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# Hydrodynamic Partitioning of a Mixed Energy Tidal Inlet

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**ABSTRACT**

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The inlet modeling system, developed by the U.S. Army Corps of Engineers Coastal Inlets Research Program, was used to investigate the intermittent movement of sediment throughout the Shinnecock Inlet ebb shoal complex. Circulation, sediment transport, and morphology change were calculated by a two-dimensional finite-difference model that was coupled with a steady state finite-difference model based on the wave action balance equation for computation of wave-driven currents. The inlet modeling system, forced with various combinations of incident waves and tide, was applied to three configurations of Shinnecock Inlet (13 August 1997, 28 May 1998, and 3 July 2000) to determine the distribution of hydrodynamic forces and investigate the dominant pattern of morphology change. This pattern was previously identified through principal component analysis of five scanning hydrographic operational airborne LIDAR (light detection and ranging) system surveys of Shinnecock Inlet from June 21, 1994, to July 3, 2000. The numerical simulations suggested these dominant variations in morphology could be generated through the integration of tidal transport, wave transport, and sediment movement associated with the deflection of the ebb jet by longshore currents. The ebb jet generated sand waves within the interior of the ebb shoal and supplied sediment to the most seaward regions of the system. Longshore currents induced by incident waves from the east and west quadrants redirected the tidal transport, resulting in a supply of sediment to the bypass and attachment bars. During less energetic incident wave conditions, both tide and wave patterns of transport coexisted and interacted, resulting in a broad range of morphologic features. As wave energy increased, the tidal transport pattern was overshadowed and morphology change was concentrated along the western barrier and bypass bars.

**ADDITIONAL INDEX WORDS:** *Inlets, modeling, morphology, sand waves.*

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## INTRODUCTION

Tidal inlets pose an interesting problem for numerical modelers. Inlets are under the influence of both incident wave forcing and tidal wave propagation. The relative strength of each factor will control the morphology and evolution of the inlet. This has long been recognized because inlets have been classified based on average significant wave height and tidal amplitude (HAYES, 1979). This classification categorizes inlets into tide-dominated, wave-dominated, and mixed energy regimes. For strong, tidally dominated inlets, wave processes may have a minimal impact on morphology and could potentially be ignored while still accounting for the general evolution of the system. For both wave-dominated and mixed energy regimes, incident wind wave forcing is considered a key process, and tidally driven transport cannot account for the transport pathways and evolution of inlet morphology in its entirety. Mixed energy barrier systems are found throughout the world. Some of the previously studied regions include the northeast coast of the United States, the East Friesian Islands of Germany, and the Copper River delta barriers of Alaska. Prediction of sediment transport around inlets within these systems requires a fully coupled, wave and tide modeling system. The inlet modeling system (IMS) developed by the U.S. Army Corps of Engineers (USACE) Coastal Inlets Research Program (CIRP) was applied to Shinnecock Inlet to quantify regions where transport and morphology change were dominated by the ebb tidal jet, wave-driven currents, or the complex interaction between incident wave field and tidal currents.

Shinnecock Inlet, a stabilized, mixed energy, wave-dominated inlet, is the easternmost of six permanent openings in the barrier island chain that runs along the south shore of Long Island, New York (Figure 1). The morphologic evolution of Shinnecock Inlet has been controlled by the natural migration and artificial realignment of the main navigation channel. Principal component analysis (PCA) of recent bathymetric surveys documented these trends (BUONAIUTO, BOKUNIEWICZ, and FITZGERALD, 2007). The analysis was advantageous because it provided an unbiased, quantitative identification of the most important changes within the inlet system for the period covered by the surveys. PCA distinguished structures within the data that explained the variance observed in the inlet system and identified three accreting features: (1) the eastern (updrift) bypass bar complex; (2) the western (downdrift) bypass bar; and (3) shore perpendicular bars along the western barrier (Figure 2). Bathymetry and wave analysis suggested that these features were formed un-

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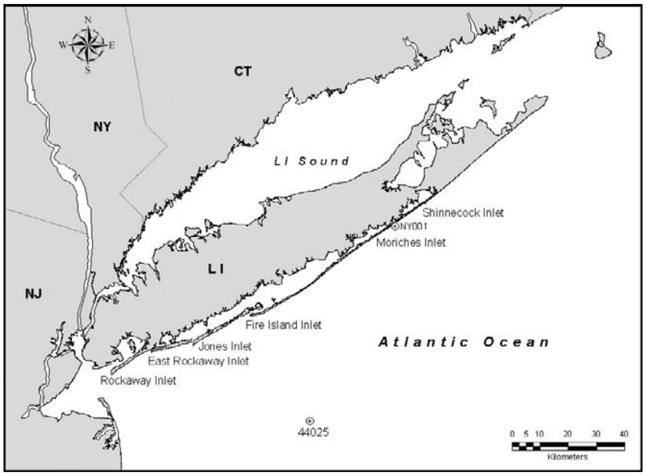


Figure 1. Map of Long Island indicating the locations of the six south shore inlets and National Data Buoy Center Station 44025. Shinnecock Inlet is the easternmost open ocean inlet.

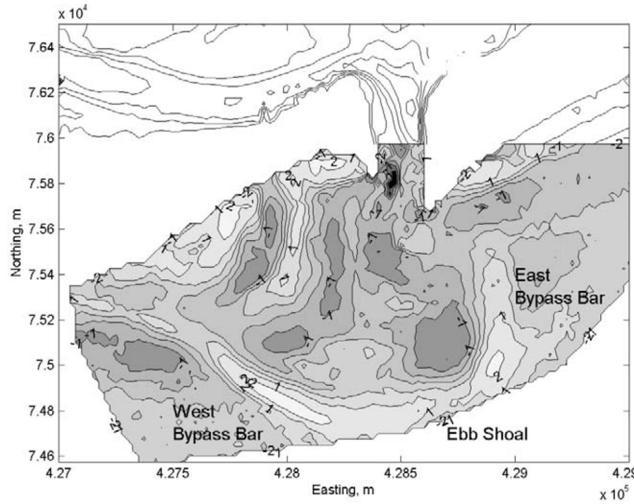


Figure 2. Patterns of sediment movement predicted by the first principal component. Morphology changes are reported in meters.

der different conditions. The eastern bypass bar complex results from the eastward deflection of the channel and erosion of the west side of the shoal by waves (Figure 3). Growth of the western bypass bar results from the westward deflection of the ebb jet and erosion of the eastern regions of the ebb shoal due to wave activity from the east. This is consistent with aerial photographs, which show features being formed and evolving due to the east- and west-shifting jet caused by channel orientation and wave interaction.

The most noticeable alterations in morphology, encompassed by the five scanning hydrographic operational airborne LIDAR (light detection and ranging) system (SHOALS) surveys, occurred during the 1997 to 1998 fall and winter season as increased transport and wave activity enhanced the natural westward migration of the main navigation channel (Figures 4a and b) (BUONAIUTO, BOKUNIEWICZ, and FITZGERALD, 2007). Channel reorientation potentially altered the transport conduits and delivery of sediment to the morphologic features that comprise the ebb shoal complex (Figure 3). The movement of sediment was further complicated by an increase in annual wave energy from the east associated with larger climatic cycles (BUONAIUTO and MILITELLO, 2003). The inlet channel was subsequently realigned through dredging in October 1998 (Figure 4c).

## BACKGROUND

Shinnecock Inlet was opened between the Atlantic Ocean and Shinnecock Bay during the Great New England Hurricane that crossed the island on 21 September 1938 (TANEY, 1961). Since its opening, inlet evolution has been influenced by storms, dredging, beach nourishment projects, and construction and rehabilitation of two offset rubble-mound jetties originally built between 1953 and 1954. The tide on the south shore of Long Island is semidiurnal with a mean range of 0.88 m at the ocean side of the inlet. The spring tide range is 1.1 m, and the most recent estimate of the tidal prism was $3.29 \times 10^7$ m$^3$ (MILITELLO and KRAUS, 2001). The open ocean ??2
coast of New York experiences both tropical (hurricanes) and extratropical (midlatitude cyclones) storm systems, which often produce large waves, beach erosion, and coastal flooding. Midlatitude cyclones drive the predominant westward transport and the winter evolution of barrier morphology along the south shore. The littoral system begins at Montauk Point and reaches a maximum rate of $4.60 \times 10^5$ m$^3$/y at Fire Island Inlet (KANA, 1995). Estimates of net westward transport across Shinnecock Inlet range between $1.04 \times 10^5$ m$^3$/y and $1.15 \times 10^5$ m$^3$/y (KANA, 1995; ROSATI, GRAVENS, and GRAY-SMITH, 1999). Seasonal wind reversals (west and southwest in the summer; TANEY, 1961), localize southwest wind swells, and hurricanes can induce short-term reversals in littoral transport along the eastern half of Long Island. Prior to stabilization, orientation of the main ebb channel was closely

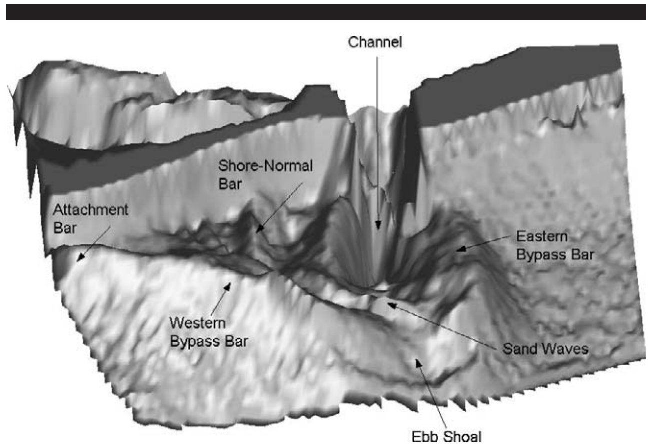


Figure 3. Shinnecock Inlet ebb shoal complex on 3 July 2000. The photograph illustrates the basic morphologic features referred to in the text. Northings, eastings, and depths are reported in meters.

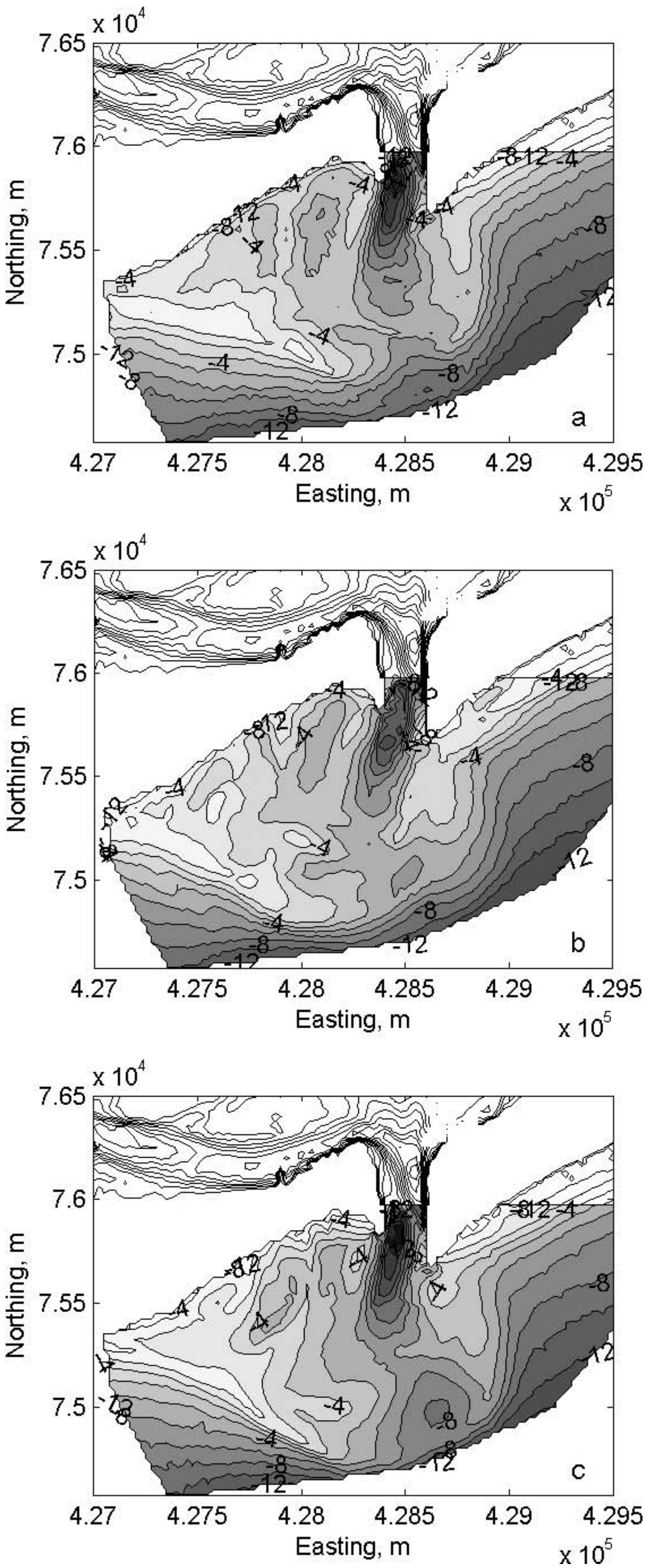


Figure 4. Contoured bathymetry data obtained by USACE SHOALS surveys. Shaded, filled contours represent regional extent of the principal component analysis. Inlet configurations correspond to (a) 13 August 1997; (b) 28 May 1998; and (c) 3 July 2000. Depths are reported in meters.

related to incident wave energy. Because the channel migrated in response to the dominant littoral transport direction and changing wave climate, various sediment bodies experienced active deposition. Once the throat was stabilized with jetties, the inner channel became fixed and did not change orientation. However, the outer channel continued to migrate downdrift (westward) due to the preferential supply of sediment from the dominant westerly sand transport regime. Periodically the channel is reoriented through dredging to provide safer passage between Shinnecock Bay and the Atlantic Ocean. A previous investigation (BUONAIUTO, BOKUNIEWICZ, and FITZGERALD, 2007) suggested natural sediment bypassing at Shinnecock Inlet may be occurring through migration and bifurcation of the outer main channel, a conceptual bypassing model for partially engineered systems proposed by FITZGERALD, KRAUS, and HANDS (2001). This process has been observed at Moriches Inlet (Figure 1).

The complex interaction between tide- and wave-driven currents at Shinnecock Inlet makes it difficult to determine the principal factors controlling transport of sediment across the inlet and to the various sand features that construct the ebb shoal system (Figure 3). The relative importance of each hydrodynamic factor varies both temporally and spatially across the inlet region. Further complication is introduced because the morphologic features that comprise the ebb shoal respond differently to changes in the hydrodynamic regime. The ebb shoal proper responds directly to channel position and direction of the ebb jet (Figure 3). Changes to the bypass bar and attachment point appear to be a function of the availability of littoral transport material, which would be directly controlled by the incident wave regime at some times and, at other times, by the redirection of the ebb jet by longshore currents. In wave-sheltered regions of the ebb shoal, it is more difficult to discern the controlling factors. Initial numerical simulations presented in this paper suggest the pattern of bathymetry change observed in this region must be the result of an interaction of the wave regime, tidal jet, and position of the main navigation channel.

## MODELING APPROACH

Numerical modeling applied to inlets must include three main processes: (1) tide-driven currents; (2) wave-driven currents; and (3) sediment transport arising from both tide and wave current interactions along the sea bed. The interactions among these three main processes are dynamic because changes in the seabed arising from convergence and divergence in sediment transport concentrations will alter the overlying tidal currents and wave transformation processes. In this application, wave-driven currents are directly linked to tidal currents through the inclusion of stress terms in the momentum equation that exhibit both spatial and temporal variations in magnitude and relative dominance of the momentum equations. ??3

The IMS was used to simulate these processes at Shinnecock Inlet and partition the ebb shoal based on various combinations of hydrodynamic forces. The IMS consists of a suite of models implemented within the surface water modeling system (ZUNDEL, 2000) and designed to compute tidal hydrodynamics, wave transformation, sediment transport, and ??4 morphology change. Models can be coupled for specific application requirements. For this investigation, water-surface elevations and current velocities were computed by a localized two-dimensional, depth-integrated, hydrodynamic model (M2D) developed for shallow water regions (Militello, Reed, and Zundel, 2003). M2D solves finite-difference approximations of the nonlinear equations of mass and momentum conservation on a variably spaced rectilinear grid. Advection, mixing, quadratic friction, flooding and drying, and wind speed dependent wind drag coefficients are represented in the model. In addition, the M2D momentum equations account for stresses applied to the fluid resulting from incident wave transformation and breaking processes.

Table 1. *Simulation forcing conditions.*

| $H$ (m) | $T$ (s) | $\alpha$ (°) | Comments |
|---|---|---|---|
| 0 | 0 | 0 | Representative tide, no incident waves |
| 0 | 0 | 0 | Spring tide, no incident waves |
| 3 | 9.5 | 101 | East-southeast incident waves, representative tide |
| 1.6 | 7 | 101 | East-southeast incident waves, representative tide |
| 1.26 | 9 | 146 | South-southeast, incident waves, representative tide |
| 2 | 11 | 146 | South-southeast, incident waves, representative tide |
| 2.4 | 7 | 213 | Southwest, incident waves, representative tide |

Spatial and temporal variations in the incident wave field were computed using STWAVE, a steady state finite-difference model based on the wave action balance equation ??5 (Smith, Sherlock, and Resio, 2000). The model simulates depth- and current-induced wave refraction and shoaling, depth- and steepness-induced wave breaking, wave growth due to local wind stress, and wave-wave interactions and white capping. STWAVE operates on a user-defined spectrum represented as a linear superposition of monochromatic waves. M2D and STWAVE were coupled for calculation of wave-driven currents. Radiation stress gradients calculated by STWAVE were passed to M2D and incorporated into the equations of motion. M2D-simulated water surface elevations were then mapped back to STWAVE, enabling the incorporation of both tides and setup and setdown into wave transformations.

The coupled wave and tide model was linked with a sediment transport and morphology change module. The sediment transport equation used for this investigation was a form of the Watanabe (1992) formulation. The Watanabe model is a total load formulation, which can incorporate forcing from both waves and tides calculated by M2D and STWAVE. The influence of waves and tides enter the equation through both the current velocity and the calculation of bed shear stress. For this investigation, the sediment in the inlet was considered to be homogeneous medium sand (0.35 mm), and the bottom shear stress was derived from the local Reynolds number. Through mass conservation, the bathymetry was updated giving the morphology change of the inlet, shoals, and nearshore region.

The IMS was applied to Shinnecock Inlet under various combinations of wave and tidal forcing in order to determine the processes responsible for the variability pattern depicted by the first principal component (Figure 2), mainly growth and migration of east and west bypass bars, shifting channel orientation, and enhancement of sandbar features perpendicular to the western barrier. Model simulations ranged in duration from 2 to 16 days. Hydrodynamics were calculated at 0.5-s time steps, morphology was updated every 100 s, and steady state wave conditions were determined at 3-h intervals. Patterns of change in morphology at the end of the simulations were then compared to the long-term morphologic changes described in the PCA. Bathymetric changes were modeled on three inlet configurations defined by LIDAR surveys on 13 August 1997, 28 May 1998, and 3 July 2000 (Figure 4). These configurations were selected because they encompass the period of natural channel migration and realignment through dredging (13 August 1997 and 3 July 2000), and represent the maximum extent of westward deflection of the channel axis (28 May 1998). The actual region of influence determined by the model is a combination of the three simulated transport patterns. The main channel within the inlet throat is heavily armored with marine encrusted gravel (Morang, 1999). Because the sediment transport algorithm could not simulate movement of multiple grain sizes, calculations were terminated at the mouth.

Both M2D and STWAVE computational grids cover all of Shinnecock Bay and extend up- and downdrift of the inlet to regions unaffected by the ebb tidal shoal. The seaward boundaries extended offshore to 30-m water depths, which are well beyond the wave shoaling zone, closure depth, and farthest reach of the ebb jet. The STWAVE grid was constructed using 10-m intervals across the entire domain. The M2D grid utilized variable finite-difference grid spacing to reduce computation time. In deeper offshore waters, grid nodes are 100 m apart. Along the coastline, inside the shoaling zone, and around the flood and ebb shoals and inlet throat where there is rapid wave transformation and a desire for increased resolution, the grid interval approaches 10 m. Bathymetry data, constructed from NOS (National Ocean Service) and SHOALS surveys, was linearly interpolated onto the numerical grids for each of the three inlet configurations. NOS hy- ??6 drographic surveys were used to describe those regions not surveyed by SHOALS around the inlet and ebb shoals; however, the analysis was limited to the extent of the three high-resolution LIDAR surveys. ??7

M2D was forced using sea surface elevations along the seaward boundary, Shinnecock Canal and Quogue Canal. These water levels were extracted from the U.S. Army CORPS regional tidal model of Long Island (Militello and Kraus, 2003). Seven simulations forced with various incident wave fields and tides (Table 1) were conducted for each of the three SHOALS-bathymetry model grids (13 August 1997, 28 May 1998, and 3 July 2000). Hydrodynamics and sediment transport patterns were first calculated for mean and spring tidal conditions prior to inclusion of forcing from varying incident wave regimes. Wave heights ($H$), periods ($T$), and directions ($\alpha$) were changed in order to understand the relative importance of each on the developing inlet morphology. Representative incident wave conditions were selected based on a previous analysis of buoy data collected off the coast of Fire Island Inlet and West Hampton Beach (Figure 1). Simulated incident wave fields are indicated in Table 1. By convention, wave angles indicate the direction from which waves propagate relative to north. Of the five wave forced simulations, two utilized waves from the east-southeast, two involved waves more normal to the south shore of Long Island (south-southeast), and one was forced with large southwest incident waves. For both the south-southeast and east-southeast wave simulations, the incident angle was held constant and two combinations of height and period were used to represent mean and peak high-wave energy conditions. The steep southwest incident wave field, which was observed in the buoy data, was chosen to illustrate the periodic reversals in transport around Shinnecock Inlet.

## RESULTS

### Tidal Simulation

M2D was validated, without wave forcing, using 16 days worth of field measurements collected in November 1998 as part of a field-monitoring system sponsored by the USACE New York District, the CIRP, and the New York State Department of Environmental Conservation (BUONAIUTO and MILITELLO, 2003). During this period, transport was dominated by tidal forcing, and daily averaged incident wave
??8 heights rarely exceeded 0.5 m. M2D-predicted current fields and water levels simulated on the 28 May 1998 bathymetry grid were compared to data collected at seven sites throughout Shinnecock Bay and Inlet and velocity fields simulated by the regional tidal model of Long Island. Sixteen-day experiments were also run for the bathymetry grids of 13 August 1997 and 3 July 2000. Simulated transport patterns and morphology change derived entirely from tidal currents were documented, and the regional influence of both average and spring tidal forcing was delineated.

For all three simulations, velocities in the throat reached magnitudes approaching 2 m/s. During ebb flows, two gyres were formed on either side of the jet. The western gyre rotated clockwise and persisted until the end of slack water. The eastern updrift gyre, which persisted through much of the flood cycle, rotated counterclockwise and migrated westward with the passage of the tidal wave, partially deflecting the ebb jet to the west, a process previously documented by MILITELLO and KRAUS (2001). The western gyre also migrated westward along the coast, becoming trapped between the ebb jet and the bypass bar.

In general, transport for the inlet driven by the tidal oscillation is relegated to the regions under the direct influence of the ebb jet (Figure 5). Scour was predicted at the seaward ends of both the east and west jetties associated with the formation of the two gyres on either side of the jet. The ebb jet broadens as it moves offshore, which is also reflected in the transport pattern. Transport rates are greatest upon exiting the inlet throat where current velocities are large. The transport rates are less in the offshore region where the jet broadens and tidal velocities decrease. Sediment transported by the ebb jet appeared to move as rhythmic sand waves (Fig-

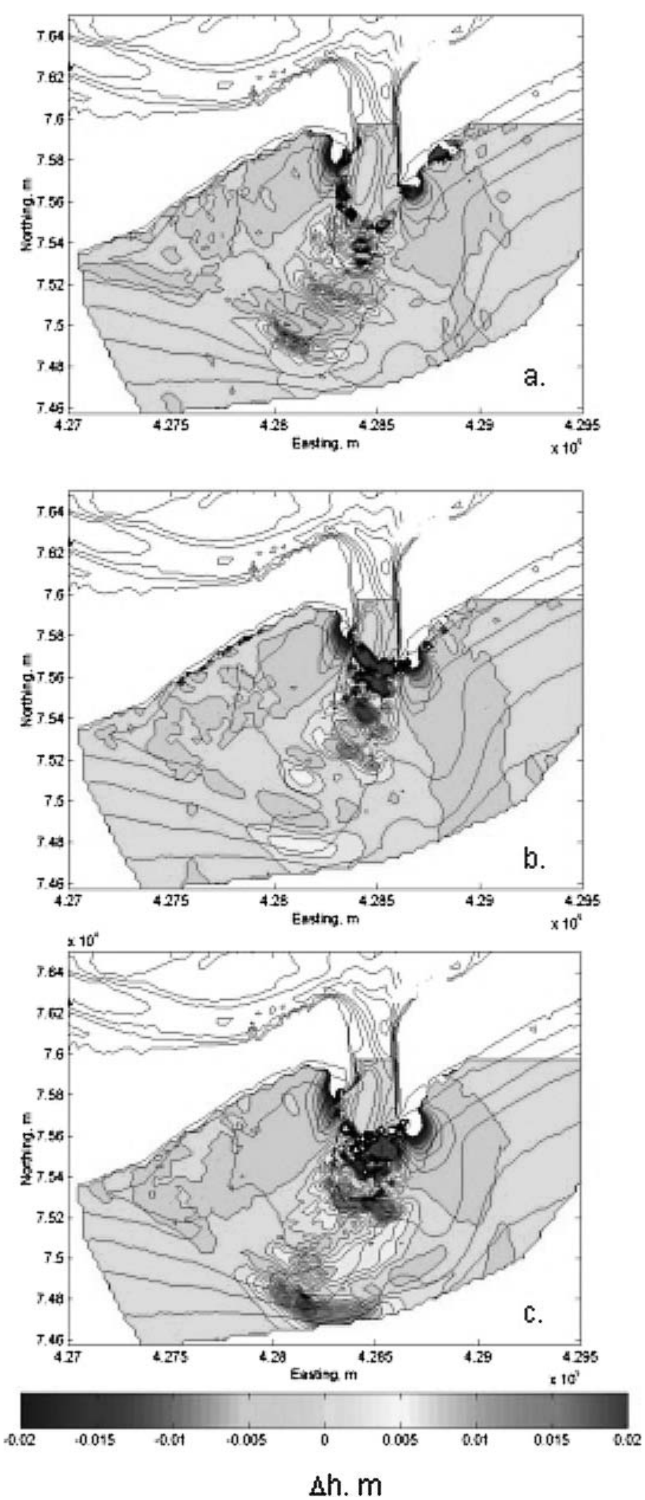


Figure 5. Tidal simulation depth change for 1997, 1998, and 2000 inlet surveys. Region of significant transport is restricted to the fan of the ebb jet. General pattern indicates rhythmic bar movement in the vicinity of the ebb jet and scour at the jetty terminals.

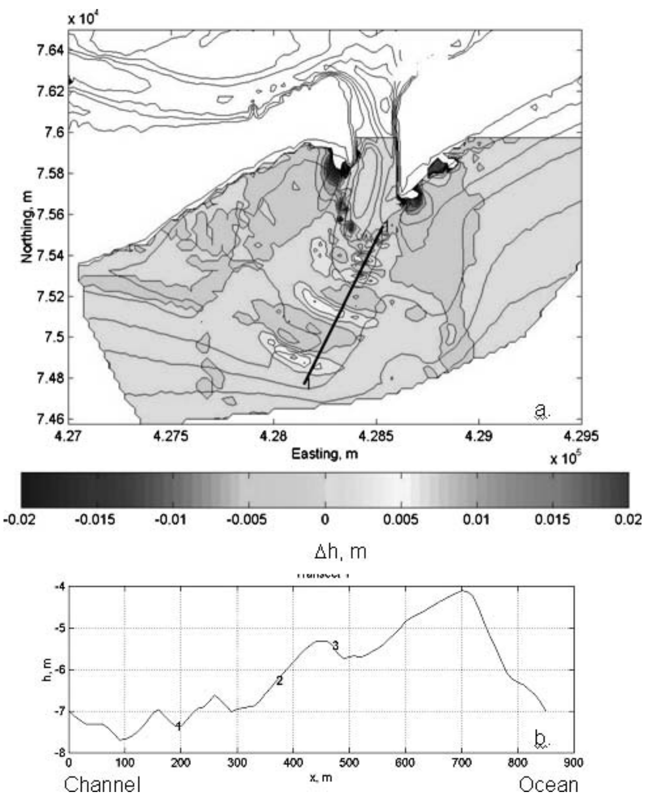


Figure 6. Location of bathymetric transect constructed perpendicular to sand waves for the 13 August 1997 simulation.

ure 5), having lengths on the order of 100 m and heights ranging between 0.5 and 1 m.

In order to analyze the development and migration of these features, time series of bathymetry and fluid velocity were constructed along a transect perpendicular to the sand waves ??9 (Figure 6a) for the 13 August 1997 simulation. The transect begins along the east side of the channel and is directed toward the southwest over the ebb shoal running parallel with the ebb jet. Depths were linearly interpolated each hour at a 10-m interval. The interpolated morphology indicated the sand waves were present in the initial bathymetry and were ebb oriented with the steep face toward the Atlantic Ocean, indicating they were created or modified by the ebb currents (Figure 6b). The time series of fluid velocity indicated maximum ebb velocities reached magnitudes of 0.73 m/s along transect whereas maximum flood velocities were approximately 0.3 m/s. In addition, modeled changes in morphology were greatest during the ebb stage of the tidal cycle. Ebb currents removed sediment from the shoreward face of the bedforms and deposited it on the seaward (steep) face. Some of the deposited sediment was remobilized during the flooding stage of the tidal cycle and placed back onto the shoreward face of the sand waves, but overall there was a net seaward movement of the features.

Aside from the ebb jet, transport along the ebb shoal was minimal. The 3 July 2000 simulation indicated a broader area of ebb jet influence with the sand waves aligned more in the direction of the throat (Figure 5c). In addition, a great- ??10 er quantity of sediment appeared to be delivered to the periphery of the ebb shoal when compared to transport patterns predicted by the 13 August 1997 (Figure 5a) and 28 May 1998 (Figure 5b) simulations. The 13 August 1997 simulated morphology changes shifted toward the western bypass bar, whereas, the 28 May 1998 predicted changes in morphology were dominated around the mouth of the inlet where the eastern bypass bar had extended into the channel. During spring tide cycles, sediment was transported and deposited off the edge of the ebb shoal, beyond the SHOALS surveyed region of the inlet for both 13 August 1997 and 3 July 2000 simulations.

## South-Southeast Wave Simulations

Two simulations were conducted for each of the three inlet configurations, forced by a representative tide and incident waves from the south-southeast (146°). The two incident wave fields chosen consisted of: (1) a wave height of 1.26 m and a period of 9 s, and (2) a wave height of 2 m and a period of 11 s (Table 1). In general, simulations involving low to moderate incident wave energy from the south-southeast resulted in a westward deflection of the tidal transport pattern (Figure 7). Deposition at the edge of the ebb shoal from the ebb tidal jet was still prominent but deflected to the west more in accord with the first principal component (Figure 2). Sand waves within the interior of the ebb shoal were less prominent than in the case of tides alone, and sand eroded from the updrift bypass bar was compensated for by sand deposited along the eastern side of channel. Scour was evident along the east and west jetties, and for the simulation based on the bathymetry of 3 July 2000, sandbars seaward of the western barrier appeared to migrate offshore. The simulations indicated substantial transport along the western barrier between the inlet and the attachment bar. Overall, sediment was removed at the shoreline with reworking and deposition as small pocket bars just offshore. There is a westward migration of the attachment bar and a seaward advancement of the western bypass bar. When the modeling system was forced with the more energetic incident wave field (height of 2m and period of 11 s), wave-driven transport began to dominate (Figure 7b). Deposition on the crest of the bypass bar intensified, and substantial erosion was evident along the eastern flank of the shoal. This material was transported and deposited in the interior of the ebb shoal west of the channel.

## East-Southeast Wave Simulations

In order to investigate the natural deflection and migration of the main navigation channel across the ebb shoal, which occurred between the 13 August 1997 and 28 May 1998 surveys, the IMS was applied to each inlet configuration using east-southeast incident wave forcing. During this period, the continuous westward movement of the outer reaches of the channel associated with tidal eddies (Militello and Kraus, 2001b) was enhanced by an increase in wave energy from the east. The peak incident wave conditions between these two

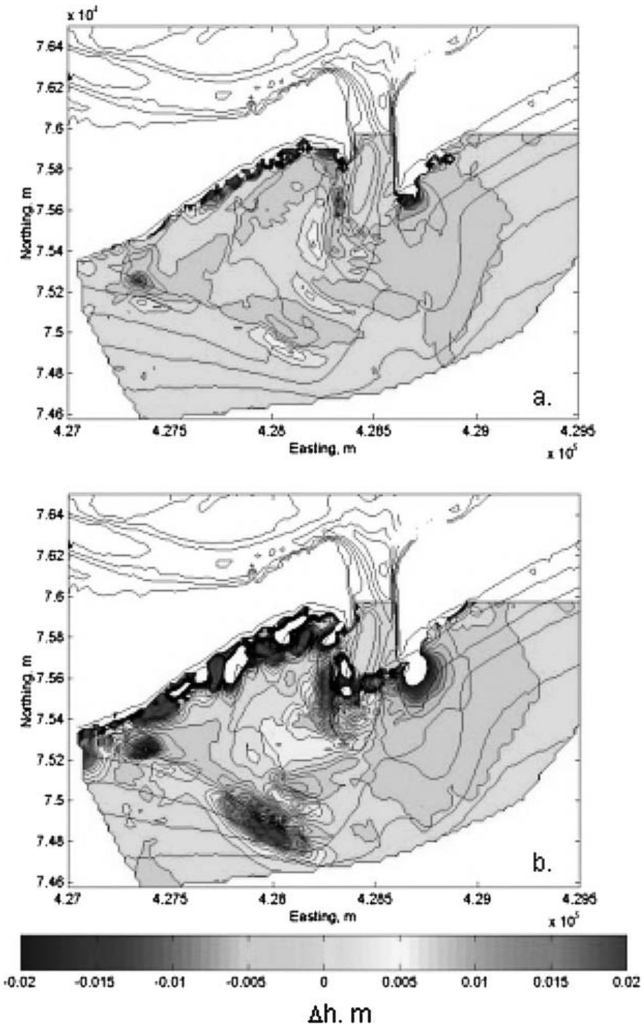


Figure 7. Calculated morphology change for the 13 August 1997 simulations. Incident waves are from the southeast consisting of (a) a height of 1.26 m and period of 9 s, and (b) of a height of 2 m and period of 11 s.

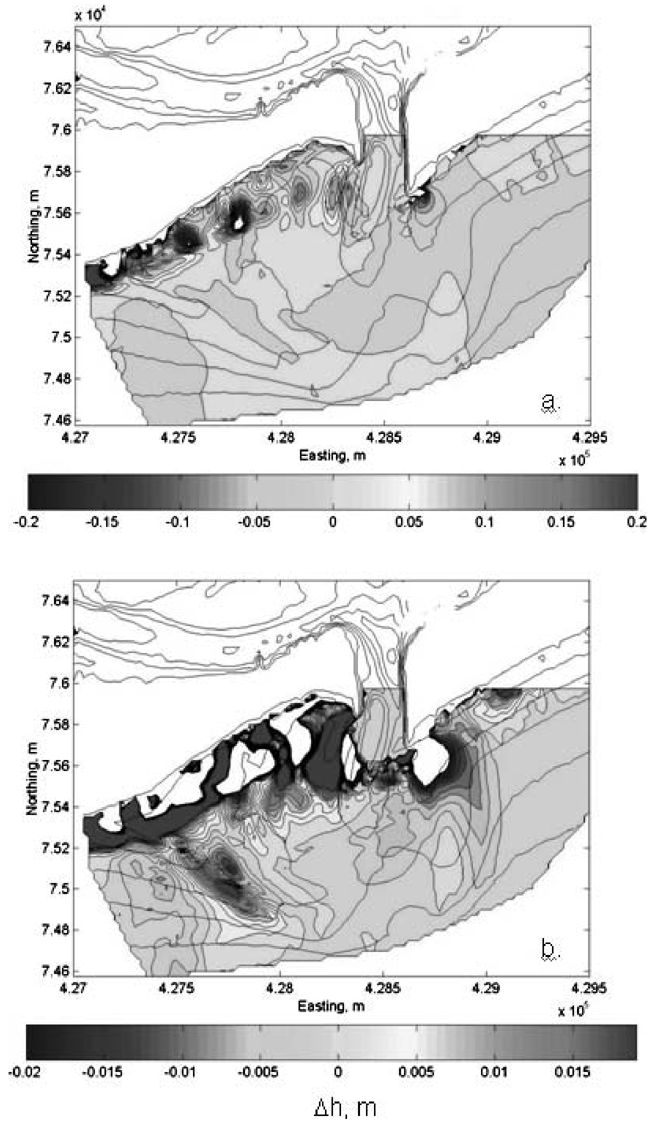


Figure 8. Calculated morphology change for the 3 July 2000 simulations. Incident waves are from the east-southeast consisting of a height of 3.0 m and period of 9.5 s. Two maps of morphology change were necessary to illustrate the various scales of change predicted by the model.

surveys, determined in a previous analysis of local buoy data, consisted of a height of 3 m, period of 9 s, and incident wave angle of 101° with respect to north. The mean incident wave field for this period was composed of a height of 1.6 m and a period of 7 s. Each of these wave fields were propagated across the three inlet configurations during representative tidal conditions (Table 1). These large, long-period waves generated strong longshore currents in the surf zone and resulted in the deflection of the main ebb jet toward the west. The simulated changes in morphology consisted of erosion of the eastern portion of the ebb shoal because it is in the direct path of wave attack (Figure 8). Sediment appeared to be deposited in the main channel even though a great deal bypassed to the downdrift beach and was deposited in large bar formations that extend from the shoreline. The bypass bar in both simulations eroded along the crest as it was scoured from wave-generated currents that were directed westward. Changes in morphology were contoured using two scales in order to visually enhance the magnitudes of change associated with the ebb tidal jet. The deflected ebb jet pushed the sand wave transport pattern to the west, supplying sediment to the wave-shadowed regions along the western barrier (Figure 8b). Some of this material was incorporated into the large, shore perpendicular bar formations.

## Southwest Wave Simulations

The net direction of littoral transport is from east to west along the coast of Long Island. Periodically there will be reversals in transport as waves approach the coast from the south and southwest, caused by the prevailing winds during late spring and summer and by conditions just after the pas-

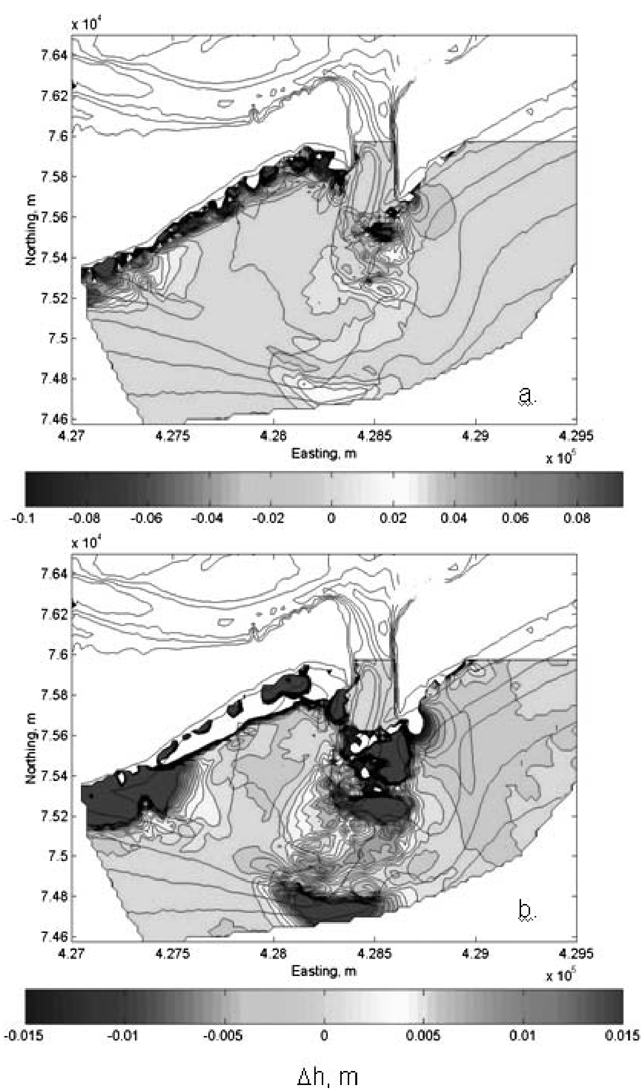


Figure 9. Calculated morphology change for the 3 July 2000 simulations. Incident waves are from the southwest consisting of a height of 2.5 m and period of 7.0 s. Two maps of morphology change were necessary to illustrate the various scales of change predicted by the model.

sage of hurricanes (BUONAIUTO, BOKUNIEWICZ, and FITZGERALD, 2007). In order to investigate changes in ebb shoal morphology arising from reversal events, a representative southwest incident wave field experiment was conducted. The incident wave field, which was propagated across each inlet configuration during representative tidal conditions, consisted of a height of 2.4 m, a period of 7 s, and an angle of 213° relative to north (Table 1). Under these conditions, the simulated changes in inlet morphology were focused along the western barrier and in the region associated with the shore perpendicular bars (Figure 9). Sediment was deposited on the attachment point. Such conditions exert a strong influence on the growth of the attachment point and reinforce the rhythmic deposition at the shoreline between the attachment point and the inlet influencing the shore perpendicular bars. The source of the deposits along the western barrier appeared to be bars seaward of the deposition zone (Figure 9a). Sediment was also deposited as a spit extending from the western jetty. The rhythmic bedforms generated by the tide persisted in each simulation; however, their axes were shifted toward the east. The eastward shift was most ??11 noticeable in the simulation based on the bathymetry of 3 July 2000 because sediment was deposited along the east bank of the channel (Figure 9b) as a result of the partial deflection of ebb jet by wave-driven currents. In addition, some of the material eroded from offshore bars along the western barrier may have been deposited in the main ebb channel as evident in Figure 9b.

## DISCUSSION

The evolution of morphology is a continuous dynamic process in which bed forms and undulations interact with the overlain current to further evolve their structure. Small bar formations migrate and coalesce into larger complexes over the course of several months to years. For many inlets, migration of these larger complexes accounts for the majority of sediment bypassing (FITZGERALD, 1996). These small bar features may also be destroyed or absorbed into larger morphologic entities such as the attachment point, bypass bar, ebb shoal proper, or shore perpendicular bars. The simulations conducted during this investigation could represent the formation and movement of small bar complexes and large bedforms (sand waves); however, the migration, coalescing, and long-term evolution could not be reproduced simply because of the duration of the experiments and limited representation of forcing functions. The pattern predicted by the PCA is the long-term result of these bar migration and coalescing processes. Future investigations will involve modeling the entire period from 13 August 1997 through 3 July 2000 and comparing the morphology change with the first principal component. For this study, PCA was advantageous because it provided an unbiased and quantitative determination of the most predominant changes in the configuration of Shinnecock Inlet. PCA determined the spatial relationship between the morphologic forms, and the IMS was used to illuminate the intermittent movement of sediment around the system. Combined with knowledge of inlet processes, a theoretical explanation of the behavior and development of Shinnecock Inlet was constructed.

The seaward advancement of the ebb shoal and bypass bar were found to be due to the positions of the main channel and ebb jet. Even though the main channel and location of the ebb jet are interrelated, the migration of the main channel is, of course, not instantaneous. It requires time for the deposition of a sufficient volume of sediment, either as individual sand grains or larger bar formations, along the updrift flank. The deflection of the ebb jet, however, is more frequent and instantaneous. It can be attributed to migrating tidal eddies and longshore currents during periods of intense wave activity. Sediment is transported by the ebb jet in the form of rhythmic sand waves, which migrate seaward, gradually extending the toe of the ebb shoal. Sand waves have been documented in other inlet navigation channels, including the

Columbia River (Washington/Oregon); East Pass, Panama City, Fort Pierce, and St. Marys Entrance (Florida); Merrimack River (Massachusetts); and Kennebec River (Maine) (WHITMEYER and FITZGERALD, 2006). These features are often considered navigation hazard if they extend 1 m or higher above the channel floor (ASHLEY, 1990; BOOTHROYD and HUBBARD, 1974; POPE, 2000).

In all of the tidal simulations, the accumulation of sand at the seaward margin of the shoal was similar to that seen in the first principal component. However, in the first principal component, the depositional region (coinciding with the western bypass bar) was shifted slightly to the west, potentially indicating the deflection of the ebb jet by incident waves from the southeast. In addition, the sand wave pattern closer to the inlet was only very weakly present. Simulations involving high incident wave forcing from the south-southeast and east-southeast initiated the removal or obliteration of sand waves over the shoal just outside the inlet. However, these same wave conditions did produce strong, rhythmic depositional areas subparallel to the shoreline between the inlet and the western attachment bar, reminiscent of the shore perpendicular bars.

During periods of mild wave activity, transport patterns caused by the ebbing tide dominate morphology changes along the shoal. When the channel was aligned with the inlet throat, sediment was supplied to the ebb shoal proper. For example, the 3 July 2000 tidal simulation indicated that the inlet was delivering sediment to the periphery of the ebb shoal and was more efficient at transporting sediment offshore than either the 13 August 1997 or 28 May 1998 configurations. When the channel position was oriented to the west, sand is transported to the western bypass bar, as indicated by the 13 August 1997 simulation. Prolonged periods of wave activity from the east initiate channel migration; sediment was deposited along the eastern flank of the channel because the deflected ebb jet was no longer in position to scour the channel clean. This situation was illustrated during the 28 May 1998 simulation. Sediment supply to the periphery of the ebb shoal was reduced and morphology changes were concentrated around the mouth of the inlet where an eastern bar complex impinged on the channel.

The deflection of the ebb jet by longshore currents was a frequent process. Incident waves from the east shifted the tidal transport pattern westward. This supplied sand to the western bypass bar and attachment bar and created rhythmic sand features along the western barrier. Historically, three shore perpendicular bars tend to be found in this region, which are identifiable on some of the earliest photographs of Shinnecock Inlet (BUONAIUTO, BOKUNIEWICZ, and FITZGERALD, 2007; MORANG, 1999). Our simulations suggest that these perpendicular bars may be formed, or, at least, enhanced, by flow convergence as wave refraction along the bypass bar and attachment bar generate eastward flowing currents that converge with tidal eddies west of the inlet. The ebb jet can also be deflected toward the east during periods of waves from the south and southwest. Such events supplied sediment to the eastern bypass bar and the channel-flanking shoal extending from the west jetty. Typically south and southwest wave events are usually of a duration too short to result in the eastward migration of the channel.

## CONCLUSIONS

The integration of all the transport patterns derived from various combinations of incident wave conditions and tide construct the broad range of sand features of the Shinnecock Inlet ebb shoal. The IMS is capable of representing the intermittent movement of sediment between the morphologic features that comprise the Shinnecock Inlet ebb shoal system; however, neither waves nor tides alone will account for the principal changes in morphology. Deflection of the tidal jet by waves is required. Features in different regions of the ebb shoal complex, however, seem to be formed by different, specific combinations of hydrodynamic forces. The ebb shoal proper responds directly to channel position and direction of the ebb jet. Changes to the bypass bars and attachment point appear to be a function of the availability of littoral transport material, which is influenced by both the incident wave regime and the redirection of the ebb jet, either to the east or west, by wave-generated longshore currents. Along the western barrier, in wave-sheltered regions of the ebb shoal, the pattern of bathymetry change is the result of an interaction of the wave regime, tidal jet, and position of the main navigation channel. Because of the length of time required to transform the morphology of mixed energy inlets under any particular condition, some features are inactive and relict while others are being formed or modified. Therefore, the evolution of the morphology, recycling of sediment within the ebb shoal system, and transport of sand across the inlet (bypassing) are strongly dependant on the sequencing of wave and tide forcing.

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