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Reservoir Model for Calculating Natural Sand Bypassing and Change in Volume of Ebb-Tidal Shoals, Part I: Description

by Nicholas C. Kraus

PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) herein provides information on a mathematical model developed to calculate natural sand bypassing and change in volume of ebb-tidal shoals. Subsequent CHETN's in this series will describe the interface and generalizations of the model to cover flood-tidal shoals, inlet-entrance channel, and other morphologic features at inlets.

BACKGROUND: An inlet is an opening through a landmass that hydraulically connects a large body of water such as an ocean or sea to a smaller body of water such as a bay or lagoon. The ebb and flood currents generated by the tide (or by seicheing in the case of large lakes and inland seas) redistribute sediment transported toward the inlet channel by the wave-generated longshore current. The dynamic balance of the various sediment-transporting mechanisms creates morphologic features such as shown for in Figure 1 for Shinnecock Inlet, on Long Island, NY. The picture was taken on a calm day, and the various sand bodies around the inlet can be seen through the water. Interpreted sediment-transport pathways among the sand bodies or morphologic features are drawn in Figure 2.

On this coast, longshore transport is directed strongly to the west (to the left in Figure 2). Sediment (predominantly sand) moving to the west reaches the updrift attachment bar (labeled "A. Bar") and can deposit on the shore, move into the inlet channel, or move out onto the updrift bypassing bar. Attachment bars (also called weldment or tie-in areas) typically protrude from the shore and connect the bypassing bars to the beach. If sand moves into the channel, it can either remain there, possibly to be dredged, or be transported by the tidal current to the ebb shoal or the flood shoal. Bypassing bars connect the attachment bars to the ebb shoal and are created primarily by wave action and wave-induced currents. Sand moving from the bypassing bar can reach the ebb shoal, from where it can stay on the shoal, move offshore, move into the channel, or continue bypassing the inlet and go to the downdrift bypassing bar. From the downdrift bypassing bar, transported sand can continue on the large downdrift attachment bar and to the beaches on either side of it. Typically, sand transported alongshore reaches the inlet channel, from where it is jetted toward the flood shoal or the ebb shoal by the tidal current.

As seen in Figure 2, it is possible that sand can move cyclically around the inlet, such as back and forth between the flood and ebb shoals via the channel or around the ebb shoal, downdrift bypassing bar, beach, channel, and back to the ebb shoal. Ebb shoals store sand and serve as a conduit for sand bypassing around inlets. Bypassing to the downdrift beach occurs according to the state of maturity of the shoal, wave conditions, magnitude of the tidal prism, and other factors. Not all inlets bypass sand as described for Shinnecock Inlet. FitzGerald, Kraus, and Hands (2001) describe other morphologic types of inlets and bypassing mechanisms. Recently, Gaudio and Kana (2001) quantified bypassing at inlets in South Carolina that tend to move

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sand around them in discrete events once every several years, rather than continuously. Carr and Kraus (2001) describe asymmetries in inlet morphology based upon the nomenclature given in the present CHETN. Kraus (1998) develops a model for the minimum inlet channel cross section based upon a balance between sand brought to an inlet by the longshore transport and the scouring action of the tide.

This CHETN presents a simple model developed to describe growth of tidal inlet features and natural sand bypassing based upon knowledge typically available to or estimated by the coastal engineer. Continuous bypassing is assumed.

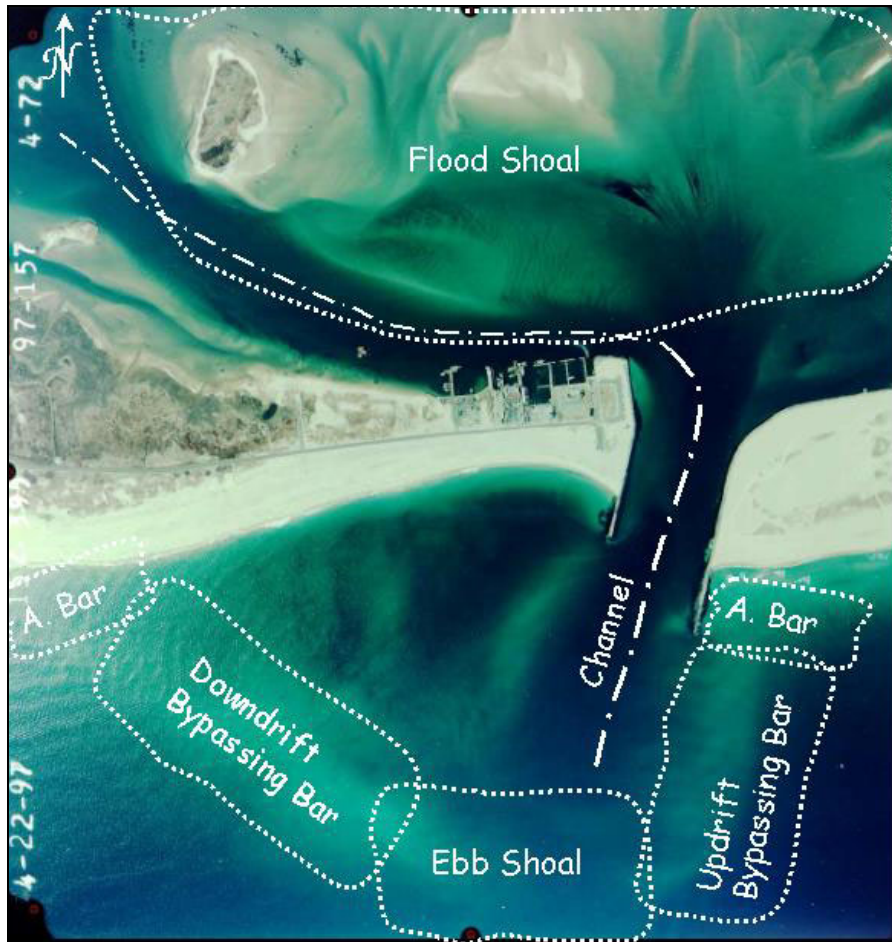


Figure 1. Morphologic features at Shinnecock Inlet



Figure 2. Sediment-transport pathways at Shinnecock Inlet

RESERVOIR MODEL: The reservoir model is based on the conservation of sand volume, ability of the engineer to identify sediment pathways, existence of an equilibrium volume of morphologic features, and a “reservoir assumption” that is described in the following paragraphs. Bypassing bars grow in the direction of predominant transport, similar to growth of a spit. At inlets with left- and right-directed longshore transport or with a small tidal prism, two large bypassing bars can emerge from the ebb shoal, creating a nearly concentric halo about the inlet entrance. As the bypassing bar merges with the shore, an attachment bar is created, thereby transporting sand to the beach. At this point in evolution of the ebb-shoal complex, substantial bypassing of sand can occur.

Inlet Morphology and Pathways: The ebb-shoal complex is defined as consisting of the ebb shoal proper, one or two ebb-shoal bypassing bars (depending on the balance between left- and right-directed longshore transport), and one or two attachment bars. These features are shown schematically in Figure 3. The model distinguishes between the ebb-tidal shoal proper (hereafter, ebb shoal), typically located in the confine of the ebb-tidal jet, and the ebb-shoal bypassing bar (hereafter, bypassing bar) that grows toward shore from the ebb shoal, principally by the transport of sediment alongshore by wave action. In this figure, for the model discussed in the next section, only sediment pathways indicated by solid arrows with numbers are discussed. Other potential pathways as indicated with dashed lines are omitted.

Previous authors (e.g., Walton and Adams 1976) combined the ebb shoal and the bar(s) protruding from it into one feature referred to as the ebb shoal. For the reservoir model, the shoal and bypassing bars are distinguished because of the different formation processes. When an inlet forms, a shoal first becomes apparent within the confines of the inlet ebb jet. Bypassing bars form later by sediment transported off the shoal through the action of breaking waves and wave-induced longshore current (tidal and wind-induced currents can also play a role). Also, a bar cannot form without a sufficient sediment source, similar to the growth of a spit from a sediment source (Kraus 1999). In simplified applications of the model, however, the ebb shoal and bypassing bar could be considered as a unit.

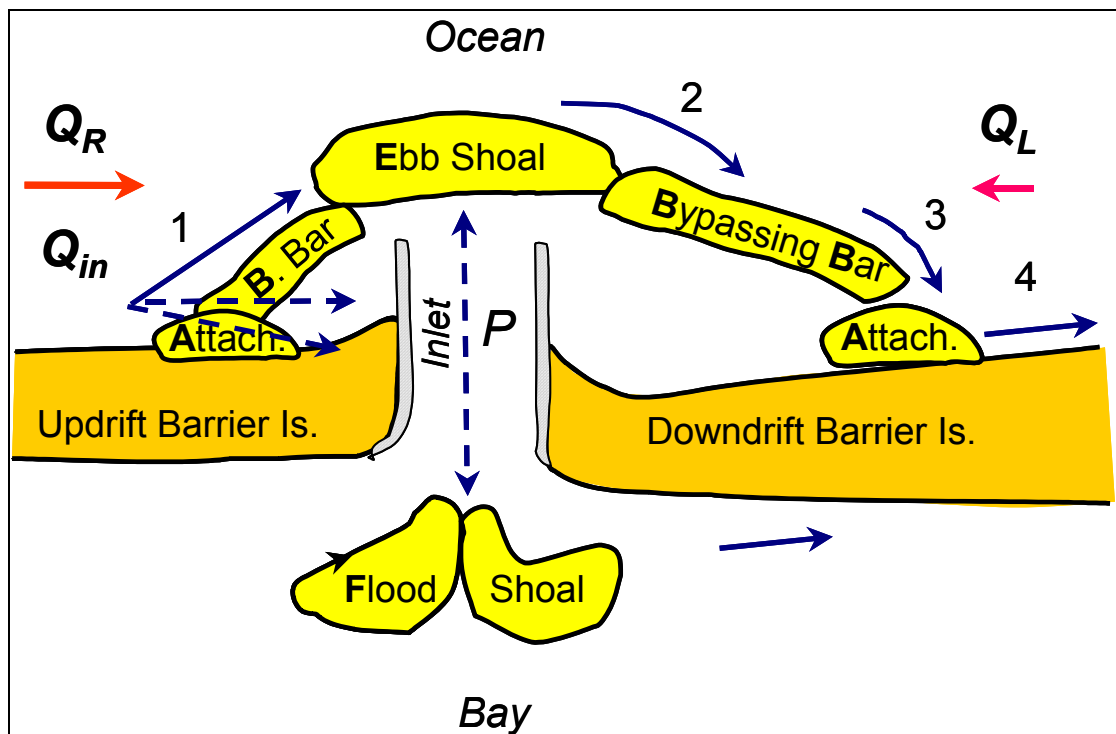


Figure 3. Definition sketch for idealized inlet morphology and simplified sediment pathways. In this figure, sand is bypassed from left to right in the order of the numbers shown

The ebb-shoal complex described in the preceding section is represented mathematically by analogy to a series of reservoirs or beakers, as shown in Figure 4. Sand is brought to the ebb shoal at a rate Q_{in} , equivalent to the right-directed transport Q_R in Figure 3. Also, the volume V_E in the ebb shoal at any time tends to increase while possibly “leaking” or bypassing some amount of sand to create a downdrift bypassing bar. The manner and rate at which sand leaks to the next reservoir depends on assumptions described in the following paragraph.

The volume of sand in the shoal (reservoir) can increase until it reaches an equilibrium volume V_{Ee} (the subscript e denoting equilibrium) according to the hydrodynamic conditions. Sand leaks to the bypass bar from inception of the shoal, and after equilibrium is achieved (the reservoir is full), all sand brought to the ebb shoal is bypassed in the direction of transport at the particular time. Similarly, the bypassing bar volume V_B grows as it is supplied with sediment by the littoral drift and the ebb shoal, with some of its material leaking (bypassing) to the downdrift attachment bar. After the bypassing bar reaches equilibrium volume V_{Be} , all sand supplied to it is contributed to the volume of the attachment bar V_A . The attachment bar transfers sand to the adjacent beaches. After it reaches its equilibrium volume V_{Ae} , all sand supplied to it by the bar is bypassed. The model thus requires values of the input and output rates of transport from each feature, and their respective equilibrium volumes.

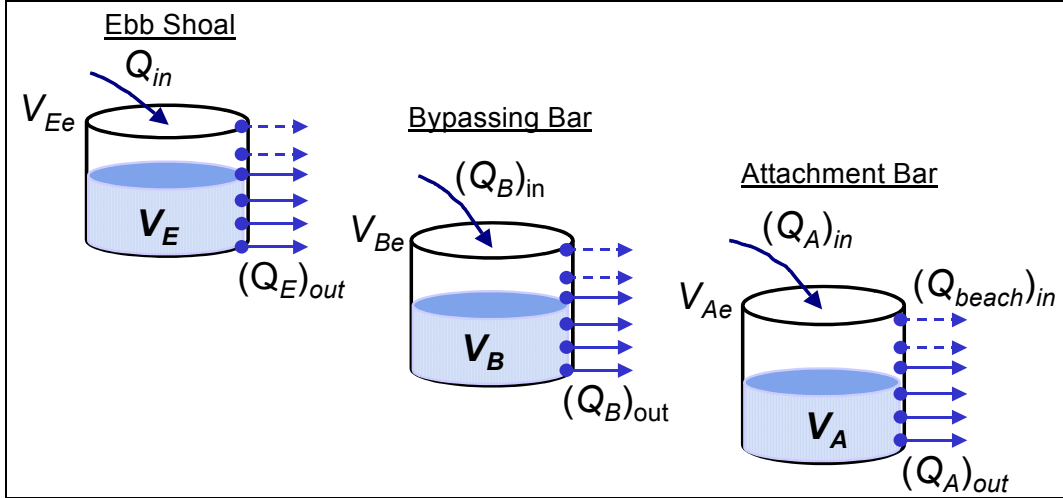


Figure 4. Concept sketch for reservoir inlet morphology model

Analytical Model: The continuity equation governing change of the volume V_E of the ebb-tidal shoal is:

$$\frac{dV_E}{dt} = Q_{in} - (Q_E)_{out} \quad (1)$$

where t = time, and $(Q_E)_{out}$ = rate of sand leaving (going out of) the ebb shoal. The input transport rate is assumed known as, for example the right-directed transport Q_R or the left-directed transport Q_L .

The remaining unknown is the output transport rate. The “reservoir model assumption” is to assume that the output rate is proportional to the input rate times the volume of sand in the beaker as a proportion to the equilibrium volume. A linear form of bypassing is specified to arrive at a simple analytical solution. Therefore, the rate of sand leaving or bypassing the ebb shoal, $(Q_E)_{out}$, is specified as:

$$(Q_E)_{out} = \frac{V_E}{V_{Ee}} Q_{in} \quad (2)$$

in which Q_{in} is taken to be constant, although this is not necessary in a numerical model. For the present situation, Equations 1 and 2 give:

$$\frac{dV_E}{dt} = Q_{in} \left(1 - \frac{V_E}{V_{Ee}} \right) \quad (3)$$

With the initial condition $V_E(0) = 0$, the solution of Equation 3 is:

$$V_E = V_{Ee} (1 - e^{-\alpha t}) \quad (4)$$

in which

$$\alpha = \frac{Q_{in}}{V_{Ee}} \quad (5)$$

The parameter α gives a characteristic time scale for the ebb shoal. For example, if $Q_{in} = 1 \times 10^5 \text{ m}^3/\text{year}$ and $V_{Ee} = 2 \times 10^6 \text{ m}^3$, which are representative values for a small inlet on a moderate-wave coast, then $1/\alpha = 20$ years. The shoal is predicted to reach 50 and 95 percent of its equilibrium volume after 14 and 60 years, respectively, under the constant imposed transport rate. These time frames are on the order of those associated with development of inlet ebb shoals. Equations 4 and 5 are the central results of the reservoir model.

The parameter α has a physical interpretation by analogy to the model of bar bypassing introduced by Bruun and Gerritsen (1960) and reviewed by Bruun, Mehta, and Jonsson (1978). Bruun and Gerritsen (1960; see also, Bruun and Gerritsen 1959) introduced the ratio r as:

$$r = \frac{P}{M_{tot}} \quad (6)$$

in which $P = \text{tidal prism}^1$, and $M_{tot} = \text{average annual volume of littoral sediment brought to the inlet}$. Inlets with a value of $r > 150$ (approximate) tend to have stable, deep channels and are poor “bar bypassers” from updrift to downdrift, whereas inlets with $r < 50$ (approximate) tend toward closure and are good bar bypassers. Because the equilibrium volume of the ebb-tidal shoal has been empirically shown to be approximately linearly proportional to the tidal prism, $V_{Ee} \propto P$ (Walton and Adams 1976), α is therefore approximately proportional to $1/r$.

Following the same procedure, the reservoir model gives the volume of the bypassing bar as:

$$V_B = V_{Be} \left(1 - e^{-\beta t'}\right), \quad \beta = \frac{Q_{in}}{V_{Be}}, \quad t' = t - \frac{V_E}{Q_{in}} \quad (7)$$

and the volume of the attachment bar, as:

$$V_A = V_{AE} \left(1 - e^{-\gamma t''}\right), \quad \gamma = \frac{Q_{in}}{V_{AE}}, \quad t'' = t' - \frac{V_B}{Q_{in}} \quad (8)$$

The coefficients β and γ function similarly to α in representing time scales of change for the bypassing bar and attachment bar, respectively.

The quantities t' and t'' in Equations 7 and 8 are lag times that account for a delay in development of the bypassing bar and attachment bar, respectively. After formation of an inlet, a

¹ The tidal prism is the total volume of water that flows into a tidal basin with a flood tide and then out again with the ebb. Typically, for inlet stability the tidal prism at spring tide or diurnal tide is considered. The diurnal tide range is defined as the difference in height between mean higher high water and mean lower low water.

certain time is required for the bypassing bar to receive a significant amount of sand from the shoal and a longer time for the attachment bar or beach to receive sand as it moves around the inlet from the updrift side.

The following results are obtained for the bypassing rate of the bar $(Q_B)_{out}$, which is equal to the input of the attachment $(Q_A)_{in}$, and the bypassing rate of the attachment $(Q_A)_{out}$, which is also the bypassing rate or input to the beach, $(Q_{beach})_{in}$:

$$(Q_B)_{out} = \frac{V_E}{V_{Ee}} \frac{V_B}{V_{Be}} Q_{in} = (Q_A)_{in} \quad (9)$$

$$(Q_A)_{out} = \frac{V_E}{V_{Ee}} \frac{V_B}{V_{Be}} \frac{V_A}{V_{Ae}} Q_{in} = (Q_{beach})_{in} \quad (10)$$

The rate $(Q_A)_{out}$ describes the amount of sand reaching the downdrift beach as a function of time and is a central quantity in beach nourishment and shore-protection design near inlets.

EXAMPLE APPLICATIONS: In this section, two applications of the reservoir model are given. These applications are considered simple because several sediment pathways have been neglected. A more comprehensive application is described by Militello and Kraus (2001), for which mining of a flood was evaluated by generalization and numerical solution of a simultaneous system of equations such as Equation 3.

Example 1: Jupiter Inlet, FL. Mehta, Dombrowski, and Devine (1996) developed a numerical model for calculating the growth of an ebb shoal by computing the deposition of sediment brought by the ebb jet on a morphologic feature of fixed planar area. Of the four examples given by Mehta, Dombrowski, and Devine (1996), here the reservoir model is evaluated with the data from their first example – Jupiter Inlet, FL. This inlet opened in 1947, and several measurements of the volume of the total ebb shoal are available, plotted in Figure 5. The equilibrium volume of the total ebb shoal (ebb shoal proper and the bypassing bar) by Walton and Adams (1976) is $V_{Ee} = 0.74 \times 10^6 \text{ m}^3$. It is seen that the inlet has had periods of substantial deflation of the ebb shoal, as given by the group of three lower points. This rapid change in volume suggests the shoal is small in comparison to the transporting capacity of the wave forces.

The value for Q_{in} was taken from Dean and O'Brien (1987) as $1.76 \times 10^5 \text{ m}^3/\text{year}$ (net rate from the north). The calculation is shown in Figure 5, where the dashed lines denote deviations in Q_{in} by ± 30 percent. Reasonable agreement is obtained between calculations and measurements and similar to that found by Mehta, Dombrowski, and Devine (1996). For this inlet, $1/\alpha = 4$ years, which means that the ebb shoal achieves full volume relatively quickly – implying the inlet is a good bar bypassing system (the tidal prism is weak in relation to the littoral drift).

The bypassing rates calculated by the reservoir model for the total ebb shoal and the attachment bar (arbitrarily assigned the value of $V_{Ae} = V_{Ee}/10$) are plotted in Figure 6, where the dashed lines again denote rates calculated with $Q_{in} \pm 30$ percent. Because of the relative small value of $1/\alpha$,

within 20 years of formation the inlet is calculated to bypass more than 80 percent of the material that arrives to it from the north.

Calculation for the other three examples given by Mehta, Dombrowski, and Devein (1996) showed similar reasonable agreement, which is satisfying because both Q_{in} and V_{Ee} were taken from the literature.

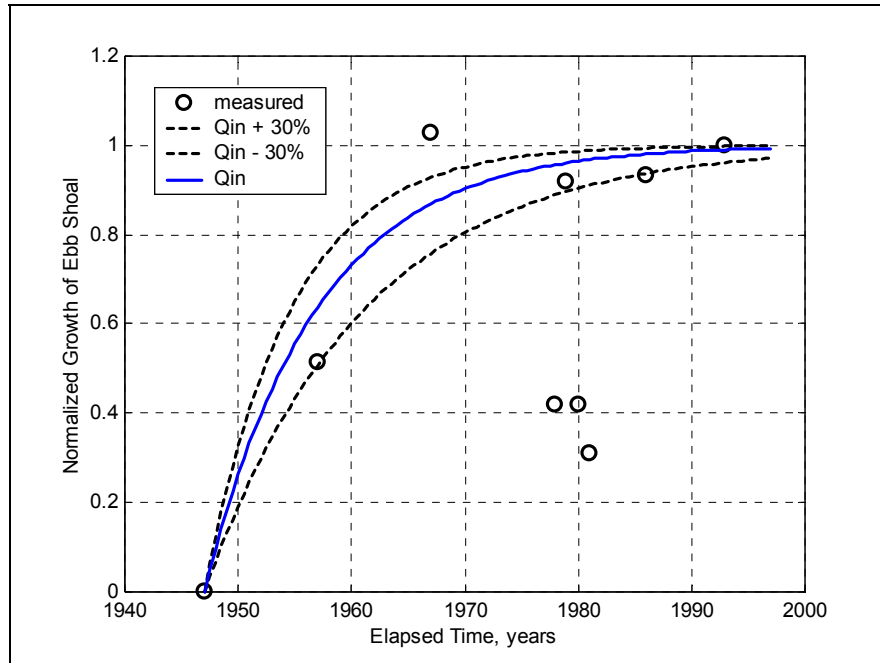


Figure 5. Calculated and measured growth of total ebb shoal, Jupiter Inlet

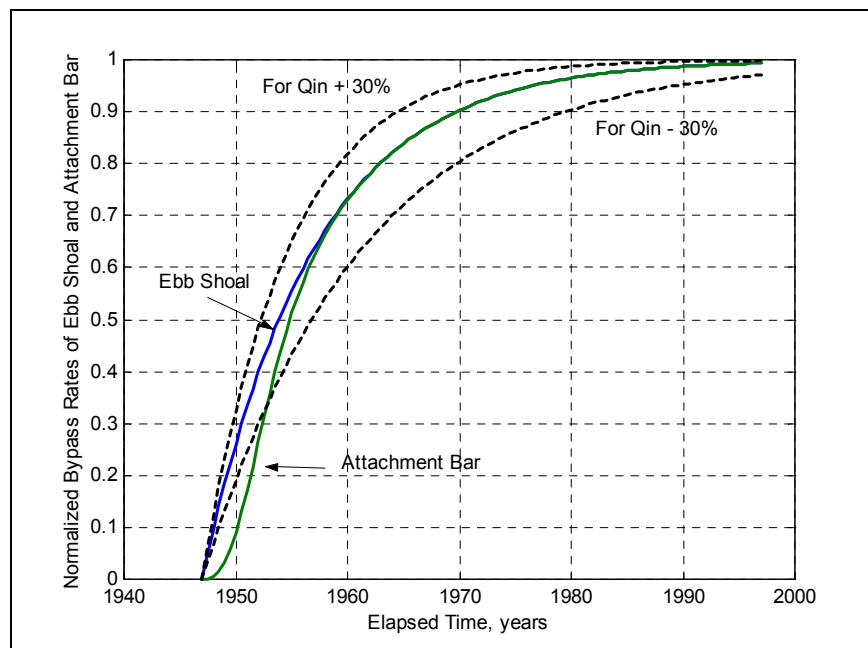


Figure 6. Calculated bypassing rate of total ebb shoal and attachment bar, Jupiter Inlet

Example 2: Ocean City Inlet, MD. Ocean City Inlet (Figure 7) was opened by a hurricane in August 1933, and considerable information is available for this inlet (Dean and Perlin 1977; Underwood and Hiland 1995; Rosati and Ebersole 1996; Stauble 1997). Stabilization of the inlet began one month later by placement of jetties, making this relatively large inlet an ideal site to evaluate models of ebb shoal evolution. Because of the sudden and near-complete interruption of the longshore drift (net north to south), Assateague Island located to the south eroded severely (Leatherman 1984).

Dean and Perlin (1977) estimated the long-term net (southward) longshore sand transport rate as between approximately 1.15×10^5 and $1.50 \times 10^5 \text{ m}^3/\text{year}$, based on impoundment at the north jetty. Underwood and Hiland (1995) estimated the equilibrium volume of the ebb-shoal complex as between 5.8×10^6 and $7.2 \times 10^6 \text{ m}^3$ based on the tidal prism of $2.3 \times 10^7 \text{ m}^3$ given by Dean and Perlin (1977) and calculation methods given in Walton and Adams (1976). With M_{tot} estimated by the upper value of net transport, one finds $r \cong 150$, indicating lack of a bar across the entrance channel and good navigation. In fact, the entrance channel is rarely dredged in maintenance of a channel to 3.7 mean lower low water (mllw) (including advance and overdredging).

Bathymetry survey data were available for the dates of 1929/1933 to define the pre-inlet condition, 1937, 1961/1962, 1977/1978, 1990, and a composite of various surveys conducted in 1995. Underwood and Hiland (1995) developed data sets prior to 1995, and Stauble (1997) assembled the 1995 data set from various sources for the U.S. Army Engineer District, Baltimore. The analysis made to distinguish the ebb shoal, bypassing bar, and attachment bar is given in Kraus (2000a, 2000b). Quality data sets made identification of distinct morphologic features possible.

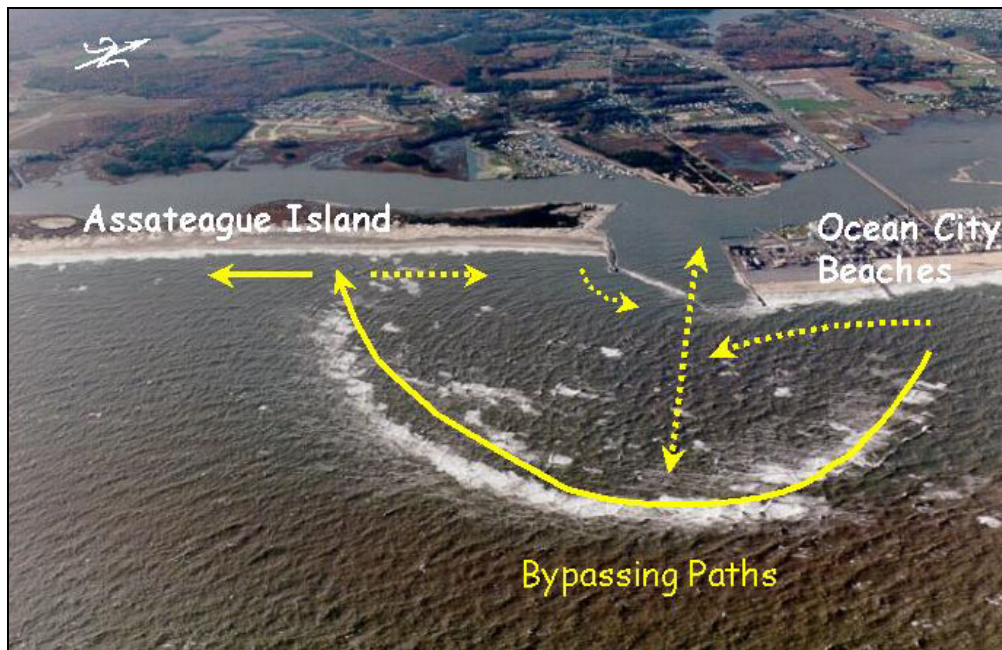


Figure 7. Ocean City Inlet, MD, and interpretation of sediment paths

For evaluation of the analytic model, input values were specified based on coastal-processes information from the aforementioned studies, with no optimization of parameters made. The

four required parameters were specified as $Q_{in} = 1.50 \times 10^5 \text{ m}^3/\text{year}$ corresponding to the upper limit of expected net longshore transport to the south, $V_{Ee} = 3 \times 10^6 \text{ m}^3$, $V_{Be} = 7 \times 10^6 \text{ m}^3$, and $V_{Ae} = 5 \times 10^5 \text{ m}^3$. The value of V_{Ae} was arbitrarily assigned as an order-of-magnitude estimate. Calculations were made for the 100-year interval 1933-2032.

The measured and calculated volumes of the ebb shoal are plotted in Figure 8, with the dashed lines calculated for values of α for $Q_{in} \pm 50,000 \text{ m}^3/\text{year}$ to demonstrate sensitivity of the solution to α and to estimate the range of predictions that may be reasonably possible. The trend in the data is well reproduced by Equation 4. Although the value of Q_{in} chosen is at the upper range for the net transport rate, this value must also account for sediment sources other than the net drift to the south. In particular, prior to 1985 when the south jetty was tightened, some sand moving north could pass through it and into the navigation channel (Dean and Perlin 1977), where a portion would be jetted offshore.

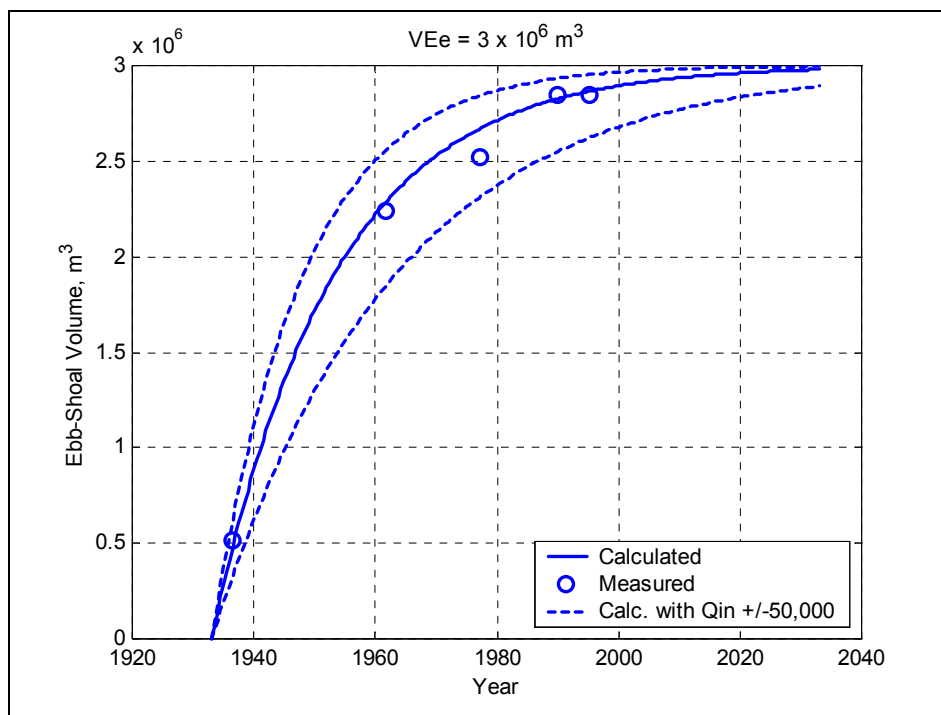


Figure 8. Volume of ebb shoal, Ocean City Inlet

Calculated and measured volumes of the ebb shoal, bypassing bar, and attachment bar are plotted in Figure 9. The calculations exhibit lags in development of the bypassing bar and attachment bar. Based on examination of aerial photographs, Underwood and Hiland (1995) concluded that downdrift attachment had occurred by 1980, when a distinct bulge in the shoreline was seen. The data and model indicate that, although the ebb shoal has achieved equilibrium, the bypassing bar is continuing to grow, so that natural bar bypassing from north to south has not achieved its full potential for sand storage.

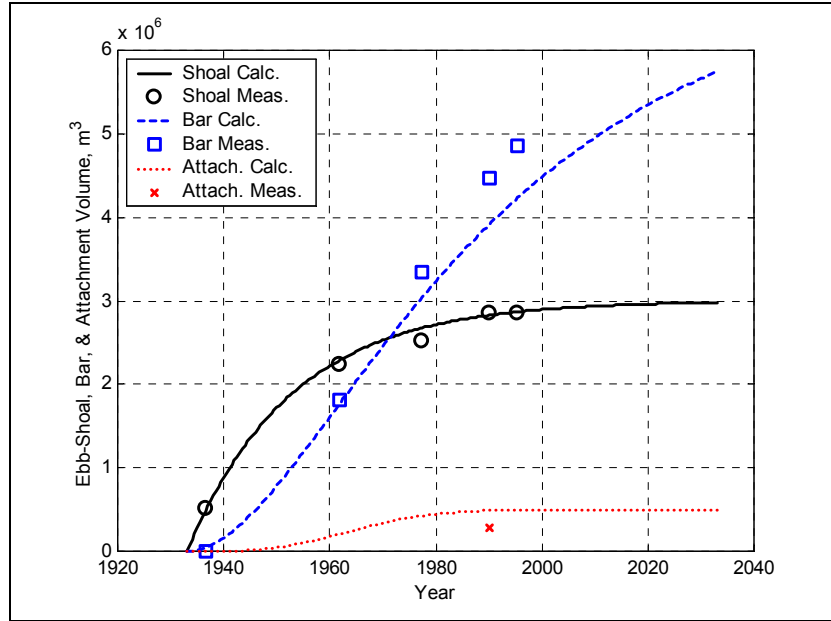


Figure 9. Volumes of ebb shoal, bypassing bar, and attachment bar, Ocean City Inlet

Bypassing rates calculated with the model, normalized by Q_{in} , are plotted in Figure 10 and indicate the approach to full potential. The calculations show a substantial lag in sand reaching the bypassing and attachment bars. The bypassing rate at the attachment equals the rate of sand reaching the downdrift beach. Its magnitude shown in Figure 10 should be interpreted with caution because the equilibrium volume of the attachment is not well known. Under the given model-input parameters, in 1999 approximately 60 percent of the net transport is reaching northern Assateague Island.

The analytical model was applied to calculate the recovery of the ebb-tidal shoal and change in bypassing rates at Ocean City Inlet in response to hypothetical mining of the bypassing bar. Limited quantitative work has been done to estimate the consequences of ebb-shoal mining (e.g., Mehta, Dombrowski, and Devine 1996; Cialone and Stauble 1998). Walther and Douglas (1993) reviewed the literature and applied an analytical model to three inlets in Florida to estimate recovery time of the shoal and bypassing rates. No time lag was included in their model, but it does yield different responses depending upon depth and location of the mining, factors not included in the present version of the reservoir model.

For this example, one million cubic yards were removed from the bypassing bar in the year 2000, which is about 30 percent of the material comprising the bar at that time. The evolution of the bar volume and the bypassing rates from the bar and from the attachment bar to the beach is plotted in Figure 11. The volume was normalized by V_{Be} and the bypassing rates by Q_{in} . Mining at the year 2000 stage of development is predicted to translate the bar growth and bypassing rates approximately 20 years back in time, with the bypassing rate to the beach moving from about 0.6 to 0.45 of the potential maximum value of Q_{in} . This example with simplified conditions is not adequate for design, but it does indicate possible applicability of the model in comparison of

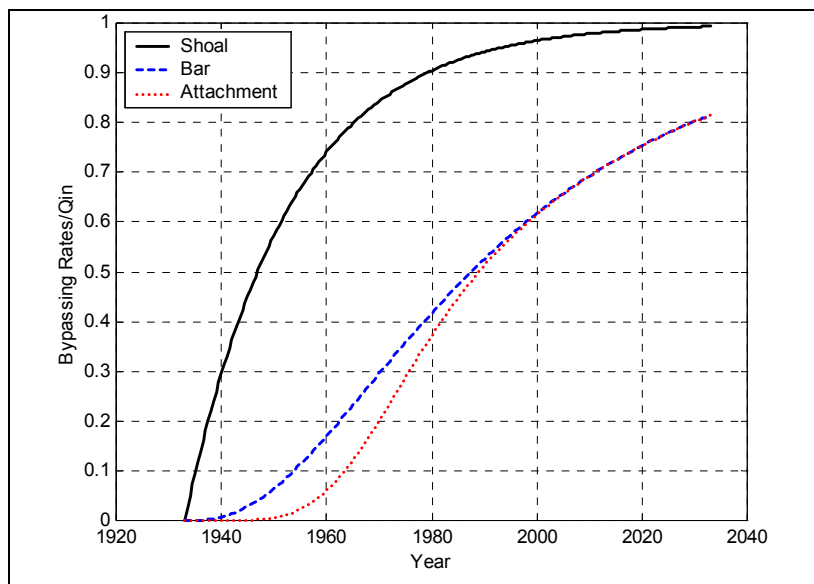


Figure 10. Calculated bypassing rates, Ocean City Inlet

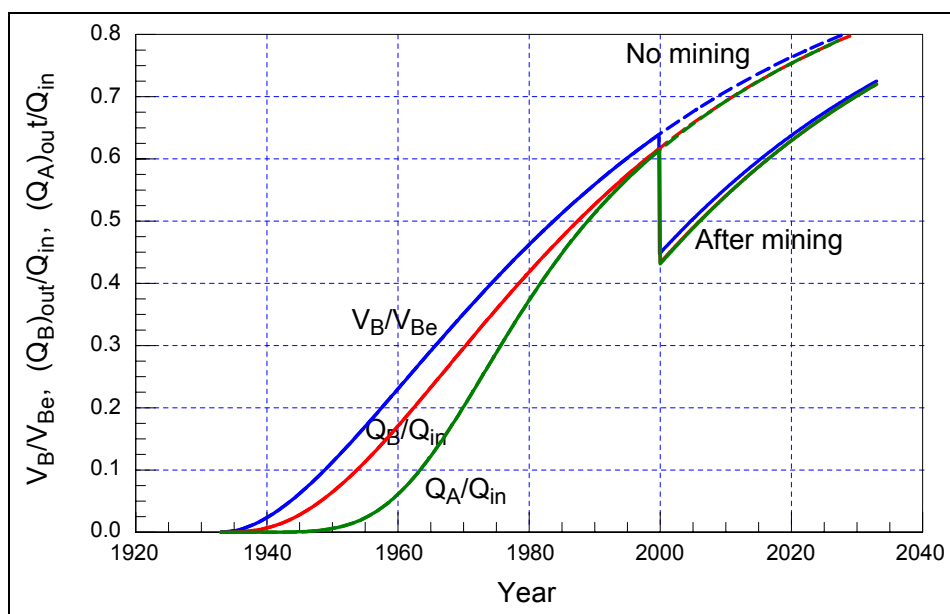


Figure 11. Hypothetical example of bypassing bar volume and bypassing rates with and without mining, Ocean City Inlet

alternative mining plans. More rigor could be introduced through inclusion of a time-dependent Q_{in} and estimation of the consequences of ranges of variability in the governing parameters.

CONCLUSIONS: The reservoir model of bypassing and ebb-shoal evolution requires inputs that are compatible with the amount and quality of data typically available in engineering and science studies. Such data are the longshore transport rate, which may be the net or gross rate depending on the inlet configuration; estimates of the equilibrium volumes of the ebb shoal, bypassing bar, and attachment bar; and qualitative understanding of sediment pathways at the

particular inlet. The model predicts a delay in sand bypassing to the downdrift beach according to the properties of the morphologic system and longshore transport rate. It is robust in that solutions are bounded. The ratio of input longshore transport rate and equilibrium volume of the morphological feature is the main parameter governing volume change and bypassing rates.

Separating the ebb shoal and the bypassing bar adds conceptual and quantitative resolution by allowing bypassing bars to develop and evolve according to the properties of the waves (longshore sediment transport) and tidal prism. However, a simplified version of the model can combine these two sand bodies, as done for the Jupiter Inlet example.

The model as presented in this CHETN does not account for sediment exchange between the inlet channel and flood shoal. However, it has been extended to describe such interactions (Militello and Kraus 2001) and will be described in a future CHETN in this series, after the user interface is developed.

ADDITIONAL INFORMATION: Questions about this technical note can be addressed to Dr. Nicholas C. Kraus (601-634-2016; e-mail: Nicholas.C.Kraus@erdc.usace.army.mil). For information about the Coastal Inlets Research Program, please contact the Program Manager, Dr. Kraus. This technical note should be cited as follows:

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