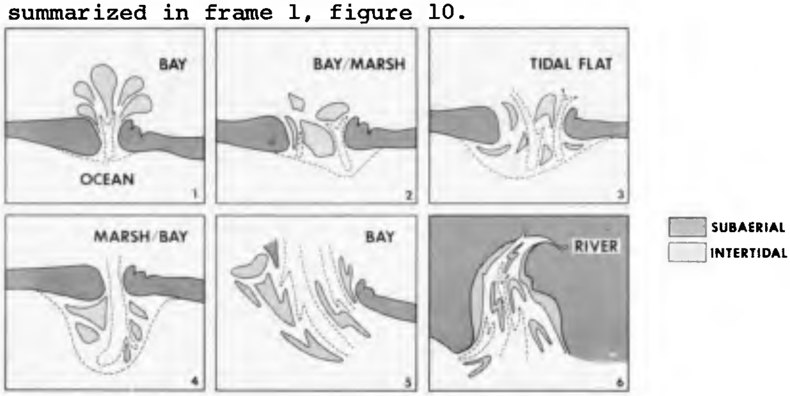


Fig. 10. Tidal inlet morphological models. Frames 1 through 6 reflect an increasing role of tidal currents in inlet sediment dispersal.

As illustrated, such an inlet is characterized by sand bodies exclusively on the landward side of the inlet gorge. The gorge itself is relatively stable, the ebb tidal delta (outer shoal) is present only as a minor subtidal shoal.

With an increase in tidal range, and consequent tidal current capacity for sediment transport, one observes an intriguing change in inlet shoal configuration. Both Little River inlet on the North Carolina-South Carolina border

(Fig. 11) and Matanzas Inlet in northeast Florida (Fig. 12) are good examples of this inlet type which will be called mixed energy, low tide range, inlets.

Based on the distribution of sand bodies within these inlets the generalized model shown in frame no. 2, figure 10, was developed. This type of inlet has a smaller, and less continuous, flood-tidal delta than inlet type no. 1, it has a wide and rather unstable inlet gorge, and a significant ebb-tidal delta reflecting main channel ebb-current dominance (Hayes et al., 1973).

The inlets between the East Friesian Islands on the coast of Lower Saxony, Germany, must also be termed mixed energy inlets. However, both tide range (Fig. 4) and wave energy (Fig. 6) exceed those within the Georgia Bight. As the gross differences in morphology appear to reflect primarily the larger tide range, these inlets are classified as mixed energy, high tide range, inlets. Excellent examples would be the inlet between Norderney and Baltrum (Fig. 13), and the Harle Inlet between Spiekeroog and Wangerooge (Fig. 14).

As demonstrated by Luck (1976) these Friesian inlets have a large ebb-tidal delta with a nearly continuous arc of swash bars along its margin, the "reef-bow." The high wave energy appears to cause rapid swash bar migration contributing to the instability of the seaward end of the main ebb channel. The inlets are very wide and the ones that are not yet stabilized by sea walls and groins on the adjacent island shores typically have multiple channels. According to historical studies by Luck (1975) prior to stabilization the Harle Inlet also had multiple sand bars in the gorge section and two or three major channels. Reduction in tidal prism as a function of the reclaiming of large areas of back-barrier tidal flat appears to be the main factor contributing to the changes morphology of the Harle Inlet.

A generalized morphological model of the Friesian inlets is presented in frame no. 3, figure 10. The only essential difference from model no. 2 is the larger ebb-tidal delta, projecting further out to sea in response to much stronger tidal currents. Strong wave action also produces a more continuous series of swash bars along the swash platform margin.

Fig. 11. Oblique air photo of Little River Inlet, North Carolina-South Carolina border. Photo, May, 1977, courtesy of Dennis K. Hubbard.

Fig. 12. Oblique air photo of Matanzas Inlet, Florida. Photo, April, 1977, courtesy of Dennis K. Hubbard.

Fig. 13. Oblique air photo of Wichter Ee, the inlet between Norderney and Baltrum, Lower Saxony. July, 1978.


Fig. 14. Bathymetric map of Harle Inlet, Lower Saxony. The contour interval is 2 meters.

True tide dominance characterizes the inlets of the central part of the Georgia Bight. Although the tide range there is less than that along the Friesian coast, tidal dominance is brought about by the extremely low nearshore wave energies. Though small, Price Inlet (Fig. 15) illustrates well the morphology of the larger tidal inlets along this segment of the coast. Descriptions, photos and maps of numerous other inlets in the central Georgia Bight can be found in Hubbard (1977), Nummedal et al. (1977), Oertel (1975), and FitzGerald et al., (1978).

Fig. 15. Oblique air photo of Price Inlet, South Carolina. Photo, March, 1977.

The morphology of tide dominated inlets is generalized in frame no. 4, figure 10. These inlets consist of a single, straight, and deep main ebb channel, a large swash platform projecting far out to sea, and numerous, often large swash bars migrating towards the inlet gorge across the swash platform. There are no sand bodies in the inlet gorge section nor on its landward side, reflecting strong ebb dominance in the main inlet channel.

With a further increase in the ratio between tide range and wave energy, beyond the conditions found in the central part of the Georgia Bight, barrier islands with distinct individual tidal inlets cease to exist. As an example one can consider the central part of the German Bight where the mean tide range in places exceeds 3.5 meters (Fig. 4).

As shown in the bathymetric maps of the entrance to the Weser estuary (Fig. 16 and 17), small, unstable, supratidal sand bodies like Alte Mellum, have replaced the barrier islands of lower tidal range. A series of linear, lunate and sigmoidal shoals dominate the estuary entrance. Their long axes are typically parallel to the main estuary axis. The total sand body associated with this estuary is large and extends much further out to sea than any of the tidal deltas of the mixed energy inlets between the Friesian Islands further west.

Inlets (or estuary entrances) of this type are summarized in frame 5, figure 10. They are high tide range, tide dominated inlets.


Fig. 16. Bathymetry of the entrances to the Weser and Jade estuaries.


Fig. 17. Bathymetry of the area enclosed by frame in figure 16. Arrows refer to hydrographic data obtained by Barthel (1976). Open arrows indicate flood dominance, solid arrows show ebb dominance.

The high tide range end member of this spectrum of inlet types had to be found outside the German or the Georgia Bights. Hayes (1975) and Hayes and Kana (1976) present maps of Nushagak Bay, Alaska, as an example of a macrotidal embayment. Extremely high tide ranges, as in Nushagak Bay, can only develop in narrow embayments where there is a significant funneling of the tidal wave. The strong tidal currents, in turn, prevent the development of barrier islands across the embayment entrance. As indicated in the simplified morphological model of frame 6, figure 10, the shoal distribution within an embayment like Nushagak Bay is fairly similar to that of the high tide range, tide dominated embayment of frame no. 5. The main difference appears to be the degree of development of the sigmoidal shoals. An increase in tide range, and the associated tidal current strength, appears to develop larger sigmoidal shoals and more distinct flood and ebb segregated channels.

## DISCUSSION

The paper demonstrates that there clearly exists a continuum of tidal inlet morphologic types. Examples of most types within this continuum can be found within the Georgia and the German Bights because of large regional variations in tide range and wave energy.

The wave dominated inlets (frame 1, figure 10) typically have the majority of the shoals on the landward side of the inlet gorge because the net direction of wave induced sand transport will be towards the lagoon. Furthermore, the existence of a largely open-water lagoon rather than a marsh or tidal flat in the back-barrier environment will reduce the ebb dominance of the main inlet channel and cause flood dominance of some inlets (Nummedal and Humphries, 1978). Complex wave-current interactions on the swash platform have been found to produce a higher concentration of suspended sediment on flooding than on ebbing tide at one inlet (Hubbard, 1977). This factor might also contribute to the landward-directed net sediment transport at some wave dominated inlets.

The mixed energy inlets within the Georgia and German Bights are all hydraulically ebb dominated, because of the extensive back-barrier marshes and tidal flats (Nummedal and Humphries, 1978). The seaward extent of the swash platform must reflect an equilibrium between the capacity for seaward transport by the ebb flow and landward transport by wave breaking on the platform. Consequently, the primary change in the ebb-tidal delta with an increase in the ratio of tidal range to breaker energy will be its seaward growth. Secondly, the inlet gorge will become better defined and less subject to changes due to bar migration as wave-induced bar development will take place on platform margins further away from the inlet. These patterns of response to increasing tidal influence on the sediment dispersal mechanism are well illustrated in models two, three and four in figure 10.

Barrier islands cease to exist along depositional coast of high tide range because the longshore sediment movement due to wave action becomes completely subordinate compared to the on-offshore movement of sediment by the tides. For the wave energy of the German coast the critical tide range appears to be about 3 meters (Fig. 4). The development of sigmoidal shoals in these high tide range embayments is an expected consequence of the deflection of a current around the leading face of any sedimentary deposit formed by another current flowing in the opposite direction. This causes strongly segregated channels for ebb and flood flow, hence the sigmoidal shape of the bar crest. This segregation of ebb and flood flow in the Weser estuary has been well documented by Barthel (1976).

## CONCLUSIONS

1. The pattern of variability in tidal inlet sand body geometries within the Georgia and the German Bights suggests the existence of continuum of inlet morphologic types. In this continuum the shoals assume a configuration which directly reflects the relative capacity for sediment transport by waves and tidal currents. Six discrete stages of inlet morphology are presented in figure 10.

2. The diagram applied by Hayes (1979) to classify barrier island shorelines is used here to show the relationship between the inlet morphologic types and the two dominant environmental parameters: wave height and tide range (Fig. 18). To establish the boundaries, 19 inlets were classified, based on shoal geometry, as wave dominated, mixed or tide dominated. The mean tide range was well known for each, mean annual breaker heights, however, are much less precisely known. Nevertheless, a distinctive pattern did emerge, permitting the establishment of fairly precise boundaries for each inlet type on this bivariate graph. The boundaries slope such that with an increase in mean annual wave height an increase in tidal range is required to produce the same type of inlet shoal geometry.

3. The regional variability of the inlets within the Georgia and German Bights can be represented by the arrow in figure 18. Towards the center of both bights one finds an increase in tidal range and a decrease in the mean annual wave height. Therefore, the inlet change from wave dominated ones at the flank to tide dominated ones at the centers.

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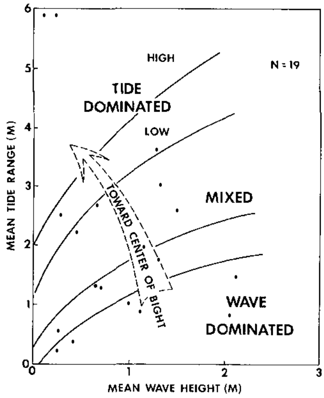


Fig. 18. Inlet morphologic types as functions of mean annual wave height and tide range. 19 barrier island coasts in North America and Europe were used to establish the boundaries.

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