CHAPTER 348

AN APPROACH TO MODELING INLET AND BEACH EVOLUTION

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Abstract

Improved understanding of the physical processes controlling inlet and adjacent beach morphology is required to manage sand resources in the vicinity of tidal inlets and to reduce costs associated with structural rehabilitation, maintenance dredging of navigation channels, and mitigation of adverse impacts on adjacent shores. A quantitative modeling capability for estimating sediment fluxes, morphology evolution, and the interaction between the inlet and adjacent beaches is a goal of engineering research. This paper presents the initial phase of work aimed at developing empirical relationships between the physical processes and resulting inlet morphologic response, which are needed to formulate a modeling capability. First, the technical and computational requirements of the model are outlined. Then, a conceptual model of inlet sediment bypassing and a brief overview of a recently developed model (De Vriend et al. 1994) which appears to satisfy most of the model requirements is given. Finally, preliminary results of an empirical analysis of inlet ebb shoal geometric characteristics are presented.

Introduction

The presence of tidal inlets along a mainland or barrier island sandy shoreline represents a major morphological perturbation in the otherwise generally linear features (dune, berm, shoreline, longshore bar) that make up the coastal zone. The shoreface morphology at tidal inlets is a product of the changes in the physical forces that form the beachface. In the vicinity of tidal inlets, longshore currents generated by waves breaking at oblique angles to the shoreline interact with concentrated cross-shore currents that pass through the inlet gorge. Littoral sediments carried in the longshore current are swept into the inlet interior or are jetted offshore by the tidal currents. Over time, if the

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inlet cross-section is stable, depositional shoal features will develop. Walton and Adams (1976), Marino and Mehta (1987), and others have shown that the ebb shoal tends toward an equilibrium volume which can be related to the tidal prism. If flood shoal volumes are also assumed to approach an equilibrium condition or a near constant growth rate, then it follows that under natural conditions, an inlet system could form and in time (10's to 100 years), reach a near-equilibrium condition, in which a large percentage of the littoral drift bypasses the inlet to downdrift shorelines.

However, because navigable tidal inlets represent an important economic resource, many inlets have been stabilized with jetties or improved for navigation by dredging. Inlet stabilization by jetties has been shown to produce a seaward displacement of the ebb shoal (Kraus et al. 1994). Seaward movement of the ebb-tidal shoal can result in an increase in the volume of material comprising the shoal. Dean (1993) presented a conceptual model together with field examples that indicate that maintaining a channel through a tidal inlet that is deeper than the natural channel depth causes sediment to flow into the maintained channel, which comes at the expense of volumetric erosion of the beaches adjacent to the inlet. Consequently, engineering practices involving inlet stabilization by jetties and navigation channel dredging are increasingly cited for their role in the observed persistent erosion of adjacent shorelines.

In the United States, federal responsibility for the design, operation, and maintenance of inlet stabilization structures and navigation channels lies with the U.S. Army Corps of Engineers. Improved sand management in the vicinity of tidal inlets will reduce costs associated with structural rehabilitation, maintenance dredging, and mitigation of adverse shoreline impacts. However, a better understanding of the physical processes controlling inlet morphology is required, including estimating sediment fluxes, morphology evolution, and the interaction between the inlet and adjacent beaches. A quantitative modeling capability can help improve our understanding of the interaction between an inlet system and its adjacent beaches. The model to be developed is intended to aid in the analysis and prediction of inlet adjacent shoreline evolution over mid- to long-term time scales (1 to 10's of years), and spatial scales up to 10's of kilometers.

Model Requirements

Goals and Development Philosophy. The primary goal of the research discussed in this paper is to develop a predictive methodology to estimate quantitatively the potential impacts of engineering activities on shorelines adjacent to modified or engineered inlet systems. The desired use of the numerical model is to predict shoreline response within the reach of shoreline influenced by the inlet in response to different engineering activities. An inlet-shoreline response model is recognized for its value in providing a quantitative basis for the comparison of alternatives. Procedures for application also will include guidance for producing an ensemble of solutions based on Monte Carlo-type simulations produced from a combination of plausible input

conditions. The ensemble of solutions then may be examined to determine the range and the frequency of the outcomes within that solution set. Because this model is being designed for use by practicing coastal engineers, model development is being undertaken with the expressed intent of capturing the evolutionary trends of the shoreline and maximizing range of applicability. This development philosophy stems from the observation that models the engineer is most likely to use are those which he or she can understand and defend, and those which require minimum adjustment of calibration parameters. Traditional approaches to coastal engineering design are expected to become more reliable with the addition of objective and quantitative estimates of an inlet's total littoral impact, which will be provided by the numerical model.

Prediction Requirements. Inlets impact adjacent shores primarily by their action as a sediment sink; therefore, a fundamental requirement of the model is the capability to predict whether and to what degree an action will change the net volume of sand lost (trapped against stabilization structures or otherwise stored in inlet associated shoal features) from the adjacent shorelines. A related requirement is the need to predict the distribution of that sand deficit along the adjacent beaches. Furthermore, regulatory agencies asking for a prediction of project performance resulting from both natural and engineered site changes leads to the requirement for model prediction of, for example, sea-level rise, extended mechanical failure of bypassing equipment, and/or planned or unexpected delays in renourishing a project or performing routine maintenance dredging of a navigation channel. The parameter of primary interest in many situations and therefore required from the model predictions is the shoreline location. For other situations the profile geometry is also of keen interest and less frequently sediment volume in various locations around the inlet-adjacent beach system are required. Table 1 provides a list of specific model requirements. Predictions are required for engineering time scales (1 to 10's of years) and spatial scales corresponding with the total longshore extent of the inlet's impact (up to 10's of kilometers).

Physical Processes. Conceptually, inlets impact adjacent shorelines in two fundamental ways. One impact is the inlet channel as a sediment sink which results in a net loss of sediment from the adjacent beach systems. The second impact is the altering of wave and current patterns, which results in a change in sediment transport patterns. Therefore, the physical processes responsible for these fundamental functions of an inlet system must be captured in the numerical model at some appropriate level. The physical processes important to determining an inlet's overall impact to the littoral system are those which result in net sediment impoundment, jetty leakage, channel shoaling, and shoal formation. Sediment conservation requires that the net volumetric impact to the adjacent shorelines equal the net volume of sediment lost to the inlet. To be useful (to estimate the inlet's impact on adjacent shores), the model must compute the rate at which sediment is delivered to the inlet, the rate at which sediment is moved through the inlet (along its axis), and the rate at which sediment is transported across, around and away from the inlet. These quantities will enable estimation of that fraction of the littoral drift which bypasses the inlet from that which is trapped within

Table 1. Model Requirements

Model Requirement	Comments
Foreshore slope changes	Beach profile slopes at stabilized tidal inlets are typically steeper updrift of the inlet and milder downdrift of the inlet as compared to beach profiles not influenced by inlet system.
Sediment point/line source and sink capabilities	To effectively evaluate many typical engineering activities (e.g., sand bypassing, beach nourishment), the capability to model point and/or line sediment sources and sinks is required.
Structure specification	To evaluate the influence of modifying inlet stabilization structures, the model must be sensitive to user-specified characteristics of the structures (e.g., length, orientation and configuration, permeability, weir sections, elevation, etc.).
Wave transformation and the possibility of multiple wave breaker lines	Wave transformation, including shoaling, refraction, diffraction and the possibility of multiple wave breaker lines with differing breaker characteristics, is required to capture the influence of the ebb shoal feature on the incident wave climate.
Hindcast capability	To demonstrate reasonability in predictions, the model must be able to simulate pre-project adjacent beach evolution.
Forecast capability	To be useful in evaluating the relative merits of competing design alternatives, the model must be able to provide mid- to long-term (1 to 10's of years) existing- condition forecasts as well as with-project forecasts.
Scoping mode / design mode applications	To quickly and efficiently provide estimates of the impact of preliminary design considerations, as well as to provide detailed estimates of refined design alternatives, the model is required to have the capability of being operated with differing levels of sophistication and data requirements.
Input data requirements	Data required to operate the model must be consistent with typically available data and/or data which can be reasonably collected.
Compatible with sediment budget methodology	Model input and output should be compatible with classical sediment budget methodologies (e.g., sediment budget information can be input to the model and model outputs can be integrated back into the sediment budget).

the inlet or is otherwise lost to the littoral system. How the net volumetric impact of the inlet is distributed along the adjacent shores is determined by hydrodynamic and sediment transport processes which exist away from the inlet. In short, modeling sediment movement in the vicinity of inlets ultimately involves essentially all of the most complicated processes of coastal sediment transport.

Target Inlet Type and Behavior. In nature, inlet systems vary widely in their characteristics and behaviors, and it is doubtful that one model or even one modeling approach would be equally applicable to all inlet systems. It is expected that the developed model will not be able to adequately predict all inlet behaviors and, therefore, will be more applicable to certain types of inlets than to others. Consequently, it is essential that the target inlet type and behavior are clearly defined. The inlet systems for which the model is being developed may be characterized as being relatively stable, often the result of stabilization structures for the purpose of providing safe navigation. The system is viewed as being in a state of dynamic equilibrium, meaning that the inlet system responds to seasonal variations in the wave and water level climate as well as to storm events. However, it is assumed that these responses are short-term or seasonal variations imposed upon an underlying state of equilibrium and do not have a destabilizing effect on the inlet system nor do they significantly alter the underlying equilibrium state. Engineering activities, on the other hand, can both temporarily displace the system from its equilibrium condition (e.g., sand mining from the ebb shoal) and in some cases change the inlet's equilibrium state (e.g., by changing the tidal prism). In either case, the inlet system will evolve toward either its old or new equilibrium state with impacts ultimately occurring on the adjacent beaches. Natural sediment bypassing is assumed to be a semi-continuous process, and the possibility of random or periodic bar welding on downdrift shorelines is excluded. The model will not allow the inlet to migrate as many natural inlet systems do. Furthermore, because sediment transport along the outer ebb delta is computed as a function of the incident wave energy the model will be more applicable to wave dominated and mixed-energy inlets than it will to tide dominated inlets.

Conceptual Model of Inlet Sediment Bypassing

Inlet sediment bypassing is the process by which littoral material delivered to the inlet from the updrift beach makes its way across the inlet system and is integrated into the littoral material on the downdrift beach. In a series of papers (Bruun and Gerritsen 1959, Bruun 1967, and Bruun 1978), a model has been presented that describes two possible pathways for inlet sediment bypassing by natural action: 1) bypassing on an offshore bar, and 2) bypassing by tidal flow action. In bar bypassing, littoral material that is delivered to the inlet from the updrift shorelines is transported along a submerged bar in front of the inlet system and delivered to the downdrift shoreline. In tidal flow bypassing littoral material is pulled through the inlet by flood currents and then discharged out of the inlet by ebb currents in the downdrift direction. Though sediment may cycle several times through the inlet, it is ultimately bypassed to the downdrift

shoreline. Bruun indicated that in most cases a combination of both of these mechanisms for natural bypassing is active but that the dominant process could be identified by examining the ratio of the tidal prism over the total littoral drift.

FitzGerald (1988) presented three conceptual models to explain inlet sediment bypassing along mixed energy coasts. These models are categorized according to the stability of the inlet throat and movement of the main ebb channel. These are: 1) inlet migration and spit breaching, 2) stable inlet processes, and 3) ebb-tidal delta breaching. In the first model, the entire inlet migrates downcoast leaving a trailing spit extending from the updrift barrier. The resulting elongation of the inlet channel becomes hydraulically inefficient for tidal flow between the ocean and the bay. Ultimately the spit is breached during a storm and the new channel which provides a shorter route for tidal exchange will normally remain open while the less efficient old inlet channel closes. In the second model, the inlet throat position and the main ebb channel do not migrate. Sand bypassing at these inlets occurs through the formation, landward migration and welding of large bar complexes to the downdrift shoreline. In the third model, the location of the inlet throat is stable, but the main ebb channel migrates. The dominant direction of longshore sediment transport causes a preferential accumulation of sand on the updrift side of the ebb-tidal delta which results in a deflection of the main ebb channel. Similar to the first model, the migration of the ebb channel ultimately results in a hydraulically inefficient channel and a new channel breaches through an updrift spillover lobe channel. Ebb-tidal delta breaching results in the bypassing of a large portion of the ebb delta sand bodies. Some of this sand fills the abandoned channel while the rest forms a large bar complex that ultimately migrates onshore and attaches to the downdrift shoreline. FitzGerald summarized by indicating that during the history of a particular inlet, all three bypassing processes may dominate at one time or another. He also states that Bruun and Gerritsen's (1959) bar-bypassing mechanism (the movement of sand around an inlet by wave action along the terminal lobe of the ebb-tidal shoal) is an active but secondary process at most mixed-energy tidal inlet systems.

For the target inlet type and behavior described previously we believe that the bypassing models of Bruun and Gerritsen (1959) are more applicable than those of FitzGerald (1988). From a long-term (10's of years) perspective the net effect of FitzGerald's bypassing models could be idealized as a sediment drift along the outer edge or crest of the ebb delta from the updrift to the downdrift island. However, for shorter time periods (up to 10 years) which are of interest to us, FitzGerald's models are not compatible with the approach we have adopted. For the development of a computational model for inlet adjacent beach evolution the mid- to long-term (1 to 10's of years), net transport patterns near the inlet are idealized as shown in Figure 1. This idealization is a substantial simplification of the real situation, but it is consistent with typically available data, the level of schematization envisioned for the computational model and our capability to estimate details of sand transport at tidal inlets.

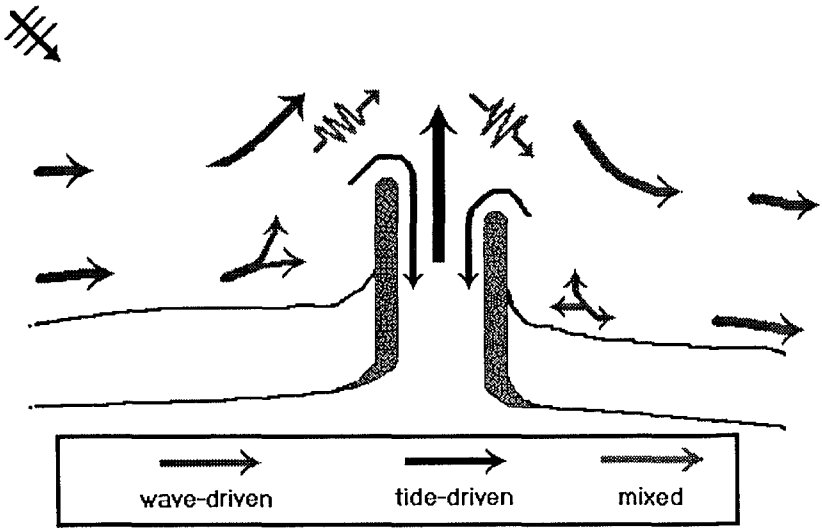

Figure 1. Conceptual model of inlet sediment bypassing.

Computational Approach

The computational approach selected for development of the inlet and adjacent beach evolution model falls into the class of models described by Kraus (1989) as multi-contour line models. This class of model was selected because the capabilities and characteristics of the model best satisfied the needs identified in a requirements analysis for inlet adjacent beach evolution modeling (Truitt and Bodge 1995). The initial development of a morphological behavior model for the outer delta of mixed-energy tidal inlets (De Vriend et al. 1994) tends to confirm that the selected computational approach has some merit and the interest of researchers. In the outer delta model, the two-line model concept of Bakker (1968) is extended to a situation where the coast is interrupted by a tidal inlet. The behavior of adjacent island coasts are modeled directly utilizing a two-line modeling approach (evolution of a beach line and a foreshore line); at the inlet, the beach line is discontinued because there is no subaerial beach profile at this location. The foreshore or inshore line, however, protrudes seaward at the location of the inlet, thereby representing the inlet delta or ebb shoal. Based on empirical relationships for the equilibrium state of the ebb shoal, the protrusion distance and geometric configuration of the ebb shoal are determined. The inlet-adjacent beach system and its evolution are described by: 1) computed wave-driven sediment fluxes along the adjacent island coasts and along the seaward edge of the ebb shoal, 2) specified net sediment fluxes through the inlet channel, and 3) the requirement for sediment continuity at six locations.

The outer delta model includes consideration of sediment fluxes through the main ebb channel as well as sediment fluxes through flood channels located near the beaches adjacent to the inlet. Sediment flux through the flood channels is fed by both the beach line and the inshore line. The equilibrium state of the delta (volume, seaward protrusion) is described using empirical relationships. A sediment balance is maintained throughout the evolution, and the sediment demand or supply by the basin is taken into account as an input parameter. The model output consists of the cross-shore positions of the beach line and the inshore line as a function of time and the longshore coordinate. It is noted, however, that the model developers (De Vriend et al. 1994) caution that the model results should be interpreted at a higher aggregation level (e.g., the trend of predicted change should be given more weight than the predicted magnitude of change). For more details on the outer delta model and its validation the reader is referred to the Master's thesis of Bilse (1993).

Empirical Analysis

Goals. To refine and expand on the initial model developed by De Vriend et al. (1994), a focused empirical analysis and parameterization of inlet geometry and processes has been undertaken. The goal of this research is to characterize the volume, geometric shape, and general location of the ebb shoal based on estimable quantities such as tidal prism, magnitude of net and gross longshore sand transport rates, and tidal range. U.S. inlets with rich temporal and spatial historical data sets are being analyzed. Specific analysis to be conducted include: 1) confirmation of the ebb shoal volume tidal prism relationship proposed by Walton and Adams (1976), 2) investigate the shoal volume to shoal protrusion relationship assumed by De Vriend et al. (1994), 3) the correlation, between the ebb shoal aspect ratio (longshore extent/cross-shore extent) and the tidal prism and/or net or gross longshore sand transport rates, 4) the relative stability of updrift and downdrift shoreline offsets, and 5) the correlation, between ebb shoal skewness (offset between ebb shoal centroid and inlet throat at jetty tips) and net and gross longshore sand transport rates.

Status. At present this analysis has included the geometric analysis of four tidal inlets along the eastern US Atlantic coast. The four inlets are: 1) Ocean City Inlet located in Ocean City, Maryland, 2) Barnegat Inlet located in central New Jersey, 3) Moriches Inlet located between Fire Island and Westhampton Beach on Long Island, New York, and 4) Shinnecock Inlet located between Tiana Beach and Southhampton Beach on Long Island, New York. The analysis has not progressed to the point where new or refined empirical relationships can be proposed, but procedures for the geometric analyses of ebb tidal shoals have been developed, and their application to the four inlet systems will be discussed in the remainder of this paper. (We plan to extend this geometric analysis to a number of other inlet systems in the future at which time a database of the physical driving forces will be integrated for the development of new or updated empirical relationships.)

Methods. The bathymetry data were obtained by three methods, standard hydrographic surveys using a vessel mounted fathometer, sea-sled beach profile surveys, and airborne LIDAR (LIght Detection And Ranging) surveys obtained using the helicopter based SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system. In all cases some combination of these survey methods were used to obtain the complete bathymetric coverage data sets. The procedure begins by developing a digital terrain model (DTM) using the original bathymetric data as input. Contours were then generated with reference to the National Geodedic Vertical Datum (NGVD). A polygon was then drawn around the ebb shoal. Typically, the offshore boundary of the polygon followed along the 10- to 11-m NGVD contour (the landward most contour that does not protrude seaward at the ebb shoal). The landward boundary followed along the 0-m NGVD contour. The lateral boundaries were selected at an alongshore location corresponding to where the contours began to protrude seaward around the shoal. A least-squares best-fit line was computed for contours at 1-m intervals outside the ebb shoal polygon. These computed best-fit contours on either side of the ebb shoal polygon were joined and then smoothed using the cubic B-spline method. The "no ebb shoal" bathymetry was estimated by digitizing the smoothed best-fit contours and then generating a DTM of the result. The next step involved taking the difference between the idealized "no ebb shoal" DTM and the original bathymetry DTM within the ebb shoal polygon. The result of this differencing operation is a DTM that we will refer to as the "residual" ebb shoal topography. This terminology describes the morphological residual of the formation of the ebb-tidal shoal; topography is used because the residual is described in terms of positive elevations and no longer represents a bathymetry. The residual ebb shoal topography was used to estimate the volume and geometric configuration of the ebb shoal. Figure 2 provides plots of the ebb shoal bathymetry, the idealized no ebb shoal bathymetry, and the residual ebb shoal topography for each of the four inlet systems examined. This procedure is similar to that used by Dean and Walton (1973) but employs modern terrain modeling software which, to some extent, reduces the subjectivity of the analysis.

Results. Figures 3-6 are contour plots of the residual ebb shoal topography with the extracted geometric characteristics indicated for Barnegat, Ocean City, Shinnecock, and Moriches inlets, respectively. Shown in the figures are the 1-, 3-, and 5-m contours of the residual ebb shoal topography with their alongshore and offshore dimensions. Also indicated is the location of the centroid of the residual ebb shoal topography with respect to the inlet throat at the tips of the inlet jetties. Without examination of the site-specific physical driving forces (e.g., tidal prism, tide range, wave energy, net and gross longshore sand transport rates etc.), we are unable at this time to draw conclusions or explain the differences in the geometric configuration of these four inlet systems.

Conclusion

This paper documents the initial phase of work that has been undertaken to develop a needed modeling capability in the vicinity of tidal inlets. The requirements

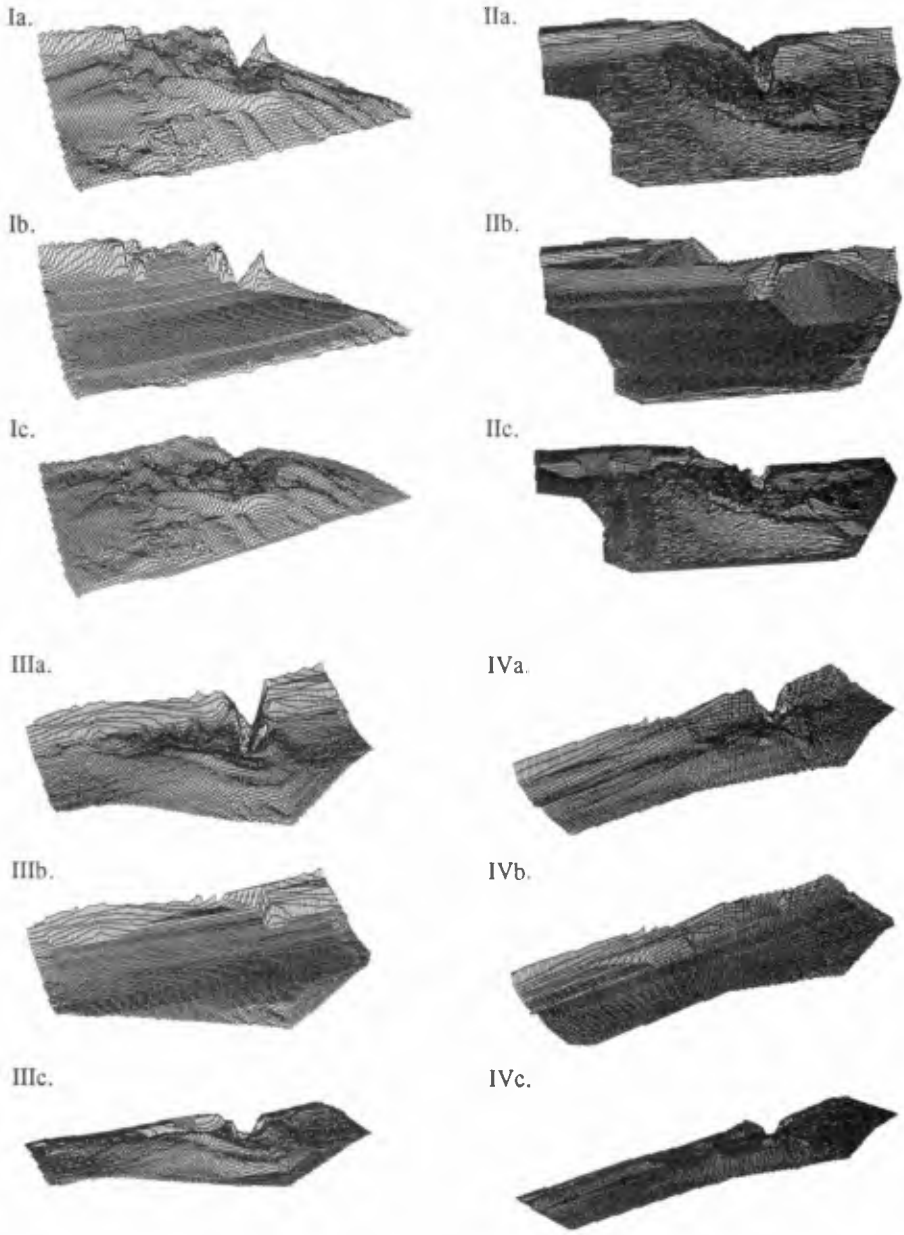

Figure 2. Plots of ebb shoal at Barnegat (I), Ocean City (II), Shinnecock (III), and Moriches (IV) inlets. (a) ebb shoal bathymetry, (b) idealized no ebb shoal bathymetry, and (c) residual ebb shoal topography.

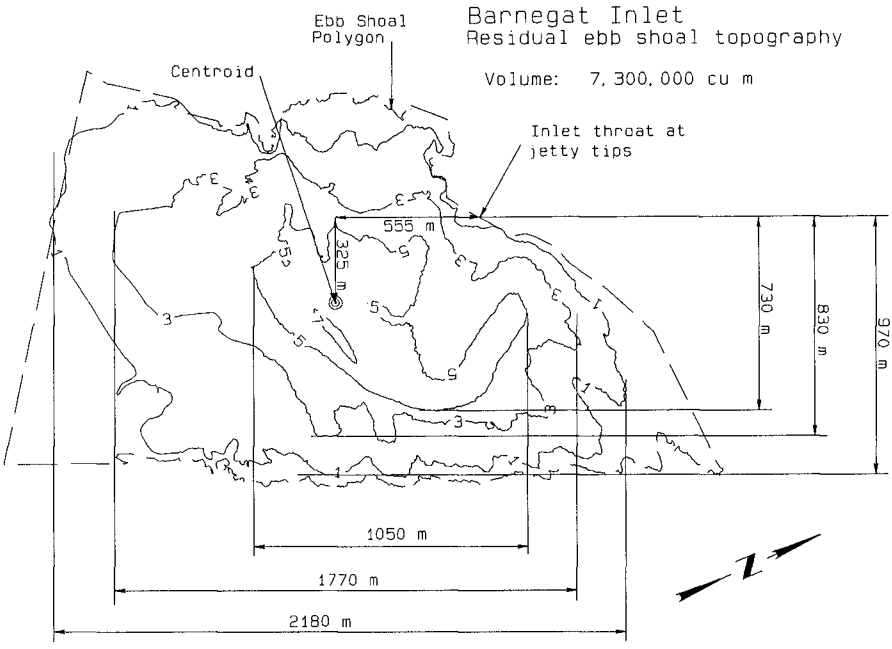

Figure 3. Barnegat Inlet residual ebb shoal topography and geometric attributes.

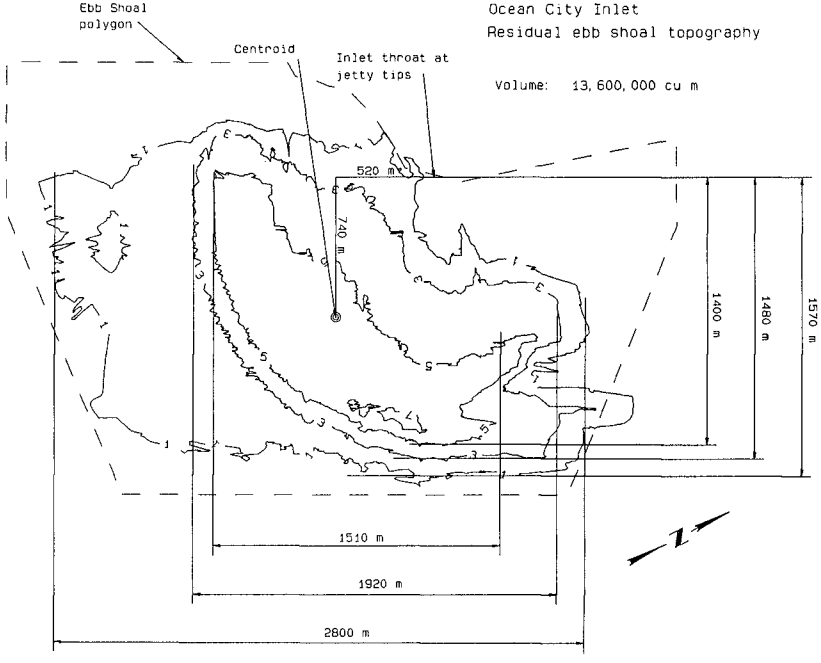

Figure 4. Ocean City Inlet residual ebb shoal topography and geometric attributes.

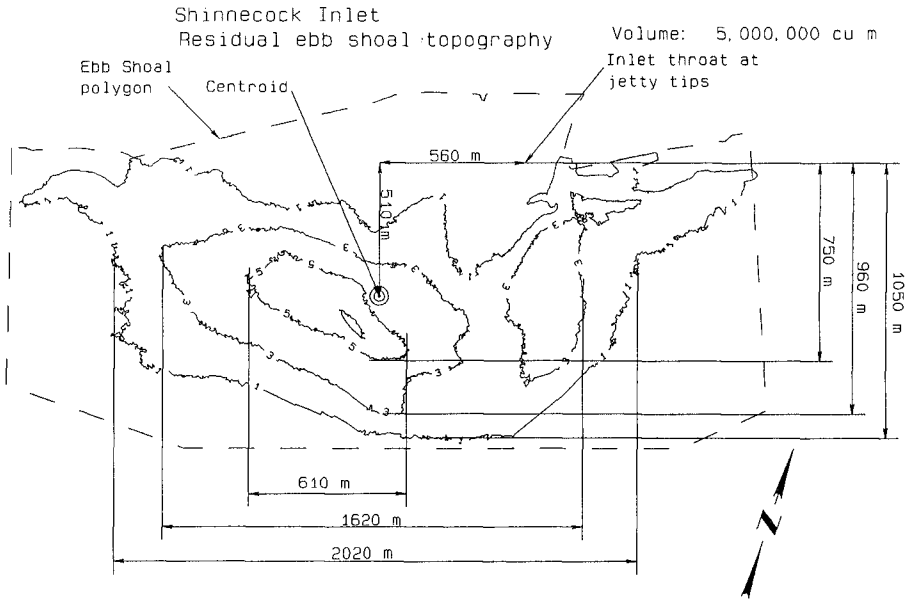

Figure 5. Shinnecock Inlet residual ebb shoal topography and geometric attributes.

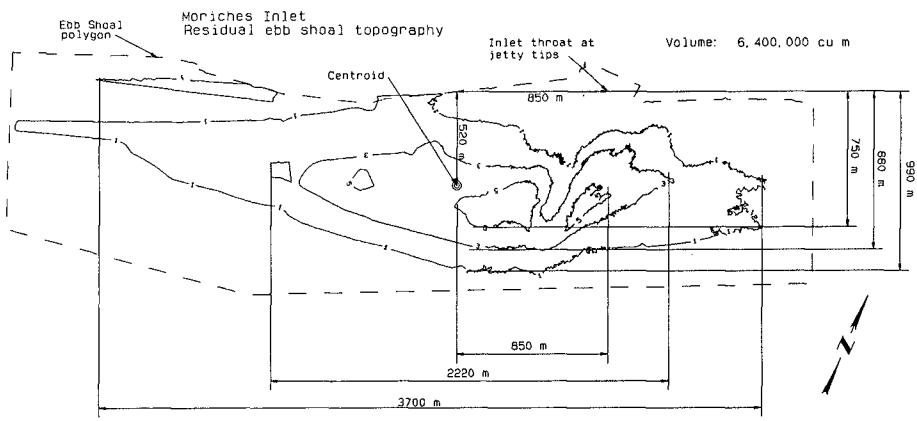

Figure 6. Moriches Inlet residual ebb shoal topography and geometric attributes.

of the numerical model from a philosophical and practical standpoint were documented. The characteristics of the inlet system for which the tool is expected to be applicable were identified. A conceptual model of inlet sediment bypassing consistent with the envisioned computational model and sediment budget methodology was presented. A recently proposed computational approach to modeling the behavior of inlet and adjacent beach systems that appears to satisfy many of the model requirements defined herein and, which we plan to extend through this research, was briefly reviewed. Procedures for characterizing the geometry of an inlet system were presented together with the application of those procedures to four inlet systems located along the central U.S. Atlantic coast.

Acknowledgments

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