CHAPTER 31

ENGINEERING OF TIDAL INLETS AND MORPHOLOGIC CONSEQUENCES

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Tidal inlets are part of the coastal sediment-sharing system, and an inlet will modify the nearshore and estuary morphology, as well as the up-drift and down-drift beaches. Morphologic response to an inlet varies over several time and spatial scales. This chapter discusses inlet morphology and related functional design considerations that must balance navigation and shore-protection requirements. The first half of this chapter reviews selected material on the morphology of inlets and introduces empirical predictive expressions found useful for engineering. The second half of the chapter concerns aspects of engineering of tidal inlets.

1. Introduction

A *tidal inlet* is a short, narrow waterway connecting a bay, estuary, or similar body of water with a larger water body such as a sea or ocean upon which the astronomical tide acts. A tidal inlet is distinguished from other possible embayments and *coastal inlets* in that the inlet channel is primarily maintained by the tidal current (FitzGerald 2005). Water flow through a coastal inlet can be caused by the tide, wind (Price 1952), long-period seiching (Sorensen and Seelig 1976), and by river discharge. For water bodies connected to an ocean or large sea by an inlet, the astronomical tide is typically the major forcing for water movement and scouring of the inlet channel. In areas where the wind can be strong and tidal range small, such as the coast of Texas, USA, wind-generated flow through an inlet can often dominate the tidal signal, as can seasonal variations in water level at inlets that experience moderate tide range (Kraus 2007). A tidal inlet can be in a natural state, or its channel can be

dredged as needed for navigation, for improving flushing, or for keeping the inlet open. Navigable inlets are usually stabilized by one or, more commonly, two jetties.

Tidal inlets serve an essential ecological function in exchanging water, nutrients, and sediment between the lagoon and ocean, as well as being a conduit for water-borne biomass exchange. Inlets are often managed as part of the transportation system for commercial, military, and recreational vessel traffic. Maintenance dredging of inlet entrance channels and construction of jetties act to preserve navigable depth and protect the channel and vessels transiting it from sediment shoaling and waves. These activities also stabilize the cross-sectional area, location, and orientation of the channel. Channel dredging, jetties, and breakwaters disrupt natural sediment transport pathways among the inlet, adjacent beaches, and estuary. The resulting morphologic responses can compromise the integrity of the beaches and estuary and, ultimately, endanger the inlet itself.

For example, the jetties at many of the larger stabilized coastal inlets in the Unites States were constructed around the turn of the 20th Century, with federal jetties in the Great Lakes being the oldest in dating to the 1840s. When these early jetties were constructed, knowledge of coastal processes was limited. Main concerns or challenges were to furnish a reliable navigation channel and perform construction in the marine environment (The Engineer School 1932). Many of the earlier inlet stabilization projects were built on the shifting sediments of tidal flats and estuaries, far from infrastructure and development. The coast of the United States was relatively unpopulated, so consideration of the beaches adjacent to the inlets was minimal. With increased utilization of the coast for residences, businesses, recreation, and nature preserves, and in recognition of the great environmental significance of beaches and estuaries, the relation between tidal inlets and their surroundings came forward in the latter half of the 20th Century. Present-day engineering practice recognizes that inlets must be managed within a sediment- (sand-) sharing system. A sediment budget serves as the foundation for coastal engineering actions at inlets (Bodge 1999; Bodge and Rosati 2002; Rosati and Kraus 1999; Rosati and Kraus 2001; Rosati 2005). For example, “inlet management plans” including sediment budgets are required by the states of Florida and North Carolina.

The intent of this chapter is to serve as a resource about concepts and information on inlet engineering and morphologic responses, with focus on navigable inlets (see also Kraus 2006). The first half of the chapter reviews selected material on understanding of the morphology of inlets and introduces some empirical predictive expressions that are useful for engineering. The

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second half of the chapter concerns engineering of tidal inlets. Material includes engineering considerations for designing new inlets and modifying and maintaining existing tidal inlets.

2. Overview of Tidal Inlet Processes

This section reviews selected features of tidal inlet morphology. Hayes (1991) and FitzGerald (1996) can be consulted for different overviews than presented here and for many other references to the literature. The seminal article by Bruun and Gerritsen (1959) is still relevant in establishing terminology and elucidating sediment pathways at tidal inlets.

2.1. *Inlet Terminology*

An inlet evolves to a characteristic planform morphology that is controlled by the geometry of the estuary, net and gross longshore sediment transport rates, relative strength of wave action to tidal flow, geologic controls such as presence of non-erodible bottom and sediment type, presence and configuration of jetties, engineering activities in the channel, estuary, and adjacent beaches, channel width and depth, storm magnitude and frequency, and other factors. Although it would appear from the preceding that inlets exhibit a diverse range of morphologic characteristics, there are many commonalities, as well as notable distinctions.

The morphology of a typical medium-sized inlet on the northeast coast of the United States was captured in the photograph shown in Figure 1, taken during calm wave conditions at the federally maintained Shinnecock Inlet, located on the south shore of Long Island, New York, and connecting Shinnecock Bay with the Atlantic Ocean. The range of the predominantly semidiurnal tide is about 1 m. Average significant wave height is about 0.8 m, and sediment size is fine to coarse on this glacially influenced coast. Although it may appear that the flood shoal in Shinnecock Bay is much larger than the ebb shoal, bay bottoms are typically shallow and flat (say, from 2 to 4 m deep), whereas the nearshore bottom under the ebb shoal slopes into much deeper water. Thus, the thickness and volume of the ebb shoal can be much greater than that of the flood shoal. The main channel of Shinnecock Inlet cuts through or displaces the ebb shoal along the axis of the inlet. The island on the west side of the flood shoal likely consists of material placed during early dredging of the navigation channel. At Shinnecock Inlet, longshore transport is directed strongly to the west, making the ebb shoal asymmetric.

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Fig. 1. Shinnecock Inlet, New York, April 22, 1997. The picture was taken during a time of small waves, revealing the inlet morphology.

The main morphologic features of a natural (non-engineered) tidal inlet are sketched in Figure 2. Of these, the inlet channel, ebb shoal, and flood shoal are typically of interest to navigation and to the integrity of the adjacent beaches. The ebb shoal serves as a pathway for sediment bypassing naturally around the inlet, and it is sometimes mined as a sand source for beach fill. At many inlets, the channel must be maintained at greater depth through the ebb shoal (sometimes called the outer bar or entrance bar) than in the inlet and bay because of breaking waves on the shoal, which cause greater vertical excursion of vessels. The flood shoal often encroaches on the inlet channel or is located where a waterway passes, and channels around or through flood shoals must be dredged. The plan form of the ebb shoal and flood shoal can vary greatly according to the relative action of waves (littoral transport) and tidal range. Coastal geologists refer to the ebb- and flood-tidal shoals as deltas in analogy to the shape of river deltas. Here the terminology shoal is employed to emphasize the typical littoral, as opposed to riverine, provenance of shoals at tidal inlets, which is also in accord with navigation usage.

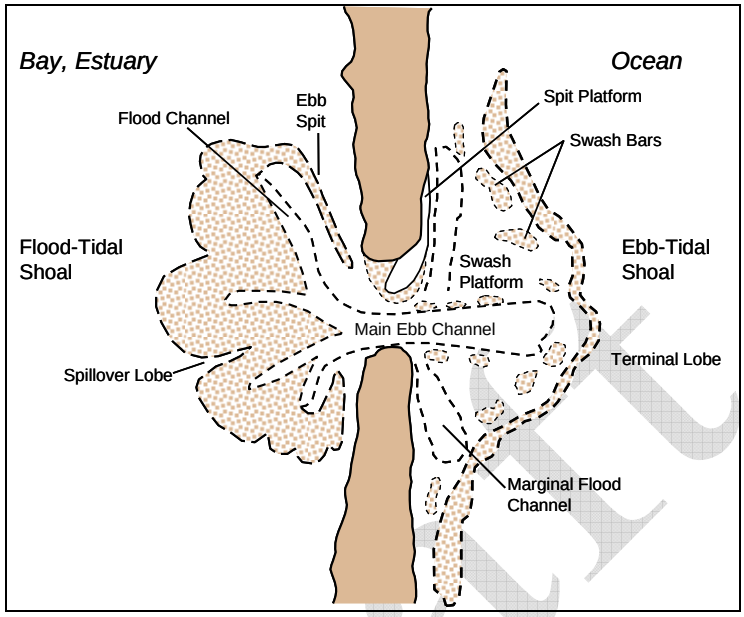

Fig. 2. Definition sketch for tidal inlet morphology (modified from Davis and FitzGerald 2004).

Galvin (1971) classified inlet planform configurations according to relative strength of longshore sediment transport rates (typically as a volume per year), in which Q_R and Q_L, represent right-directed and left-directed transport, respectively, as viewed from the inlet and facing the ocean (Figure 3). The configurations were termed as overlapping offset, up-drift offset, down-drift offset, and negligible offset. Representative locations of the main channel and the ebb (E) and flood (F) shoals are indicated.

An overlapping offset inlet forms by spit growth from the direction of strongly dominant longshore sediment transport (Q_R in top drawing of Figure 3). The inlet channel becomes longer, unless the spit growth is contained in some way. Fire Island Inlet, New York (Figure 4; Kraus et al. 2003) is a clear example of an overlapping offset inlet. Eventually, such a channel becomes so long that friction weakens the tidal flow, and the spit grows toward shore to close the inlet. The inlet channel may not be fixed by a jetty; in the case of Fire Island Inlet, the predominant transport was so strong that sediment buried the relatively short jetty and continued spit development

down drift. The channel may cut through the ebb shoal, which tends to orient towards the down-drift shoreline in a submerged extension of spit elongation.

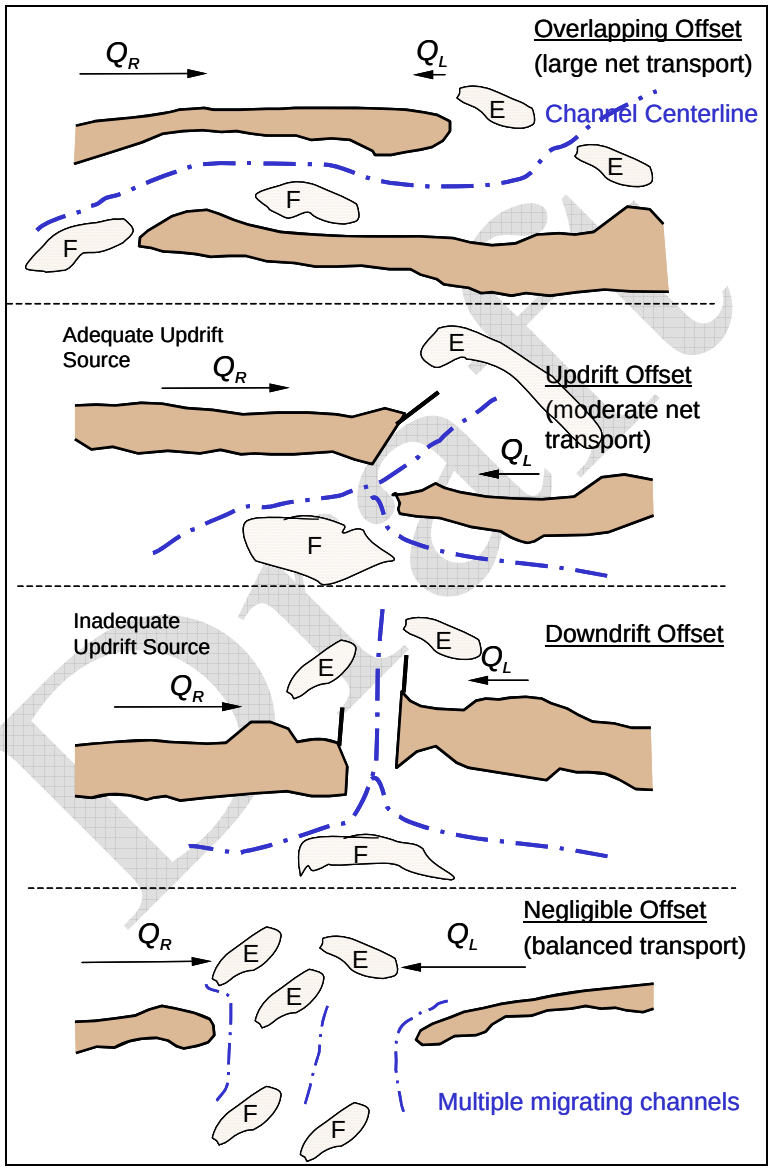

Fig. 3. Plan forms of inlets (modified and expanded from Galvin 1971). Lengths of arrows denoted relative strength of longshore sediment transport rate.

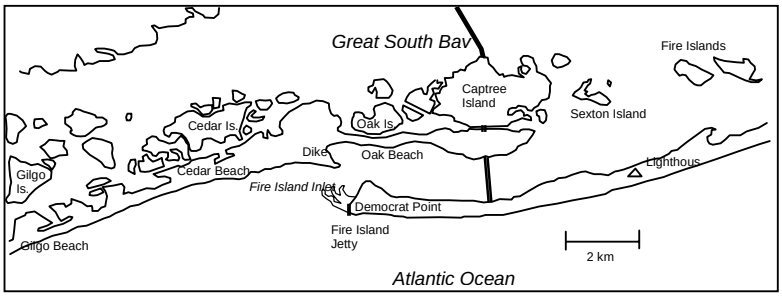

Fig. 4. Fire Island Inlet, Long Island, New York. The inlet migrated 8 km east since 1827, and a jetty placed on Democrat Point in 1939-41 was impounded and bypassed within 10 years. Shorelines oriented approximately east-west.

If there is an unequal but adequate (available) up-drift source of sediment, the inlet may be offset with only minor spit growth and not tend to exhibit strong spit growth. Bypassing will occur through a relatively well-connected ebb-tidal shoal. Shinnecock Inlet, New York, and Ocean City Inlet, Maryland, are examples of up-drift offset inlets. If there is an inadequate or limited source of sediment from the predominant direction, then a down-drift offset might occur such that the down-drift side protrudes, in part because of attachment by or feeding from the ebb shoal and its bypassing bars, and by local wave and transport reversal through wave refraction (Hayes et al. 1970). Thus, inlets can have a seaward down-drift offset even without jetties. This is the mesotidal morphology described by Hayes (1979). Finally, for Figure 3, if the longshore transport rate is balanced or weak, a natural inlet will tend to be wide and consist of multiple migrating channels and shoals.

Hayes (1979) and Davis and Hayes (1984) characterized inlet planform morphology according to the relative strength of tide and waves, as depicted in Figure 5, with tidal range serving as a surrogate for tidal prism (volume of water entering or leaving an inlet in the corresponding half tidal cycle) or tidal current (which moves the sediment).

Tide-dominated inlets tend to have larger ebb shoals that include channel margin bars similar to dual jetties. Bypassing at tide-dominated inlets can be through tidal bypassing, in which the sediment enters the channel on one side at flood tide and a portion eventually returns to the opposite side at ebb tide (Figure 6). Large volumes of sand can also be added to the barrier segment on either side of the inlet by major reorientation of the outer channel that isolates a portion of the ebb shoal from strong tidal flow (FitzGerald et al. 2001). Sand bodies can move onshore over the shallower portion of the ebb shoal exposed

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to breaking waves. During storms, portions of the channel-margin bars or other features of the ebb shoal may break off and migrate onshore.

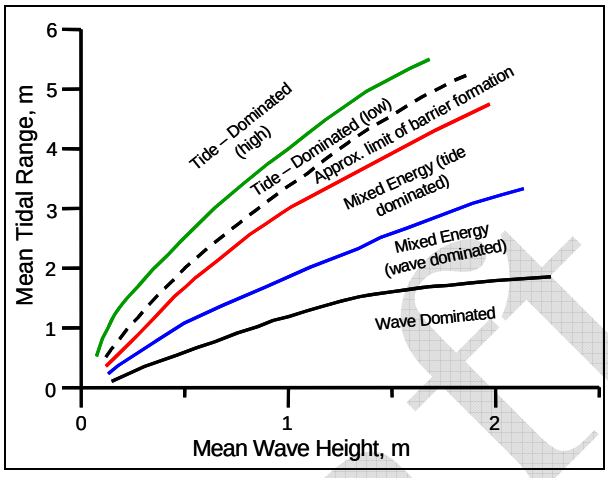

Fig. 5. Classification of tidal inlet morphology (after Davis and Hayes 1984).

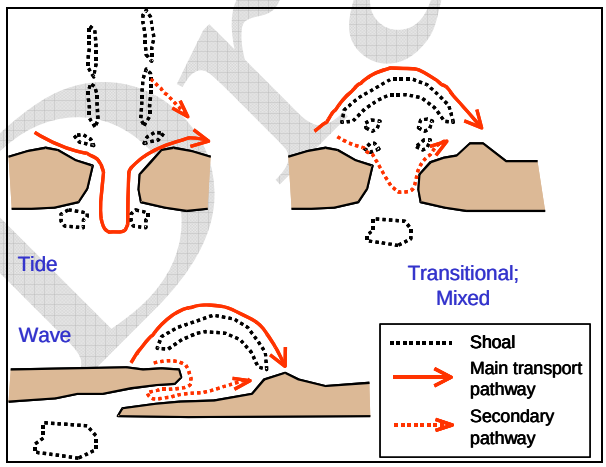

Fig. 6. Representative plan-form morphology and mode of bypassing of natural inlets, depending on wave or tide dominance.

Wave-dominated inlets tend to be ringed by a semi-circular ebb shoal (Figure 7). Bypassing of sediment around wave-dominated inlets mainly occurs through bar bypassing; sand moves around the shoal with the longshore current that is generated by waves breaking on it. On wave-dominated coasts,

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the flood shoal tends to be large, because a large amount of littoral sand is brought to the inlet, which can be swept inside by the tidal current, as well as bypassed through tidal bypassing.

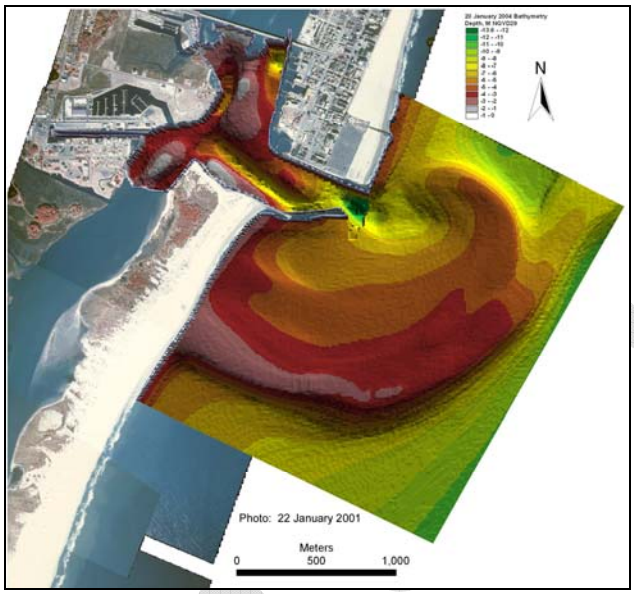

Fig. 7. High resolution survey of ebb-tidal shoal at Ocean City Inlet, Maryland, 2004, exhibiting a clear concentric shoal characteristic of a wave-dominated inlet. Longshore transport is from north to south.

Mixed-energy inlets share the features of each of the tide-dominated and wave-dominated idealized end states (Figure 6; FitzGerald 1982). Anthony and Orford (2002) investigated mixed-energy inlets on sediment-deficient coasts.

For wave-dominated and mixed-dominance inlets, the semi-circular ebb-tidal shoal can be subdivided as depicted in Figure 8 into the ebb shoal proper, bypassing bars to each side of the ebb shoal proper, and attachment bars connecting the bypassing bars to the shore (Kraus 2000). The ebb shoal was subdivided because the location and size of the ebb shoal proper is related primarily to the tidal jet. In contrast, the bypassing bars and attachment bars are controlled by sediment transport produced primarily by breaking waves. For Shinnecock Inlet (Figure 1), the strong predominant direction of longshore transport to the west pushes the up-drift attachment bar towards the beach that is fully impounded directly adjacent to the east jetty. The down-drift attachment bar is located about 1 km to the west of the inlet.

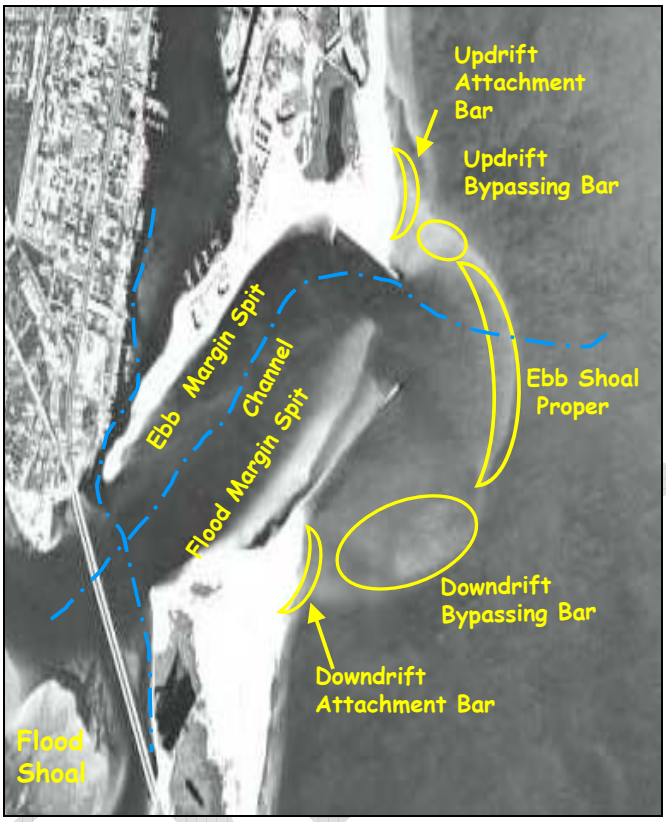

Fig. 8. Inlet entrance morphology, East Pass, FL, 1990, facing the Gulf of Mexico (adapted from Carr and Kraus 2001).

2.2. *Quantification of Natural Inlet Bypassing*

For maintaining or reestablishing the sediment bypassing rate, knowledge of the mode of sediment bypassing is helpful in assessing options and procedures for bypassing. As discussed above, Bruun and Gerritsen (1959) and Bruun (1960) identified three mechanisms for natural sediment bypassing at tidal inlets: (1) wave induced sand transport along the periphery of the ebb delta (bar bypassing), (2) transport of sand in channels by tidal currents, and (tidal bypassing), and (3) by the migration of tidal channels and sand bars. To predict bypassing type, they defined a ratio r as:

$$r = \frac{P}{M} \tag{1}$$

where P = tidal prism at spring tide, and M = total transport rate arriving at the inlet in 1 year (so that the numerator and denominator of Eq. 1 have units of volume). The parameter r expresses the relative strength of tidal flow that acts to sweep the inlet sediment as opposed to the volume of sediment brought to the inlet entrance by longshore transport during a year. Their observations led to the classification of inlets according to mechanism of sand bypassing and stability of the channel (Table 1). Implications for navigation over the ebb shoal or entrance bar based on their classification are also noted in Table 1.

Table 1. Inlet bypassing and classification of channel area cross-sectional stability (modified from Bruun and Gerritsen (1959) and supplemental information).

***r*-value**	**Channel Stability**	**Dominant Bypassing Mode**
$r < 20$	Unstable. Inlet may be closed by deposition of sediment during a storm. Not typically a navigable channel.	Bar bypassing
$r = 20 – 50$	Highly variable channel in location and area, with multiple channels possible. Dredging and jetties typically required to maintain navigable depths.	Bar bypassing; may have several bars
$r = 50 – 150$	Clear main channel and well-developed ebb shoal.	Bar bypassing and tidal bypassing
$r > 150$	Reasonable stable channel.	Episodic bypassing, tidal bypassing

Another mechanism for natural sand bypassing at inlets is episodic bypassing, by which a portion of the ebb-tidal shoal or down-drift bypassing bar detaches from the main body and migrates to the down-drift shore (Kana et al 1985; FitzGerald 1988; Gaudiano and Kana 2000). Episodic bypassing initiates after the ebb shoal, typically of a transitional or wave-dominated inlet, grows large and is disturbed by a storm. A large river flood can also discharge excess sediment that is not in equilibrium with the prevailing typical tidal-river current and waves, causing at least a portion of the new material to gradually migrate to the down-drift shore under wave action. Kraus and Lin (2002) attribute an increased rate of migration and tendency for closure of the San Bernard River Mouth, Texas, to a large volume of sediment discharged from the Brazos River, located 5.6 km up drift (to the north), during an exceptional flood in early 1992. Hands and Shepsis (1999) document periodic bifurcation and detachment of a large spit entering Willapa Bay, Washington, in association with large El Niño that occurs about every 7 years. The detached

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portion of the spit supplied material to the ebb shoal complex at this wide, natural inlet. FitzGerald et al. (2001) posit nine conceptual mechanisms for natural sand bypassing at tidal inlets, including those with jetties.

Table 2. Example empirical and theoretical equilibrium relationships for tidal inlet morphology.

Author	Morphologic Feature	Relation
LeConte (1905), O'Brien (1931, 1969), Riedel & Gourlay (1980), Hume & Herdendorf (1990)	Channel cross-sectional area, A_C (note: LeConte, Riedel & Gourlay, and Hume & Herdendorf consider the longshore transport rate magnitude)	$A_C = C_1P$
Escoffier (1940)	Inlet cross-sectional area stability	Closure curve
Floyd (1968)	Channel depth and minimum depth over the ebb shoal	--
Jarrett (1976)	Channel cross-sectional area, with and without jetties	$A_C = C_2P^n$
Bruun & Gerritsen (1959)	Inlet stability, sand bypassing type	P/M
Walton & Adams (1976), Marino & Mehta (1988); Hicks and Hume (1996)	Ebb shoal volume, V_E (note: relationships differ according to wave climate)	$V_E = C_3P^m$
Shigemura (1981)	Throat width, W_e ("e" denoting equilibrium)	$W_e = C_7P$
Gibeaut & Davis (1993)	Ebb shoal area, A_E	$A_E = C_4 P^k$
Kraus (1998)	Channel cross-sectional area relation including longshore sediment transport rate in C_2, see Eq. 8).	$A_C = C_2P^n$
Carr de Betts (1999), Carr de Betts and Mehta (2001)	Flood shoal area, A_F, and volume, V_F	$A_F = C_5P^{\,p}$ $V_F = C_6P^{\,q}$
Buonaiuto and Kraus (2003	Limiting depth h_{Cr} over crest of ebb shoal; limiting slopes around ebb shoal	$H_{Cr} \sim P^{\,j}$
P = tidal prism; A = area; V = volume; subscripts C, E, and F = channel, ebb shoal, and flood shoal, respectively; C = empirical or derived coefficient; j, m, n, p, q, = empirical or derived power; W = width of inlet throat; M = gross longshore transport in a year.		

2.3. *Empirical Geomorphic Relations*

Despite the hydrodynamic and morphodynamic complexity of tidal inlets, many empirical relations are available for estimating bulk characteristics, typically pertaining to inlet equilibrium. Table 2 summarizes selected empirical relations for predicting inlet morphology. The table indicates that the tidal prism is a dominant factor controlling (tidal) inlet morphology. It is this long-term average that is referred to as "equilibrium" in Table 2. Vincent and Corson (1981) give empirical relationships for other geometrical features of

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natural inlets. Carr and Kraus (2001) investigate empirical relations for tidal inlet morphologic asymmetries with implications for maintenance of navigation channels and sediment bypassing to the adjacent beaches.

2.4. *Maximum Tidal Current Necessary for Inlet Channel Stability*

A tidal inlet having a stable channel cross-sectional area on a sandy coast tends to have a mean-maximum velocity through it of approximately 1 m/s (Escoffier 1940; Bruun 1968, 1990). This is the current velocity necessary to maintain cross-sectional area, i.e., sweep material from the channel to maintain depth. The mean-maximum velocity is the average of a regularly occurring maximum velocity, as would occur on spring tides. If the discharge is solely related to the tidal prism and there is a sinusoidal tide with one (the first) harmonic component (Keulegan and Hall (1950) gave a simple correction for including the third harmonic), the maximum discharge D_m and tidal prism P are related as:

$$P = \int_0^{T/2} D_m \sin\left(\frac{2\pi}{T} t\right) dt \tag{2}$$

where T is the tidal period, and t is time. The integration gives:

$$D_m = \frac{\pi}{T} P \tag{3}$$

Tidal prism can also be calculated as the product of the effective bay surface area served by the subject inlet and the tidal range. It can also be obtained from a computation of water discharge, as through a numerical model. By definition of a discharge, the mean-maximum velocity V_{mm} is:

$$V_{mm} = \frac{D_m}{A_C} \tag{4}$$

where A_C = minimum inlet channel cross-sectional area below mean sea level (msl).

Although refinements have been made in empirical predictive equations relating A_C and P (see next section), it is convenient to consider the linear relation from O'Brien (1969):

$$A_C = C\,P \tag{5}$$

where A_C is in m^2, P is in m^3, and $C = 6.6 \times 10^{-5}$ m^{-1}. Then (O'Brien 1969):

$$V_{mm} = \frac{\pi}{CT} \tag{6}$$

For a pure semi-diurnal inlet, T = 12 hr, 25 min = 44,712 s. Equation 6 yields V_{mm} = 1.06 m/s, in agreement with empirical observations. For a tide that is primarily diurnal, the tidal period is 89,424 s, giving V_{mm} = 0.53 m/s. The implication is that an inlet in a diurnal tidal setting may require a smaller mean-maximum tidal velocity to maintain channel cross-sectional area stability as compared to inlets in a semi-diurnal setting, which are more common because of the prevalent semi-diurnal tide.

Jarrett (1976) compiled annual average maximum ebb velocities for 70 inlets on the Atlantic coast, 38 inlets on the Gulf coast, and 28 inlets on the Pacific coast of the United States. The compilation gives mean maximum velocities of 1.17, 0.75, and 1.06 m/s, respectively, for the inlet groups. Most inlets on the Gulf coast experience a diurnal tide and a reduced longshore transport rate (see next section) as compared to the Atlantic and Pacific coasts. The trend thus agrees qualitatively with the simple calculation given above.

2.5. *Tidal Prism-Inlet Channel Area Relations*

It is conceptually reasonable that the equilibrium area of a tidal inlet is determined by a balance between the transporting capacity of the inlet current and the littoral or longshore transport. In a short discussion paper, LeConte (1905) found a quantitative relationship between the inlet cross-sectional area and tidal prism based on his observation of a small number of harbor and inlet entrances on the Pacific coast of the United States. He gave the equations, $A_C = 1.1 \times 10^{-4} P$ for unprotected entrances, and $A_C = 1.4 \times 10^{-4} P$ for inner harbor (protected) entrances (metric units). The empirical coefficients have units m^{-1}. In forming these and similar equations to follow, it is assumed that the channel cross-sectional area is at or near its equilibrium value.

The observations of LeConte (1905) are remarkable in that not only did he deduce a direct (linear) relation between channel cross-sectional area and tidal prism, but also that the empirical coefficient is larger if less sediment is driven by waves to the inlet entrance. Unprotected harbors are exposed to wave action and longshore transport of sediment, whereas inner harbor entrances would be protected or sheltered to some degree from wave action. Therefore, for the same value of tidal prism, protected inlets can have larger channel cross-sectional area.

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The work of LeConte (1905) was followed by that of O'Brien (1931, 1969) and Johnson (1973), among others. The O'Brien (1969) relation for nine inlets on the Atlantic coast, 18 on the Pacific coast, and one inlet on the Gulf coast of the United States, is $A_C = 6.6 \times 10^{-5} P$ (metric units).

Jarrett (1976) comprehensively analyzed the relation between spring or diurnal tidal prism and inlet channel cross-sectional area. He compiled 162 data points for 108 inlets, with 59 inlets located on the Atlantic coast, 25 on the Pacific coast, and 24 on the Gulf coast of the United States. Jarrett's objective was to determine if tidal inlets on all three coasts of the United States follow the same tidal prism–inlet area relationship, and to investigate the change in that relationship for stabilized and non-stabilized (natural) inlets. The results are summarized in Table 3, referring to the equation:

$$A_C = C\,P^n \tag{7}$$

Among other observations, Jarrett (1976) noted that the smaller waves on the Gulf of Mexico coast relative to those on the Pacific coast and most of the Atlantic Ocean coast would produce smaller rates of longshore sediment transport. Kraus (1998) derived a form of Eq. 7 by consideration of a balance of sand transport by the channel-clearing inlet current and channel infilling by longshore sand transport, resulting in $n = 0.9$, and:

$$C = \left(\frac{\alpha \pi^3 N^2 W_e^{4/3}}{Q_g T^3} \right)^{0.3} \tag{8}$$

in which α = transport-related coefficient on order of 0.1-1, N is the Mannings coefficient, W_e = width of the inlet at equilibrium, Q_g = gross longshore transport rate arriving at the inlet. The prediction for C indicates that this quantity increases for wider inlets and for smaller longshore transport rates (sheltered coasts or coasts with small transport rates in general, such as on the west coast of Florida). Also, the inverse dependence on T suggests that inlets located on coasts having a predominantly semi-diurnal tide should be more stable than those experiencing a diurnal tide, all other conditions being equal. This prediction is contrary to that given in the preceding section.

The data points for all inlets tabulated by Jarrett (1976) are plotted in Figure 9. The equation at the top of the figure is that given by Jarrett, and the one on the bottom of the figure was computed by the author. There is a small difference, mainly because several points appear to have been omitted by Jarrett in his correlation calculation. The solid lines are the predictive equations which overlap, and the dashed lines give 95% confidence limits.

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Table 3. Inlet-area and spring or diurnal tidal prism regression values found by Jarrett (1976) for $A_C = CP^n$ (area units of m^2, prism units of m^3) tidal inlets on U.S. coasts.

	All Inlets		**No Jetty; Single Jetty**		**Two Jetties**	
Location	***C***	***n***	***C***	***n***	***C***	***n***
All Inlets	1.576×10^{-4}	0.95	3.797×10^{-5}	1.03	7.490×10^{-4}	0.86
Atlantic Coast	3.039×10^{-5}	1.05	2.261×10^{-5}	1.07	1.584×10^{-4}	0.95
Gulf Coast	9.311×10^{-4}	0.84	6.992×10^{-4}	0.86	Insuff. data	Insuff. data
Pacific Coast	2.833×10^{-4}	0.91	8.950×10^{-6}	1.10	1.015×10^{-3}	0.85

Byrne et al. (1980), Riedel and Gourlay (1980), and Hume and Herdendorf (1990) studied inlet channel stability on sheltered (protected) coasts and demonstrated that larger values of the empirical coefficient *C* (in accord with LeConte (1905)) and smaller values of *n* in Eq. 7 apply to coasts with limited littoral transport. The aforementioned three studies also indicate that the mean-maximum velocity required to maintain stability of the inlet channel is less (reaching approximately one-third less) than the typical 1 m/s required to maintain a channel on an exposed coast.

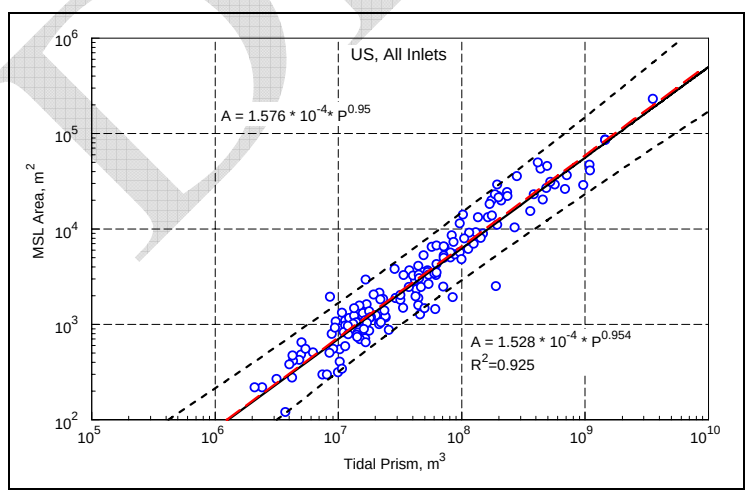

Fig. 9. Data on inlet channel area and spring tidal prisms (after Jarrett 1976).

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Trend lines from the data of Jarrett (1976) and of Hume and Herdendorf (1990) are plotted in Figure 10. For the same value of tidal prism, channel cross-sectional areas for New Zealand entrances in sheltered areas (bays, protected inlets) tend to plot higher than those for unprotected or unsheltered entrances. Entrances on the (unsheltered) northeast coast of New Zealand plot on top of the all-inlet trend line for U.S. inlets.

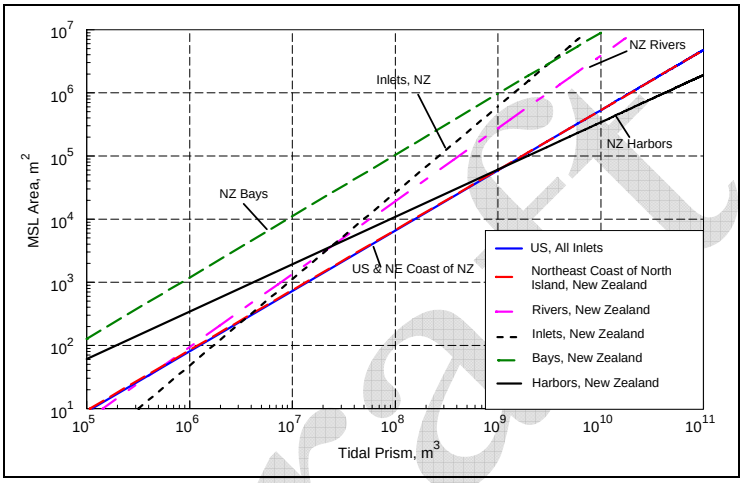

Fig. 10. Trends from Jarrett (1976) for U.S. inlets and New Zealand inlet categories as compiled by Hume and Herdendorf (1990).

2.6. *Tidal Prism vs. Ebb Shoal Volume Relationships*

Ebb shoals form under a balance of sediment transport produced by the ebb flow of the inlet and by the longshore current created by waves and wind. A portion of the sediment transported toward the inlet by waves is forced offshore by the ebb current, where it accumulates. If the inlet closes, the maintaining tidal force is lost, and the material in the ebb shoal is transported onshore by the waves, a process called ebb-shoal collapse or abandonment, whereby a portion of the ebb shoal welds to shore.

If jetties are built at the location of an existing inlet, or if existing jetties are extended offshore, the ebb jet will be confined and sustain greater velocities to a greater distance offshore. Some areas to the sides of the inlet that had been within the influence of the ebb current prior to jetty construction or extension will no longer be exposed to the current. As a consequence of confinement of the ebb jet, portions of the original ebb shoal located in areas no longer covered

by the ebb current will migrate onshore under wave action. Also, the portion of the shoal remaining in front of the now-stronger ebb jet will be translated further seaward (Pope 1991). Buijsman et al. (2003) document the century-long collapse of the northern lobe of the large ebb shoal at Grays Harbor, Washington, after long jetties were built in the late 1890s to early 1900s. The collapsing shoal increased beach width to the north of the inlet by more than a kilometer. The ebb shoal in front of the ebb jet migrated seaward to the edge of the continental shelf as a result of the jetty construction. Collapse of an ebb shoal can give a false impression as to the net direction of longshore transport. For example, at Grays Harbor the regional net direction of transport is to the north (Byrnes et al. 2003), yet the wide beach to the north created by the collapsed ebb shoal suggests (incorrectly) that the net transport is to the south.

Once an ebb shoal develops, if it is not translated too far offshore by the ebb jet, it provides an efficient pathway for sand to bypass around the inlet during times of larger waves that can break on the shoal. Therefore, the volume of an ebb shoal will approach an equilibrium value, after which sediment transported to the ebb shoal by the wave-and wind-induced longshore current will be bypassed to the down-drift beach or transported to the channel and then to the flood shoal. It has been proposed several times, but to the author's knowledge never executed, to artificially build an ebb shoal at the location of a newly cut inlet so as to more quickly reestablish natural sand bypassing.

Walton and Adams (1976) examined the volumes of ebb shoals as a function of tidal prism by analyzing 44 inlets on the Atlantic, Gulf, and Pacific coasts of the United States that were judged to be near or at equilibrium. They estimated the volume from nautical charts and other surveys by assuming that the ebb shoal formed on top of parallel-depth contours that can be estimated from those far from the inlet, a procedure developed by Dean and Walton (1973). They further classified the inlets according to slope of the continental shelf (location) and wave climate. The volume of the ebb shoal for inlets on mildly exposed coasts was larger than those on highly exposed coasts for the same tidal prism. Walton and Adams hypothesized that larger waves would tend to drive sediment toward the shore.

Others have confirmed the essential finding of Walton and Adams (1976) that the volume of the ebb tidal shoal is related to the tidal prism. Marino and Mehta (1987) examined 18 inlets on the east coast of Florida. They found that tidal prism was a leading parameter controlling ebb-shoal volume, with the ratio of inlet width to depth being a secondary factor. Hicks and Hume (1996) conducted a similar analysis for 17 inlets in New Zealand and confirmed the

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overall results of Walton and Adams. Hicks and Hume also considered the angle between the ebb jet and the shoreline in their correlations.

For the 44 inlets, Walton and Adams (1976) found:

$$V_E = C_E P^{1.23} \tag{8}$$

where V_E is the ebb-shoal volume in m^3, C_E = 2.121 x 10^{-2}, and P is in m^3. The data and correlation equation are given in Figure 11, together with the 95% confidence limits. The best-fit equation differs slightly from the original equation of Walton and Adams because of discrepancies between data they tabulated and locations of points in their figures.

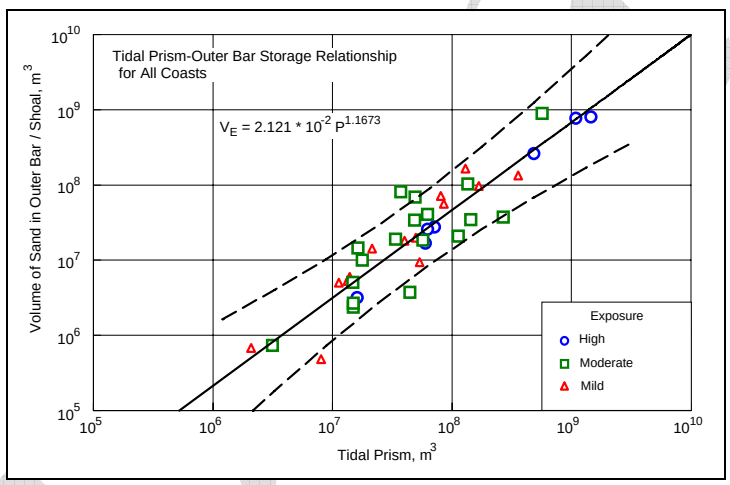

Fig. 11. Volume of ebb tidal shoal as function of tidal prism, all coasts (after Walton and Adams 1976).

2.7. *Tidal Prism vs. Flood-Shoal Volume and Area Relationships*

It is difficult to unambiguously identify the volume and area of a flood shoal. The absence of a hydrodynamic force to balance the flood flow that is comparable to waves at an ebb shoal allows sediment to be transported deep within a bay, particularly during spring tide and storms, creating a thin layer over a wide area that is difficult to distinguish from the natural bay bottom. As a practical matter, channels are often dredged through and around flood shoals, with the sediment sometimes placed as islands near the shoals, causing potential double counting. If the bay perimeter is located near the inlet,

wetlands may form in the margins of the flood shoal, making it difficult to distinguish the flood shoal from features such as washover fans and wetlands.

Despite these challenges, Carr de Betts (1999) and Carr de Betts and Mehta (1991) analyzed 67 inlets in Florida and obtained correlations between flood tidal shoal volume and tidal prism, and between the flood-tidal shoal area and tidal prism. This work distinguished the flood shoal as comprised of a near-field deposit and a far-field deposit, which together give the total volume. The near-field deposit is the visible portion of a flood shoal that may be, for example, bat-wing shaped. It was hypothesized that the near-field deposit is an equilibrium form that can reach non-filling, non-scouring equilibrium depth with typical flood tide current. Additional sediment arriving at the flood shoal will spread out around and pass it as a thin layer, forming the far-field deposit.

Quantitative relations were obtained between flood shoal area and spring tidal prism, for which it is noted that correlation coefficients were low (R^2 values in the range of 0.21 to 0.39) for widely scattered data that exhibited a broad trend. The results pertain to Florida conditions typified by mild waves, small tidal prisms; and hard limestone bottom at many Atlantic coast inlets. In the following, the first subscript, F denotes flood shoal, and the second subscripts N, F, and T denote near field, far field, and total, respectively.

2.7.1. *Flood shoal volume vs. spring prism*

$$\begin{aligned} V_{FN} &= 4.056\times10^{3}\,P^{0.314} \\ V_{FF} &= 1.5337\times10^{4}\,P^{0.314} \\ V_{FT} &= 2.0389\times10^{4}\,P^{0.296} \end{aligned} \tag{9}$$

In these equations, volume and prism are expressed in units of m^3. It is possible for these equations to give a total volume less than the sum or the near field and far field, demonstrating variability in the data available to the study.

2.7.2. *Flood shoal area vs. spring prism*

$$\begin{aligned} A_{FN} &= 1.4532\times10^{4}\,P^{0.254} \\ A_{FF} &= 3.4122\times10^{4}\,P^{0.244} \\ A_{FT} &= 4.7585\times10^{4}\,P^{0.249} \end{aligned} \tag{10}$$

In these equations, area is expressed in m^2, and prism in m^3.

2.8. *Depth Over Ebb Shoal*

The depth over the ebb shoal is of interest for navigation channel design and as a basic bulk parameter characterizing ebb shoals. Floyd (1968) examined the maximum depth of the channel h_C at the entrances to tidal rivers and the maximum depth of the ebb shoal h_E (which he referred to as the saddle of the entrance bar). The terminology saddle denotes the lowest point on the ebb shoal or entrance bar. He compiled data from several rivers each in Australia, the United States, and New Zealand, and two river entrances from other countries, and found the following simple relation, with depth referenced to mean tide level (approximately the same as msl):

$$h_E = 0.5\, h_C\,, \tag{11}$$

The equation was valid irrespective of whether the river flow was or was not trained by structures. Floyd (1968) concluded that it is not possible to increase the depth over the ebb shoal with jetties, and that the greatest depth across a bar can only be obtained by increasing the depth in the channel, as perhaps by dredging.

Buonaiuto and Kraus (2003) analyzed the bathymetry of 18 inlets around the coast of the United States to determine a predictive expression for the minimum depth over crest h_{Cr} of the ebb shoal. It was reasoned that, because both incident waves and the tidal prism are expected to be controlling independent variables for ebb shoal development, a parameter combining both average annual significant wave height H_S and tidal prism would provide the best predictive capability. The parameter $(H_S\, P)^{1/4}$, which has units of meters, was devised to represent the combination.

Correlation with the data determined the following predictive relations (metric units):

$$\begin{aligned} h_{Cr} &= 0.27 + 3.6 H_S \\ h_{Cr} &= 0.0063 P^{0.35} \\ h_{Cr} &= -0.066 + 0.046 \left(H_S P\right)^{1/4} \end{aligned} \tag{12}$$

For these equations, depth is measured with respect to mean lower low water, because waves would influence the bottom most at this lower tide level. Linear regression coefficients R^2 for the above equations were 0.81, 0.83, and 0.87, respectively. Figure 12 is the correlation plot corresponding to the last of the three predictive equations.

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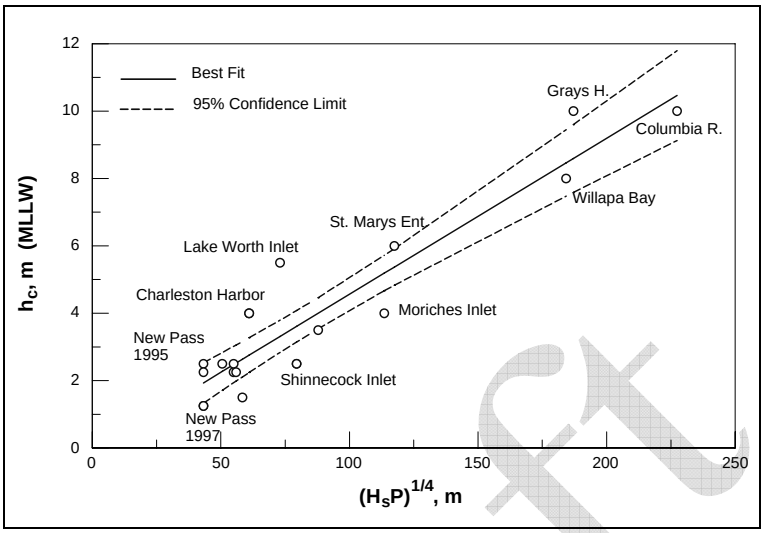

Fig. 12. Minimum depth over crest of an ebb shoal and product of average-annual significant wave height and tidal prism as $(H_sP)^{1/4}$.

3. Engineering Inlets Under Conflicting Requirements

Morphologic response to an inlet typically has a long time scale and great spatial extent. Sediment pathways are shared with the adjacent beaches and estuaries in a complex hydrodynamic environment. Therefore, consequences of the presence of inlets, both natural and engineered, can be subtle and far-ranging. It is also difficult to transfer experience and monitoring results among inlets because of different balances of kinds and strengths of the acting processes and conditions, of which tidal range, wave height and direction, wind, river flow if any, bay or estuary surface area, sediment type and surrounding sedimentary structure, types of structures, configuration of the estuary, and other factors play a role. Within this environment, modern inlet engineering attempts to balance two conflicting requirements:

(i) Maintain inlet stability (minimal dredging) while assuring sediment bypassing continues to the adjacent beaches.

(ii) Provide inlet navigability (strong tidal current to scour the channel) while assuring navigation reliability and safety (avoiding an excessively strong inlet current).

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The first conflict concerns the design objective of protecting the channel from excessive sediment shoaling so that navigable depth is maintained for the longest possible time. Traditionally, this was done by building long jetties to block infiltration by sediment moving alongshore. Jetties also promote a stable location and orientation of the channel, and partially shelter vessels from waves in the surf zone. However, long jetties will interrupt longshore transport and deprive the down-drift beach and, perhaps, the estuary of sediment. In the United States, older long jetties have been deteriorating, and it is a significant question as to whether they should be rehabilitated.

The second conflict concerns the design requirement of promoting a tidal current of adequate strength to contribute to maintenance of channel depth by scour. On the other hand, safe navigation for smaller vessels requires moderate ebb current so that steep waves that pose a navigation hazard are not created by the wave-current interaction. Numerous considerations enter in these conflicting requirements, and some are discussed below.

3.1. *Engineering Situation*

Engineering situations can be classified into three categories as a new inlet or relocated inlet, modification of an existing inlet, and maintenance of an existing inlet. Only a few aspects of each are discussed to illustrate some of the issues. Dean (1988) analyzes many of the interactions between jettied inlets and beaches.

3.1.1. *New or relocated inlet*

In design of a new or a relocated inlet, one has the opportunity to address the two conflicts with maximum flexibility. For a new inlet, one must consider:

(i) Navigation channel reliability and maintenance.

(ii) Formation of new ebb and flood shoals (removes sediment from the littoral system).

(iii) Long time scale for establishing natural bypassing.

(iv) Channel stability (dredging requirements).

(v) Navigation reliability (tidal current, entrance dimensions, etc.).

(vi) Time scale and extent of response of adjacent beaches.

(vii) Response of bay or estuary to storm surge; change in bay flushing, etc.

(viii) Optimized construction and dredging maintenance costs.

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In construction of a new inlet, the ebb and flood shoals can be assumed to be formed by sand transported from the adjacent beaches. Although this will be a long-term process, the volume removed from the beaches should be considered in the sediment budget.

For a relocated inlet, abandonment of the old ebb shoal can be an advantage in nourishing the down-drift beach and factored into the sediment budget. Kana and Mason (1988) and Kana and McKee (2003) discuss the benefit for shore preservation of moving Captain Sams Inlet, South Carolina, a pioneering and successful effort. Vila-Concejo et al. (2004) discuss morphologic change for relocation of an inlet in Portugal and also review the literature. Kraus et al. (2003) perform a regional sediment management study and evaluated tradeoffs of relocating Fire Island Inlet, New York (Figure 4). Cialone et al. (2003) discuss response of the flood shoal at Barnegat Inlet, New Jersey, to construction of a south jetty almost parallel to the existing north jetty and dredging of a shoal that had formed in the entrance of the previous arrow-head configuration jetties. As a response to this and other engineering actions, the historic growth of the flood shoal halted.

3.1.2. *Response of adjacent beaches*

If an inlet experiences a dominant direction of longshore sediment transport, the typical response of the adjacent beaches is up-drift accretion and down-drift erosion. If the inlet is in a nodal zone of longshore transport such that the long-term net rate varies around zero, shoreline response as moderate accretion on both sides can result from jetty construction. However, as opposed to the situation where jetties interrupt appreciable longshore sediment transport (large net transport rate), an equilibrium shoreline configuration at nodal points may be reached within relatively few years, as found by Komar et al. (1976) for Pacific northwest coast inlets and Williams et al. (2007) for Packery Channel, on the Texas coast. Porous jetties can cause erosion of the up-drift beach by allowing sediment to leak through to the inlet channel, increasing dredging maintenance (Dean 1988). This loss may be deleterious to the down-drift beach if sand entering the channel is lost from bypassing around the ebb shoal. Sand tightening of porous jetties near to shore can provide an immediate beach-growth enhancement (Creed et al. 1994). Dean (2003) and Dalrymple (2003) examined shoreline response near inlets through analytical investigations with the one-line (shoreline) model. The approach of Dalrymple (2003) allowed sand to pass over, around, or through the jetties. However, both these works are

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limited in not considering cross-shore transport, such as occurs at the down-drift jetty on an isolated beach, as discussed below.

Jetty construction at an existing inlet may confine the ebb-tidal current and push the ebb shoal offshore from its original location (Section 2.6). Flanks of the ebb shoal not located in the ebb jet may migrate onshore and give the appearance of accretion by longshore transport on the down-drift side of the inlet, until the abandoned portions of the ebb shoal serving as a source of sediment are fully depleted. The down-drift beaches then begin to erode.

Bruun (1995, 2005) distinguishes the near-field adjustment and far-field adjustment of the down-drift shoreline at inlets. The near field is the shoreline reach between the down-drift (and possibly up-drift) jetty and the attachment bar (Figure 13) and at many inlets near-field recession of the shoreline is chronic and requires special measures of shore protection (Hanson and Kraus 2001). This erosion may thin barrier islands to the point that breaching adjacent to the inlet becomes a concern. The far-field shoreline response can extend many kilometers beyond the inlet. The existence and extent of the shoreline adjustment depend in great part on (1) length of jetties, (2) placement frequency and location of material dredged from the channel or bypassed mechanically, (3) balance of net and gross longshore sediment transport rates, and (4) elapsed time after jetty construction, among many factors. Shoreline-change numerical models can give an estimate of adjustment of the shoreline to be expected. Such modeling must include the anticipated configuration of the ebb-tidal shoal in the wave transformation.

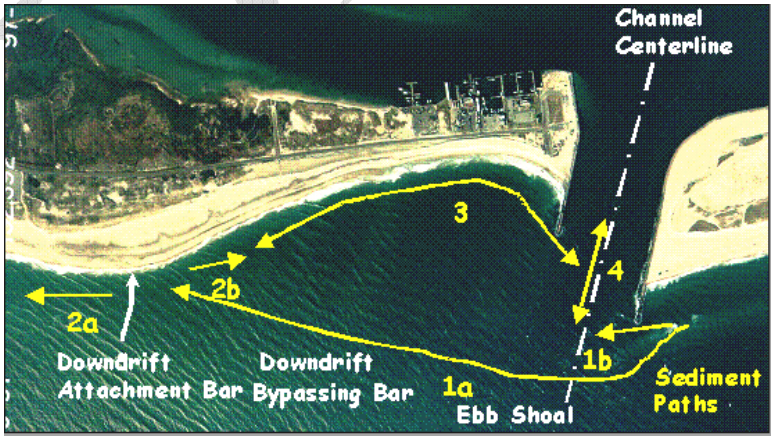

Fig. 13. Inferred sediment pathways and chronically eroding, sediment-isolated down-drift beach (area "3"), Shinnecock Inlet (from Hanson and Kraus 2001).

3.1.3. *Modification of an existing inlet*

Typical modifications of inlets are the construction, tightening, and lengthening of jetties, and deepening and widening of the navigation channel. For such modifications, one must consider, for example:

(i) Constriction or focusing of the ebb-tidal jet.

(ii) Increase or decrease in the ebb current velocity.

(iii) Translation of the ebb shoal further offshore.

(iv) Interruption of sediment bypassing.

(v) Recovery rates and interruption of sediment pathways if ebb or flood shoals are mined.

(vi) If there is a major rehabilitation, the flanks of the ebb shoal might collapse and migrate on shore (Grays Harbor, Washington; Charleston, South Carolina).

Walther and Douglas (1993) document recovery of the ebb shoal at Boca Raton Inlet, Florida, which was mined as a source for beach nourishment. Buttolph et al. (2007) observationally and numerically investigated offshore migration of the ebb shoal at Ocean City Inlet, Maryland, that resulted from raising the outer portion of the south jetty. This study was aided by high-resolution bathymetry surveys (Figure 7).

3.1.4. *Maintenance of an existing inlet navigation channel*

Maintenance of navigation channels includes the infrastructure such as jetties and breakwaters. Mobilization for dredging is a great expense, calling for the longest possible dredging cycle. Considerations include:

(i) Inlet locational stability.

(ii) Channel cross-section stability.

(iii) Annual dredging maintenance volume and material placement location (reestablishing sediment bypassing).

(iv) Interruption of sediment bypassing (erosion of down- or up-drift beaches).

(v) Possible change in tidal current speed and influence on navigation.

(vi) Translation and growth of the ebb shoal.

(vii) Growth or decline of the flood shoal.

(viii) Sedimentation in bay channels.

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(ix) Potential for breaching down drift of the inlet (avoided through bypassing and, possibly, placement of structures along the sediment-isolated beach).

(x) Integrity of the jetties and breakwaters, including factors such as elevation, permeability, scour, flanking, and stone dislodgement during storms.

4. Inlet Reservoir Model of Shoal Growth and Sediment Bypassing

Maintenance of navigation channels through tidal inlets must consider means of bypassing of sediment from the inlet to the adjacent beaches (where the sediment originated). Hydraulic and mechanical bypassing preserves the pathways of sediment in the littoral zone within the context of the natural sediment-sharing system of inlets and beaches. Seabergh and Kraus (2003) discuss sediment bypassing strategies and review the literature. Stive et al. (1998) introduced an "aggregate" model of long-term and wide-scale change in estuaries and inlets, based in part on empirical predictions of morphologic features for the Dutch coast.

Here, the Inlet Reservoir Model (Kraus 2000) is discussed as one tool for assisting in understanding of the time-dependent inlet sediment budget in support of engineering and management activities. Applications include prediction of ebb and flood shoal growth for new and relocated inlets (Erickson et al. 2003; Kraus et al. 2003), for estimating recovery of an ebb or flood shoal to be mined for beach fill (Militello and Kraus 2001), for verifying bypassing actions and consequences of shoal mining (Dabees and Kraus 2006), and examining complex and seasonal sediment pathways (Zarillo et al. 2003).

4.1. *Morphology Concepts for the Inlet Reservoir Model*

The reservoir model is based on the conservation of sand volume, ability of the engineer to identify morphologic features and sediment pathways, existence of an equilibrium volume of morphologic features, and a "reservoir assumption" that is described below. *Bypassing bar*s 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 *b*ypassing 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 (Figure 8). At this point in evolution of the ebb-shoal complex, substantial bypassing of sand can occur.

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In the context of the Inlet Reservoir Model, 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 schematically shown in Figure 8. The model distinguishes between the ebb-tidal shoal proper, typically located in the confine of the ebb-tidal jet, and the ebb-shoal bypassing bars that grow toward the shore from the ebb shoal, principally by the longshore transport of sediment by wave action.

Previous authors (e.g., Walton and Adams 1976) combined the ebb shoal proper and the bar(s) protruding from it into one feature referred to as the ebb shoal. For the Inlet 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 (Kraus 2000). 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). In simplified applications of the model, however, the ebb shoal and bypassing bar can be treated as a unit.

4.2. *Mathematical Representation*

Morphologic features such as shoals and channels can be described mathematically by analogy to a series of reservoirs or beakers, as depicted in Figure 14. Sand arrives to the ebb shoal at a rate Q_{in}, equivalent to the right-directed transport Q_R. Also, the volume V_E in the ebb shoal tends to increase while possibly bypassing some amount of sand to create a down-drift bypassing bar.

The volume of sand in the shoal (reservoir) can increase until it reaches an equilibrium volume V_{Ee} (the subscript e denotes equilibrium) according to the transporting 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 down-drift 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 equilibrium volume V_{Ae}, all sand supplied to it by the bar is bypassed to the beach. The model thus requires values of the input and

output rates of transport from each morphologic feature and their respective equilibrium volumes. Complicated sediment pathways, multiple connections, and time-varying transport can be represented (Militello and Kraus 2001; Zarillo et al. 2003; Dabees and Kraus 2006).

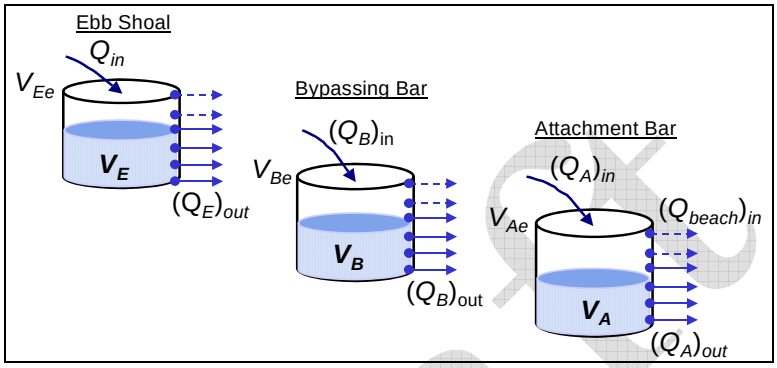

Fig. 14. Concept sketch for reservoir inlet morphology model.

Here, a simple analytic version of the model (closed-form solution) is reviewed (Kraus 2000). In applications, the governing equations are solved numerically and can treat complex, time-dependent conditions. The continuity equation governing change of the volume V_E of the ebb-tidal shoal is:

$$\frac{dV_E}{dt} = Q_{in} - (Q_E)_{out} \tag{13}$$

where t = time, and $(Q_E)_{out}$ = rate of sand leaving (going out of) the ebb shoal. The input transport rate is assumed known; for example, it could be 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 that the output rate is proportional to the input rate times the volume of sand in the beaker divided by the equilibrium volume. Therefore, rate of sand leaving or bypassing the ebb shoal, $(Q_E)_{out}$, is specified as:

$$(Q_E)_{out} = \frac{V_E}{V_{Ee}} Q_{in} \tag{14}$$

in which Q_{in} is taken to be constant here, although this is not necessary in a numerical model. For the present situation, Eqs. 13 and14 give:

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$$\frac{dV_E}{dt} = Q_{in}\left(1 - \frac{V_E}{V_{Ee}}\right) \tag{15}$$

With initial condition $V_E(0) = 0$, the solution of Eq. 15 is exponential growth:

$$V_E = V_{Ee}\left(1 - e^{-\alpha t}\right) \tag{16}$$

in which:

$$\alpha = \frac{Q_{in}}{V_{Ee}} \tag{17}$$

The quantity $1/\alpha$ is a characteristic time scale for growth of the ebb shoal. For example, if $Q_{in} = 1 \times 10^5$ m^3/year and $V_{Ee} = 2 \times 10^6$ m^3, which are representative values for a small inlet on a moderate-wave coast, then $1/\alpha =$ 20 years. The shoal would be predicted to reach 50 and 95 percent of its equilibrium volume after 14 and 60 years, respectively, under the constant imposed transport rate. The parameter α is essentially the inverse of the *r*-parameter introduced by Bruun and Gerritsen (1959) (Eq. 1).

This simple situation for constant input longshore transport magnitude and direction gives the volume of the bypassing bar as:

$$V_B = V_{Be}\left(1 - e^{-\beta t'}\right), \qquad \beta = \frac{Q_{in}}{V_{Be}}, \qquad t' = t - \frac{V_E}{Q_{in}} \tag{18}$$

and the volume of the attachment bar, as:

$$V_A = V_{AE}\left(1 - e^{-\gamma t''}\right), \qquad \gamma = \frac{Q_{in}}{V_{AE}}, \qquad t'' = t' - \frac{V_B}{Q_{in}} \tag{19}$$

The coefficients $1/\beta$ and $1/\gamma$ function similarly to $1/\alpha$ in representing time scales for the bypassing bar and attachment bar, respectively. The quantities t' and t'' in Eqs. (18) and (19) are *lag times* that account for a delay in development of the respective features. After formation of an inlet, a 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 up-drift side (delays).

The following 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 the input to the beach, $(Q_{beach})_{in}$:

$$\left(Q_B\right)_{out} = \frac{V_E}{V_{Ee}}\frac{V_B}{V_{Be}}Q_{in} = \left(Q_A\right)_{in} \tag{20}$$

$$\left(Q_A\right)_{out} = \frac{V_E}{V_{Ee}} \frac{V_B}{V_{Be}} \frac{V_A}{V_{Ae}} Q_{in} = \left(Q_{beach}\right)_{in} \tag{21}$$

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

Figure 15 illustrates the sediment pathways developed for Sebastian Inlet, Florida, accounting for seasonality in wave direction and longshore sediment transport (Zarillo et al. 2003). The inlet opens to the Atlantic Ocean on a north-south trending coast. Predictions shown in Figure 16 agree with most measurements of flood and ebb shoal volumes at Sebastian Inlet, but underestimate volumes determined for the late 1980s. The calculations and measurements match for the past decade with respect to the overall consequence of sand bypassing. The simulation shown in Figure 16 includes sediment volume removed from the sand trap to represent sand-bypassing projects conducted between 1972 and 1999. Zarillo and Brelin (2007) give an update on the status of Sebastian Inlet and its morphologic evolution.

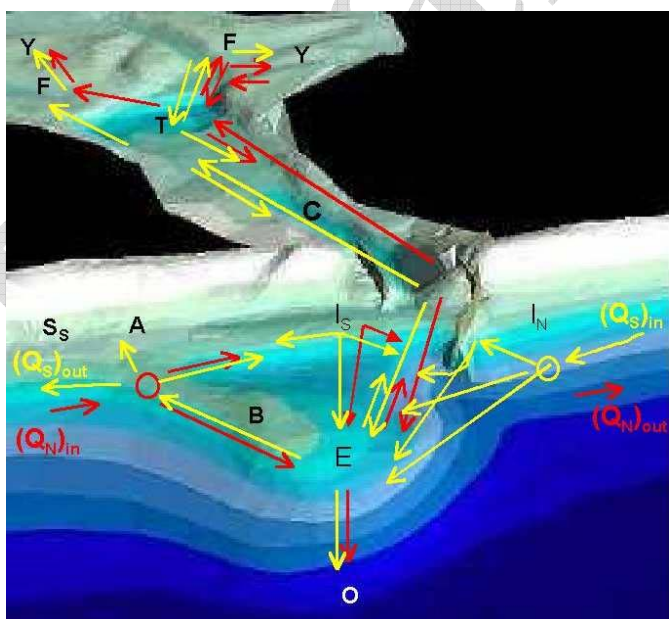

Fig. 15. Sediment pathways conceptualized for Sebastian Inlet, FL (E = ebb shoal, B = bypass bar, A = attachment bar, C = channel, T = sand trap, F = flood shoal, Y = bay, S_S = south fillet, I_N = north fillet, I_S = south fillet, O = offshore loss).

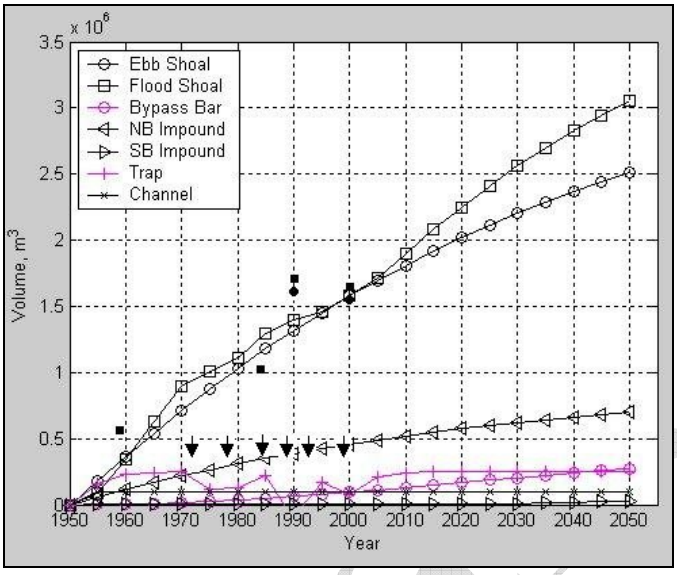

Fig. 16. Inlet Reservoir Model simulation of sediment volumes at Sebastian Inlet, Florida, 1950 to 2050. Solid symbols indicate shoal volumes estimated from topographic data and analysis of aerial images. Solid arrows indicate sand bypass events.

5. Elements of Tidal Inlet Hydrodynamics and Modeling

This chapter concerns morphology change around and engineering of tidal inlets. The hydrodynamics at a tidal inlet, the water movement that transports sediment and determines inlet morphologic forms, could not be discussed due to space limitations. Also, advanced numerical modeling of inlets was not covered. Here, some elements of these subjects are presented for completeness.

The hydrodynamics of inlets is fascinating, for which much mathematical elegance has been devoted. Keulegan (1967) developed the basic one-dimensional equation of motion that is used today. Seabergh (2003) investigated some predictions of the Keulegan approach for inlet channel stability. The reader is directed to Chapter 13 of Dean and Dalrymple (2002) and to Seabergh (2002) for thorough reviews of simple tidal inlet hydraulics that can be of great aid in understanding and engineering design. Seelig and Sorensen (1978) demonstrate the utility of such an approach.

First-order analysis of inlet stability rests on the important "Escoffier stability curve" (Escoffier 1940) that depends on a calculation of the current

through an inlet. Seabergh and Kraus (1997) discuss properties of the Escoffier stability curve and provide a desk-top PC program to calculate it. The program is based on the analytical solution for an inlet current given by DiLorenzo (1988), which represents overtides – higher harmonics of the dominant tide component generated through tidal wave shoaling (see Friedrichs and Aubrey 1988). The Escoffier stability curve also requires a predictive relation for the minimum channel area for a given tidal prism, as discussed in Section 2.5.

Sediment pathways and morphology change around an idealized dual-jetty inlet similar to Shinnecock Inlet were investigated by Militello and Kraus (2003) with a sophisticated numerical model. This work demonstrates significant differences in sediment transport depending on the wave climate as either typical or a storm condition. Recently, Fortunato and Oliveira (2007) report an interesting two-dimensional numerical model application investigating inlet stability and minimization of channel dredging. Consideration of non-linear processes associated with tidal flats is included. Such works are among many demonstrating the engineering utility of numerical models of inlet hydrodynamics and morphology change.

6. Concluding Discussion

In considering options for design or maintenance of a navigable tidal inlet, two contradictory requirements of inlets must be balanced or reconciled in the engineering design. These are (1) maintaining inlet stability while assuring natural functioning of sediment bypassing around the inlet, and (2) providing inlet navigability while promoting safe navigation. Requirement 1 implies inlet morphology retains equilibrium plan form and depths over which sediment moves in an efficient way, whereas Requirement 2 implies that inlets must be dredged to a necessary depth in support of navigation. A channel deeper than the natural channel depth will intercept more of the sediment moving toward it, which must subsequently be dredged. Sediment may be jetted farther offshore by the constraining jetties, depriving the beaches of that material or delaying its arrival. If the inlet has a shallow channel, sediment can cross or bypass easily, but the depth may not be adequate for navigation.

Williams et al. (2007) describe the design and functioning of a new inlet, Packery Channel on the Texas coast, for which monitoring during its first 3 years has indicated no need to dredge and no significant negative response of the adjacent beaches. The inlet was designed with awareness of many of the considerations described in this chapter (Kraus and Heilman 1997), in particular that the jetties not intercept all sand moving alongshore and that the

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hydraulic efficiency (entrance width to depth ratio) be less than 100 (Jarrett 1976).

The main issues in sediment management are interruption of the littoral drift by the inlet jetties; creation, growth, and mining of ebb- and flood-tidal shoals; and resultant changes in position of the shoreline, which may advance seaward on the up-drift side and recede on the down-drift side. Optimal placement of beach-quality material on the adjacent shores that is removed from the channel during new-work dredging (original dredging) and maintenance dredging operations, as well as mechanical bypassing of littoral material that is blocked by the up-drift jetty, are also central elements of a sediment-management plan. Dean (1988) has discussed such processes and associated policies. Inlet design and sediment management considerations are therefore linked through interruption of the littoral drift, dredging of an inlet, increase in tidal current through the dredged channel, and the water and sediment circulation around the inlet.

Larger tidal inlets can evolve over hundreds of years, indicating that regional responses must be appreciated or anticipated in engineering design. Kraus et al. (2003) took a regional sediment management approach in hypothetical relocation of Fire Island Inlet, New York. Among several aspects, ebb-shoal collapse as a form of beach nourishment was found to yield a large benefit for a chronically eroding down-drift beach. Regional applications will typically involve multiple tidal inlets to the same or connecting bays. Changes in one inlet can cause a response in the others. Batten et al. (2007) made a morphologic study documenting the decrease in size of Pass Cavallo, the natural tidal inlet to Matagorda Bay, Texas. This inlet is estimated to be about 2,600 years old and has been at the same location for the past 200 years. Opening of the deep-draft Matagorda Ship Channel to the bay in the early 1960s "captured the tidal prism," causing a loss of prism through Pass Cavallo and reduction in size of the ebb-tidal shoal. Seabergh (2007) investigated the stability of two inlets serving the same bay system in Guatemala, taking an engineering approach with Escoffier stability diagrams.

The science and engineering of tidal inlets are a challenge, and it is hoped that this chapter will be of some small assistance to those interested in this complex coastal environment.

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