CHAPTER 75

CASE STUDIES OF DELAWARE'S TIDAL INLETS: ROOSEVELT AND INDIAN RIVER INLETS

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ABSTRACT

Studies were undertaken to document the past and present characteristics and trends of Delaware's two major tidal inlets, Roosevelt and Indian River Inlets.

It was found that both inlet complexes are effective sediment traps causing considerable downdrift erosion. The major mechanism by which sand enters Indian River Inlet is by overtopping the impounded south jetty. At Roosevelt Inlet sediments are readily transported past the severed steel sheet pile jetties.

The results of a one-dimensional hydraulic model, as well as field measurements, predict the presence of a mean southerly flow through the canal and bay system which connects these two inlets. This flow is shown to have a substantial effect on the behavior and stability of these entranceways, causing major assymmetries on the depositional patterns at each location. Roosevelt Inlet was found to have a strong tendency to trap sediment within its throat; whereas, Indian River Inlet, on the opposite end of the system, was found to retain large quantities of sand on its developing ebb tidal shoal.

INTRODUCTION

The state of Delaware's coastline, along the shore of Delaware Bay and the Atlantic Ocean, features two major inlets which are coupled via the Intracoastal Waterway (Figure 1). These inlets, which were recently studied independently by Lanan and Dalrymple (1977) and Dennis and Dalrymple (1978), were shown to have various similar characteristics as shared with most tidal inlets as well as various contrasting features. Roosevelt Inlet, which serves as the northern entrance to the waterway, lies on the extreme southern edge of Delaware Bay, approximately 3 nautical miles west of Cape Henlopen. The inlet is bordered on the

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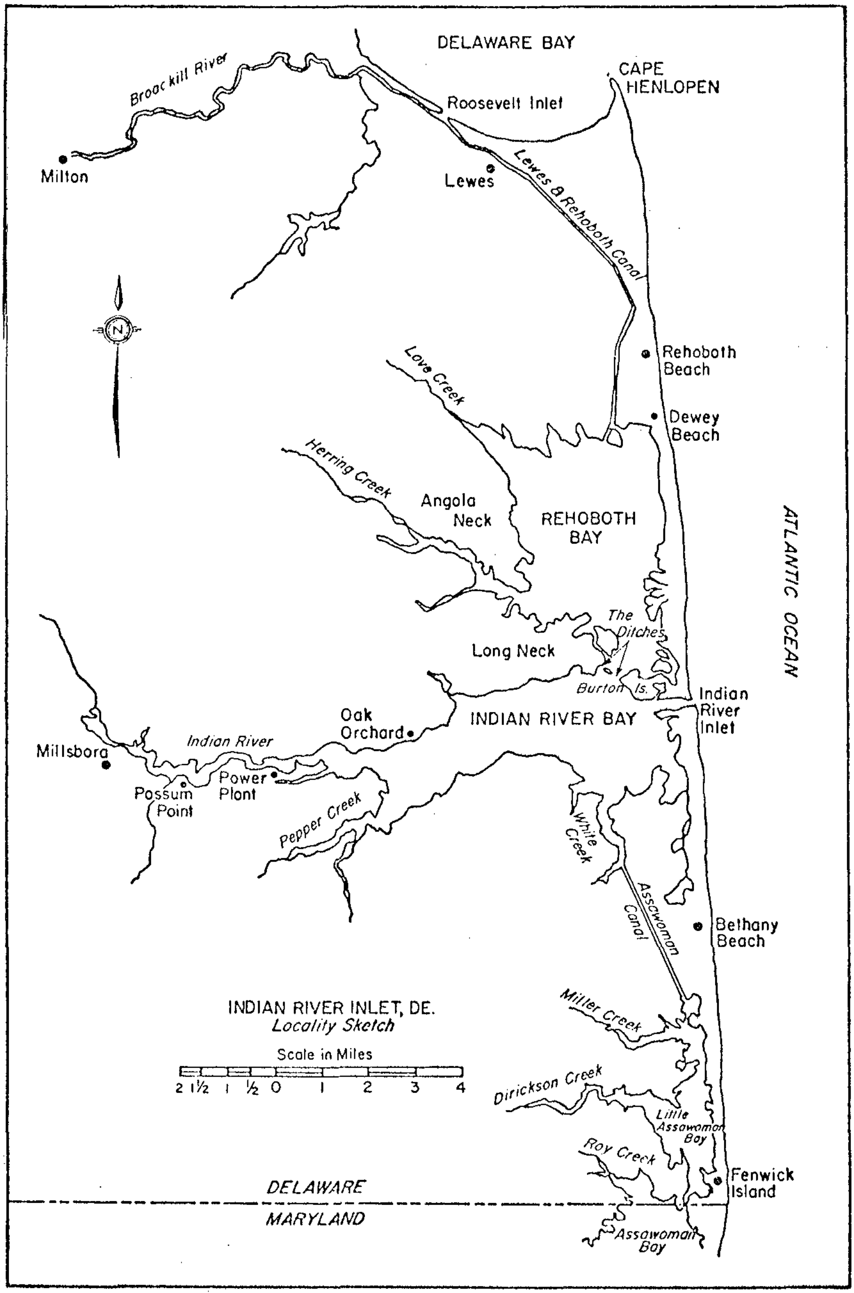

Figure 1 Locality Sketch of Indian River Inlet, Delaware

west by an undeveloped barrier beach known as Beach Plum Island and on the east by the small coastal community of Lewes Beach. Indian River Inlet lies about the midpoint of Delaware's Atlantic coast 11 nautical miles south of Cape Henlopen. The adjacent northern and southern barrier beaches are both contained in the Delaware Seashore State Park. These two inlets are connected by the Lewes and Rehoboth (L&R) Canal and the Rehoboth and Indian River Bays.

The wave climate in the vicinity of each of these inlets varies considerably due to the relative exposure of each location. Indian River Inlet, lying along the fully exposed Atlantic coast, is subjected to waves which average approximately a meter over the year; however, the possibility of two or three moderate-to-intense "northeasters" over that period, or the presence of a hurricane, are always a likelihood. The most effective wave energy arrives out of the southeasterly quadrant, driving the net littoral drift northward toward Cape Henlopen.

Roosevelt Inlet, on the other hand, is situated along a more sheltered shoreline. The wave climate is much less than that of the open ocean coast, with waves rarely exceeding a meter due to the limited fetch of Delaware Bay, particularly in the northeastern quadrant. Waves emanating from this direction are attenuated by the sheltering effect of the Cape as well as by the presence of two detached breakwaters at the southern entrance of Delaware Bay. Generally, the largest waves are generated along the major axis of Delaware Bay as a result of the sustained north to northwesterly winds. The biased wave climate results in an easterly net littoral drift along this reach, again toward Cape Henlopen.

BACKGROUND

Both of the inlets were stabilized about the same time. Roosevelt Inlet was established through the excavation of nearly 522,000 yd^3 (399,300 m^3) of mud, clay, and sand across the barrier beach commencing in the latter part of 1936. The construction of twin steel sheet-pile jetties followed the excavation and were completed by October 1937. The two structures were each 1,700 ft. (518.5m) in length extending bayward to the 6-foot (1.83m) depth contour, with a parallel spacing of 500 ft. (152.5m). This new inlet was to serve as a dependable and essential navigable northern entranceway of the recently completed L&R Canal after previous attempts at an alternate entrance (Broadkill Inlet), about 2 1/2 miles (4 km) to the west, had failed.

Unlike Roosevelt Inlet, Indian River Inlet occurred naturally, although its history has been one of migration, shoaling and closure. Repeated closure of the inlet in its natural state led to several pertinent problems, the most damaging of which was its effect on the local seafood industry. Not only did the inlet closure render vessel passage impossible, but normal fish migration into the feeding and spawning areas of the Rehoboth and Indian River Bays was disrupted. Furthermore, the large numbers of fish and shellfish trapped in the bays gradually died off as freshwater runoff reduced the salinity of the bay waters beyond tolerable limits. Many unsuccessful efforts were made to alleviate these problems by both State and local interests through excavation and dredging until, finally, in 1937 a Federal project was approved to stabilize the inlet. Construction of two parallel stone jetties spaced 500 ft. (152.5m) apart was begun in 1938 and completed in 1940. Each structure extended seaward 1,556 ft. (474.6m) to the 14-ft. (4.3m) depth contour. The shoreward 904 ft. (275.7m) on the north side and 890 ft. (271.5m) on the south side were constructed of steel sheet piling for bank protection. For further historical details on Indian River Inlets, the reader is referred to Thompson and Dalrymple (1976).

INLET STABILIZATION AND RESULTING PROBLEMS

For both inlets office, as well as field studies, were undertaken to identify and document the various past and present coastal processes and associated problems. These studies included hydrographic surveys, beach profiles, current measurement, sand tracer experiments, collection and comparison of past and present charts and aerial photographs, as well as the documentation of all dredging and beach nourishment activities for each inlet. The following will present a discussion of the major problems and pertinent processes uncovered by these studies:

a. Downdrift Erosion. As with most tidal inlets along sandy coastlines, the presence of these inlets has resulted in significant erosion experienced by the adjacent beaches. Following the stabilization of Indian River Inlet, the south jetty began to trap sediment until the impoundment capacity was reached. Recent surveys of this area have revealed that approximately 319,000 yd^3 (244,000m^3) have been impounded since 1938 or an annual rate of 8,600 yd^3 (6,580m^3) per year. Presently, the sand passes rather freely around and over the south jetty entering into the confines of the inlet. At this point, the sand is entrained by the strong tidal currents reaching velocities as high as 6 feet/sec (1.8m/sec) and is ultimately deposited in either the flood or more extensive ebb tidal shoals. Thus the inlet complex acts as an effective sediment trap causing major erosion along the downdrift beaches. The shoreline response to the inlet stabilization is shown in Figure 2, which is based on comparison of aerial photographs, 1938 to 1975. In an effort to alleviate the sediment deficit, both the State and Federal governments have been nourishing the beach north of the inlet since 1957. To date, a total of 2,019,549 yd^3 (1,544,955m^3) have been placed along this reach.

The major mechanism by which the sand enters into Indian River Inlet and, to a lesser degree, Roosevelt Inlet, is by overtopping of the jetty. The beach berm crest along the reach adjacent to the south jetty at Indian River Inlet is generally one foot (0.3m) higher than the jetty crest. During periods of high tides, waves sweep up the beach, across and through the jetty, and into the channel, carrying large volumes of sand in the swash (Figure 3). At Roosevelt Inlet sediment occasionally overtops the shoreward portion of the east (downdrift) jetty during periods of northeasterly winds and high tides via a similar swash transport. The jetty at this location is essentially a low crested rubble revetment, primarily functioning as bank protection,

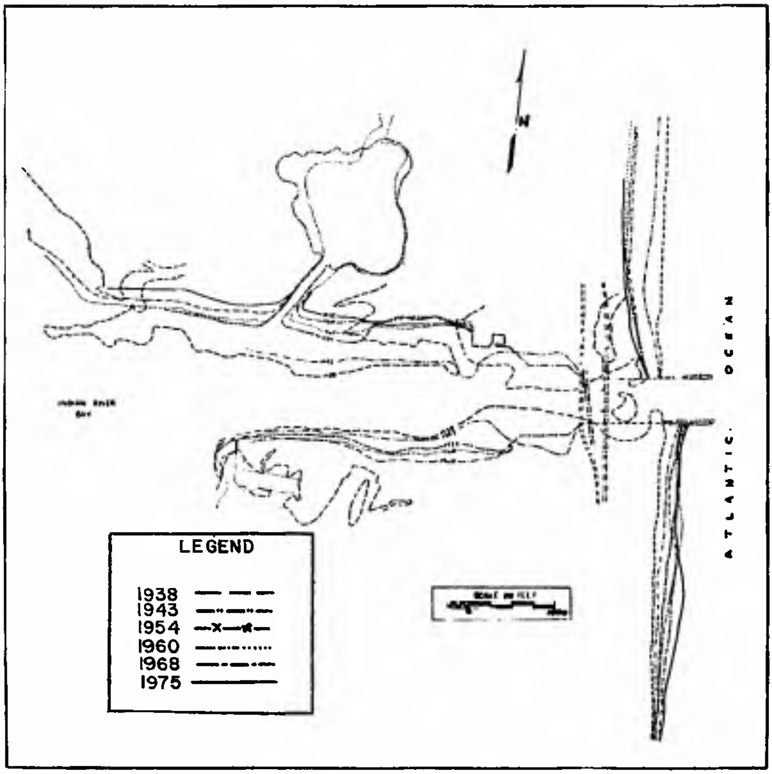

Figure 2 Shoreline Changes at Indian River Inlet

Figure 3 Sand Being Carried Over Indian River Inlet South Jetty by Ocean Waves

the crest of which varies 1-2 feet (0.3-0.6m) below the adjacent beach profile. A similar problem has also been noted to occur at Ocean City Inlet, Md., where the low and permeable inshore portion of the south jetty allows sand to flow downslope past the jetty and onto the northern tip of Assateague Island (Dean and Perlin, 1977).

b. Jetty Corrosion. A problem of greater impact which became apparent within two years after the jetty construction at Roosevelt Inlet was the corrosion and deterioration of the steel sheet-piling. At present no repairs have been made to the ailing structures which have deteriorated well beyond their effectiveness (most of the piling is only visible during low tide). As a consequence of the condition of the jetties, wave action easily moves sand through, around and over the severed sheet pile. Upon entering the inlet channel, the sand is reworked by wave and current action and is usually deposited in lobe-shaped shoals which build along both the east and west banks. The west lobe is usually larger, being on the updrift side of the inlet (Figure 4). Once the sand is worked within Roosevelt Inlet, there appears to be no effective mechanism to return the sand to the littoral regime other than by dredging. Therefore, in its present condition the inlet acts as an effective sink, trapping the gross littoral drift. The mechanism for this trapping will be explored more fully in the Section, Inlet Hydraulics. This trapping action has resulted in major erosion along Lewes Beach, which has again prompted both the State and Federal governments to provide remedial measures in the form of beach nourishment and the construction of nine groins.

FIGURE 4 Sand easily passing the deteriorated jetties at Roosevelt Inlet and depositing along the western bank.

c. Channel Bank Erosion and Channel Enlargement. Another major problem encountered following the stabilization of Indian River Inlet was the flanking of the jetties at the shoreward ends, causing erosion of the channel banks. The flanking probably was caused by the refraction of waves entering the inlet and striking the channel banks obliquely. Also, the expansion of the flood currents, upon exiting from the guides of the jetties, cause eddies to form which may result in scour of the unprotected banks. Following stabilization and the accompanying dredging, the unprotected channel banks began to widen dramatically. At a point about 650 ft. (198m) west of the present highway bridge, the channel widened 580 ft. (176.9m) during the following year and a half. In an effort to curtail the erosion, steel sheet-piling and riprap were extended along the channel banks in 1943 and again in 1963. However, each addition merely displaced the erosion pattern more westward. Today the erosion west of the protected channel banks is still continuing. The progressive widening can be seen by referring back to Figure 2.

Concomitant with the general widening of the unstabilized portion of Indian River Inlet was also a general deepening and thus a trend of increasing cross sectional area. This trend has caused the hydraulic characteristics of the inlet to change over time, including an increase in the tidal prism, enhancing the water quality of the adjoining bays. Comparison of past survey charts has revealed that the average cross sectional area has increased 15 fold since 1936. This increase has been manifested by a three-fold increase in the average width, 380 to 1,160 ft (116 to 354m) and a five-fold increase in the average depth of 3.5 to 18 ft (1.1 to 5.5m).

INLET HYDRAULICS

a. Development of Numerical Model. In order to gain a better understanding of the overall hydraulics, a one-dimensional numerical model was developed which encompassed all the bays and waterways from Indian River Inlet to Roosevelt Inlet. It provided a basis for simulating the tides and the cross sectionally averaged currents at any location within the system. The tides and currents (discharges) predicated by the model were compared with measured field data at specific locations and gave surprisingly accurate results. No effort was made to "fine tune" or calibrate the model to exactly predict the field data since the simplicity of the model would preclude such accuracy and also it was uncertain whether or not these measured data were representative of the average conditions.

The governing equations used in the model are the depth-integrated equations of motion and continuity. The effect of wind and the addition of freshwater inflow were neglected in the application and development of this model, although they are easily added. The vertically integrated differential equation of motion can be written in a semi-linearized form for flow in the x-direction as follows:

$$\frac{\partial q}{\partial t} = -g\ D\ \frac{\partial \eta}{\partial x} - \frac{\tau}{\rho} \qquad (1)$$

where q = discharge per unit width in the x-direction

t = time

g = gravitational constant

D = total depth = $h+\eta$

h = depth at mean sea level

η = tide displacement above mean sea level

x = horizontal distance coordinate in flow direction

ρ = mass density of salt water

τ = frictional stress on the bottom of water column

$= \dfrac{\rho f\ q|q|}{8D^2}$

f = Darcy-Weisbach friction factor

The continuity equation for one dimension is expressed as:

$$\frac{\partial \eta}{\partial t} + \frac{\partial q}{\partial x} = 0 \qquad (2)$$

For computation these equations were cast into finite difference form, and the bays and waterways of the system were divided into finite segements. In the operation of the model a time and space staggered procedure is used in which the equation of motion is applied between midpoints of the adjacent segments (i.e., across segment boundaries) at full time steps, t, and the continuity equation is applied at each segment at half time step increments.

The finite difference form of Equation (1), expressed in terms of total discharge onto the n^{th} segment Q_n, follows, as:

$$Q_n' = \frac{Q_n - \overline{WD}\ g\left[\eta_n - \eta_{n-1}\right]\frac{\Delta t}{\Delta x}}{1 + \dfrac{\overline{W}\Delta t f|Q_n|}{8(\overline{DW})^2}} \qquad (3)$$

where Δt = time step

Δx = space step

W = segment width

The primed quantities indicate unknown quantities whose values are determined at time $t + \Delta t$, from the unknown quantities on the right-hand side of the equation. The over-barred quantities represent averages based on the n^{th} and $(n-1)^{th}$ segments.

The continuity equation is expressed in finite difference form as:

$$\eta_n' = \eta_n + \frac{\Delta t}{\Delta x}\frac{1}{W_n}(Q_n - Q_{n+1}) \tag{4}$$

The segment characteristics used in the model are given in Table 1 and their locations, in Figure 5. Where small inlet segments connect two very large bodies of water, such as Indian River Inlet and "The Ditches", a Keulegan (1967) type inlet equation is used. The equation may be expressed as an example for Indian River Inlet as:

$$Q_2 = \frac{A_c \sqrt{2g|\eta_1 - \eta_2|}\ \mathrm{sign}\ (\eta_1 - \eta_2)}{\sqrt{K_{en} + K_{ex} + f\ell/4R}} \tag{5}$$

where A_c = cross sectional flow area of Indian River Inlet

Q_2 = flow onto Indian River Bay from the Atlantic Ocean

η_2 = Indian River Bay tide

η_1 = Atlantic Ocean tide (specified)

K_{en} = entrance loss coefficient = 0.3

K_{ex} = exit loss coefficient = 1.0

R = hydraulic radius of the inlet

ℓ = length of the inlet

f = Darcy-Weisbach friction factor

The boundary conditions to be specified are the ocean and Delaware Bay tides at the mouths of Indian River Inlet (3.8 ft (1.2m) mean, 4.6 ft (1.4m) spring) and Roosevelt Inlet (4.4 ft (1.3m) mean, 5.2 ft (1.6m) spring), respectively (NOAA, 1977). The average time lag between each location was calculated to be 0.77 hours based on a month's tidal prediction, with the tides of Roosevelt Inlet lagging behind those of Indian River Inlet.

The development of the model was based on a similar study at Navarre Pass, Florida, (Coastal and Oceanographic Engineering Laboratory, University of Florida, 1973).

Bay and Waterway Segments

#	Length(ft)	Width(ft)	Depth(ft)	f	Description
1					Atlantic Ocean Tide
2	31,000	11,000	6	0.03	Indian River Bay
3	21,000	16,000	6	0.03	Rehoboth Bay
4	4,800	100	3	0.03	
5	4,800	100	3	0.03	
6	6.600	75	6	0.03	Lewes
7	4,500	100	6	0.03	and
8	4,500	100	6	0.03	Rehoboth
9	4,500	100	7	0.03	Canal
10	4,500	100	7	0.03	
11	4,500	100	7	0.03	
12	4,000	150	10	0.03	
13	4,000	150	10	0.03	
14	800	500	12	0.03	Canal-Inlet Junction
15	3,700	150	9	0.03	Lower Broadkill
16	3,700	150	5	0.03	River Section
17	3,700	150	5	0.03	
18	9,000	1,000	3	0.03	Effective Marsh System
19					Delaware Bay Tide

Inlet Characteristics

Length(ft)	Width(ft)	Depth(ft)	f	$K_{en}+K_{ex}$	Description
6,000	800	16	0.03	1.3	Indian River Inlet
4,000	1,000	5	0.03	1.3	"Ditches"
2,000	470	12	0.03	---	Roosevelt Inlet

Table 1 Characteristics of Hydraulic Model Segments

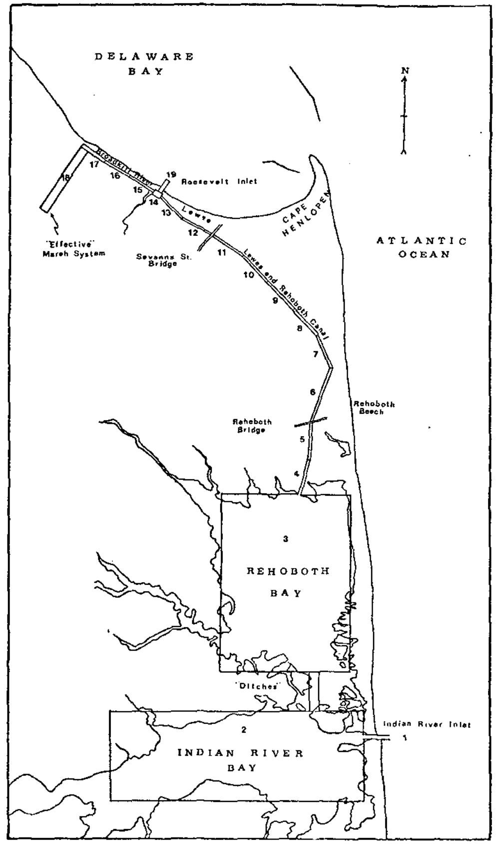

Figure 5 Schematization of the Bay and Waterway Segments, Roosevelt to Indian River Inlet

b. Results and Data Comparison. The results of the model were compared to tide and current measurements recorded at Roosevelt Inlet and the L&R Canal (Savannah Street Bridge - see Figure 5 for location) during June 1977, as well as with any other readily available source, such as the NOAA tide tables. Generally, the model showed good correlation with the field data but underpredicted the peak discharges and over predicted the peak tidal amplitudes. At Roosevelt Inlet the discharge peaks measured in the field were underpredicted by the model by as much as 40%.

Table 2 lists the predicted flow volumes for various locations in the system. The total volume passing the mouth of the Broadkill River $8.36\text{x}10^7$ ft^3 ($2.34\text{x}10^6 m^3$) was adjusted in the model by varying the dimensions of the "effective marsh" Segment No. 18 to match field measurements by DeWitt (1968).

The most apparent result indicated by Table 2 is the net southerly flow present throughout the system. The net volume pumped during each tidal cycle is approximately $6.3\text{x}10^6$ ft^3 ($1.76\text{x}10^5$ m^3) for mean tide conditions and $7.8\text{x}10^6$ ft^3 ($2.18\text{x}10^5$ m^3) for spring tide conditions. This net volume pumped is represented by a mean flow of 141 and 176 cubic feet (3.9 and $4.9m^3$) per second per tidal cycle for mean and spring tidal conditions, respectively (roughly 0.2-0.3 ft/sec (0.09m/sec) in the L&R Canal). The net volumes listed for all locations seem to indicate that mass is not conserved within the system (i.e., $6.3\text{x}10^6$ ft^3 enter through Roosevelt Inlet and $7.15\text{x}10^6$ ft^3 exit through Indian River Inlet for mean tide conditions). This error (18%) is a result of the computer accuracy in performing the integration routine for net volume over the complete tidal cycle and is not reflective of the time marching solution.

The current measurements recorded for this study also indicate the presence of a net southerly flow. For instance, a net southerly flow volume of $1.0\text{x}10^7$ ft^3 ($2.8\text{x}10^5$ m^3) was recorded at Savannah Street Bridge, which reduces to a mean flow of 230 ft^3/sec ($6.4m^3$/s). This phenomenon has also been indicated in another set of recent field data (Jensen, 1977). More interestingly, a study dated back to the year 1930, undertaken to determine the effect of the Lewes and Rehoboth and Assawoman Canals on the behavior of Indian River Inlet, also revealed a net southerly flow out of the L&R Canal, which at this time was calculated to be $5.5\text{x}10^6$ ft^3 ($1.54\text{x}10^5$ m^3) (Indian River Inlet Commission, 1931).

The mean pumping to the south within the system is due to the combined effect of the mass transport of the two tidal waves entering each inlet, as well as the frictional characteristics of the system. A reasonable approximation of the net discharge quantity through the canal results, if one considers two separate tidal waves entering at each inlet and subtracts the respective mass transports for the net result. From long-wave theory the mass transport per unit width, M, is expressed as:

$$M = \rho q = E/C \qquad (6)$$

TABLE 2. Predicted Flow Volumes* for Various Locations

Location	Mean Tide Conditions				Spring Tide Conditions			
	Volume Over One Tide Cycle $ft^3 \times 10^{-6}$		Net Volume $ft^3 \times 10^{-6}$	Mean Flow $ft^3/s \times 10^{-2}$	Volume Over One Tide Cycle $ft^3 \times 10^{-6}$		Net Volume $ft^3 \times 10^{-6}$	Mean Flow $ft^3/s \times 10^{-2}$
	North	South			North	South		
Roosevelt Inlet	59.1	65.4	6.3 S+	1.41	66.6	74.4	7.83 S	1.75
Broadkill River Mouth	41.8	41.8	0	0	47.1	47.1	0	0
Savanna Bridge	13.3	19.6	6.3 S	1.41	14.7	22.6	7.85 S	1.76
Rehoboth Bridge	9.08	15.4	6.3 S	1.41	9.61	17.5	7.86 S	1.76
"Ditches"	253	259	6.6 S	1.49	271	279	8.48 S	1.89
Indian River Inlet	940 (flood)	947 (ebb)	7.15 (ebb)	1.60	1063 (flood)	1072 (ebb)	9.10 (ebb)	2.04

* Numbers Rounded Off After Computation
+ S or N indicates direction

where

$$E = \text{wave energy} = \frac{\rho g H^2}{8} \tag{6}$$

$$C = \text{wave celerity} = \sqrt{g\,h}$$

with all other terms previously defined. Solving for q and expanding:

$$q = \frac{gH^2}{8\sqrt{g\,h}} \tag{7}$$

Defining the net discharge per unit width as $q_{net} = q_c - q_o$ where the subscripts "c" and "o" refer to the canal and Altantic ocean entrances, respectively, equation (7) may be cast in the following form:

$$q_{net} = \frac{g}{8}\left[\frac{H_c^2}{\sqrt{g\,h_c}} - \frac{H_o^2}{\sqrt{g\,h_o}}\right] \tag{8}$$

Substituting the appropriate quantities of H_c = 4.4 ft (1.34m) and h_c = 10 ft (3.05m) for the canal and H_o= 3.8 ft (1.16m) and h_o= 16 ft (4.88m) for Indian River Inlet into equation (8), we find q_{net}= 1.77 ft^2/s (0.17m^2/s). For the canal, which is approximately 100 feet (30.5m) in width, the net discharge would be 177 ft^3/s (5.0m^3/s). This estimate is reasonably close to that quantity predicted by the model of 141 ft^3/s (4m^3/s) for mean tidal conditions.

The effect of friction within the system can be evaluated from the following results. The model predicts that high tide occurs roughly about the same time in Indian River Bay and in the southern end of the L&R canal, with high tide occurring in Rehoboth Bay approximately 1.9 hours later, hence the tidal division line lies within Rehoboth Bay. In addition, low tide in Indian River Bay is predicted to occur nearly 1.4 hours before it occurs at the southern end of the canal. This indicates that Rehoboth Bay starts to drain through "The Ditches" into Indian River Bay long before it drains into the L&R Canal.

Therefore, in summary, it is felt that the mean pumping throughout the system is caused by the dominate southerly discharge, propagating completely through the canal into Rehoboth Bay on flood tide, whereupon during ebb tide Rehoboth Bay drains more favorably toward the south through a less frictionally resistant passage.

c. Effects of Net Flow. The amount of sediment carried into or out of an inlet is dependent on the power available in the ebb and flood flows to move the sediment plus the amount of sediment supplied to the inlet by littoral transport. When a mean flow is present over the tidal cycle, a bias in the tidal power exists, and this can materially affect the depositional characteristics of the inlet. A study by Costa and Isaacs (1975), using both a physical and numerical hydraulic model, showed that the superposition of a small current upon an unbiased tidal flow significantly altered the deposition pattern around the inlet. In fact, the results of their physical movable bed model indicate that a secondary flow of one percent of the main flow directed in the ebb direction results in at least a twelve percent increase in sediment load being carried seaward.

Following the ideas and developments set forth by Costa and Isaacs, the effect of the anisotropic flow through the bay and canal system on the tidal power available for sediment transport was investigated. Within this development it is assumed that the work done in transporting sediment in the flood and ebb directions can be expressed as:

$$I_{f,e} \sim \int_{f,e} P(t)dt \sim \int_{f,e} \varepsilon V^3(t)dt \tag{9}$$

where $I_{f,e}$ = work accomplished in transporting sediment in the flood and ebb directions

$P(t)$ = power utilized in sediment transport

$V(t)$ = velocity in the inlet as predicted by the model

ε = transport efficiency

The transport efficiency developed empirically by Costa and Isaacs after data presented by Inman is shown to be a function of the stream power as given by:

$$\varepsilon = 0.01 \left[\left(\frac{V}{V_C}\right)^3 \right]^{1.86} , \quad V_C^{\ 3} < V^3 < 5V_C^{\ 3} \tag{10}$$

where V_C = velocity at which incipient motion begins

It was assumed that for the range of particle sizes present in the inlet, approximately 0.4mm to 1.0mm, that 20 cm/sec or 0.66 ft/sec would be representative of the critical velocity, V_C, based on a curve developed by Hjulström (1935) contained in Graf (1971).

The work done on sediment transport for both flood and ebb tide at Roosevelt Inlet was computed from the numerical integration of Equation 9 with the results given in Table 3.

TABLE 3 Sediment Transport Work Per Tidal Cycle at Roosevelt Inlet

Tide Condition	Available Work Per Tidal Cycle (ft-lbs)			Work Ratio Flood/Ebb
	Flood	Ebb	Net	
Mean	148	26	122 F	5.7
Spring	470	72	394 F	6.2

It is readily apparent that the mean pumping into the inlet results in a signficant bias of the available tidal work to transport sediment into the inlet. In fact, the results show that the sediment transport work is approximately six times greater for flood than ebb. Although no investigation of the tidal power at Indian River Inlet was undertaken, it is clear that a similar, but opposite, (ebb to flood) bias exists.

The effects of the sediment transport bias should be reflected in the depositional characteristics of each inlet. At Roosevelt Inlet, the majority of the sediment that enters the channel deposits in lobe-like shoals along both banks (as mentioned previously), eventually clogging the rear of the entrance channel. In addition, strong evidence of the presence of on ebb-tidal shoal was not found (at least within the survey limits of this project). Both of these factors suggest a net flood transport as predicted in the model.

At the other end of the system, indications of a net seaward sediment transport should be evident. One indication of this has been the development of a rather extensive ebb tidal shoal currently estimated to contain 4,884,000 yd^3 (3,763,260m^3). Secondly, the sediment introduced to the system through erosion and scour of the inlet channel seems to have been dominated by ebb tidal flows since an overall loss within flood tidal shoals has been evident. Estimates of the material within the general vicinity of the flood shoals show slightly over one million cubic yards ($7.65 \times 10^5 m^3$) has been removed.

STABILITY ANALYSIS

In the preceding section it was surmised that the bias of tidal power can significantly influence the depositional patterns and hence the sedimentary stability of the inlets. At Roosevelt Inlet there was a tendency toward closure as sediment was continually trapped within its throat. On the other hand, Indian River Inlet is thought to be quite stable against closure with scour and enlargement present. In this section, the sedimentary stability of these two inlets will be further investigated by adopting the concepts developed by Escoffier (1940), O'Brien (1969) and Jarrett (1976).

A stability curve of maximum inlet velocity, V_{max}, versus the inlet cross sectional area, A_c, based on the concepts first developed by Escoffier, was generated for Roosevelt Inlet through the use of the numerical model discussed previously. Historic cross sections were fed into the computer, and a corresponding V_{max} was calculated using spring tidal conditions. Further cross sectional area data were generated, assuming the area could continually decrease with a minimum width of 200 ft (61m). The resulting curve is shown in Figure 6. It is seen that the inlet has always been in the stable portion of the curve. The change in cross section along this portion of the curve has been principally dominated by dredging activity. A closer look at the data indicates a general trend of increasing cross sectional area following dredging activity prior to June 1963. After this date, reductions in cross sections are evident following dredging activity.

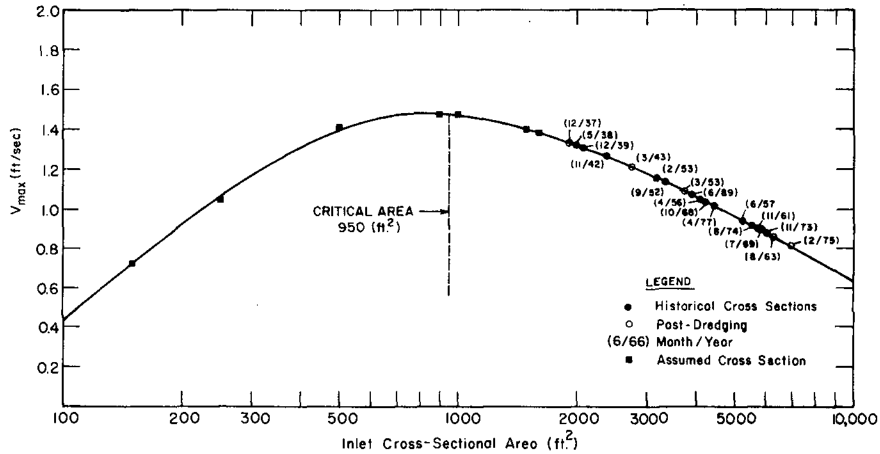

Figure 6 Stability Curve for Roosevelt Inlet

This trend reversal has presumably been caused by the rapid deterioration of the jetties accompanying the devastating 6-8 March 1962 storm which, in turn, altered the nature and rate of deposition.

Other approaches to inlet stability by O'Brien and Jarrett have been based on empirical relationships between the inlet throat cross sectional area and the tidal prism. These relationships are mostly based on data of inlets that connect the ocean with a bay or bays; thus Roosevelt Inlet is a unique case. With this in mind the effect of the mean flow on the sedimentary stability of the inlet may somewhat supersede the prism area relationships at hand.

If it is assumed that the tidal prism can be closely represented by the following:

$$P = A_c \int_0^{T/2} V_{max} \sin \frac{2\pi t}{T} dt = \frac{A_c V_{max} T}{\pi} = \frac{Q_{max} T}{\pi} \tag{11}$$

where T is the semidiurnal period of 44,700 seconds. The tidal prism-area relationships of these investigators may be plotted with the stability curve. Where intersection occurs between the stability curve and the prism-area curve, the inlet is expected to reach an equilibrium satisfying both hydraulic and sedimentary properties. These curves are shown plotted in Figure 7. The figure shows that the stability curve lies below the prism-area curves for all cross sections, indicating a strong tendency for closure to occur. However, the exact position of the stability curve is open to question since: (1) The model used in generating the curve generally underpredicted the peak flows measured

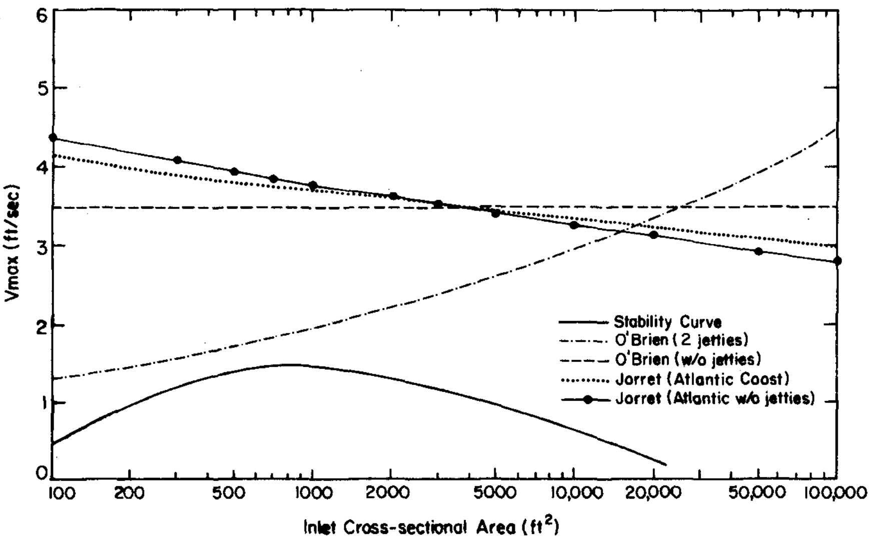

Figure 7 Stability and Prism-Area Curves for Roosevelt Inlet

in the field and (2) the prism-area relationships were developed from inlets on fully exposed coasts unlike Roosevelt Inlet, and (3) the prism-area relationships are not directly applicable since they were derived mostly from inlets without net flows.

Similar curves were also generated for Indian River Inlet through analytical means. Historic average inlet cross sections were plotted, based on theoretical relationships presented by O'Brien and Dean (1972). These points are shown in Figure 8, marked with the appropriate date.

Additional points corresponding to cross sectional areas larger than the present were computed for the inlet deepening but not widening. The solid line was computed, based on a constant rectangular cross sectional shape, the width 20 times the channel depth. It is seen from the figure that the inlet has progressed from the unstable (frictionally dominated) portion of the curve, through the critical area and into the stable portion with a present cross sectional area of about 20,000 ft^2 (1,860m^2).

The solid stability curve was also plotted with the various tidal prism area relationships as shown in Figure 9. All these prism-area curves intersect the stability curve near A_c = 31,000 ft^2 (2,883m^3) and V_{max} = 3.6 ft/sec (1.1m/sec). As mentioned beforehand, the inlet could be expected to reach an equilibrium state when it suffices both relationships simultaneously. The present enlargement trend of the inlet channel may be an attempt to reach this equilibrium area.

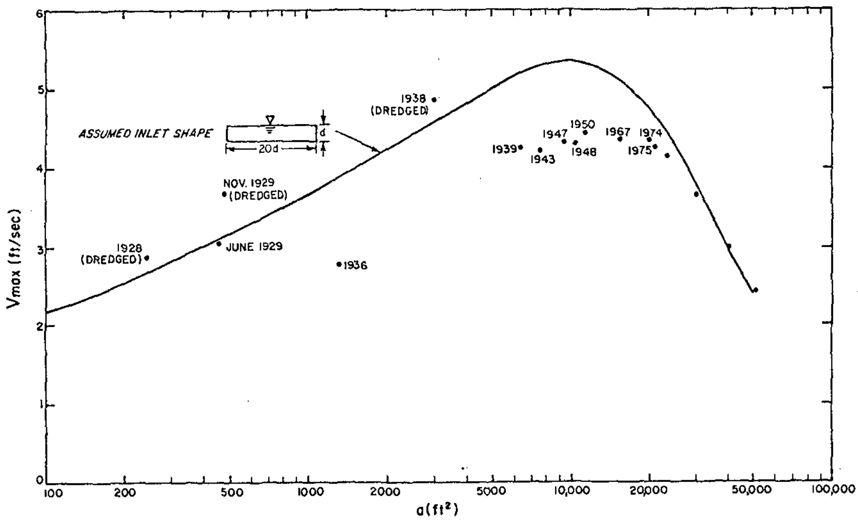

Figure 8 Stability Curve for Indian River Inlet for Historical and Assumed Cross Sections

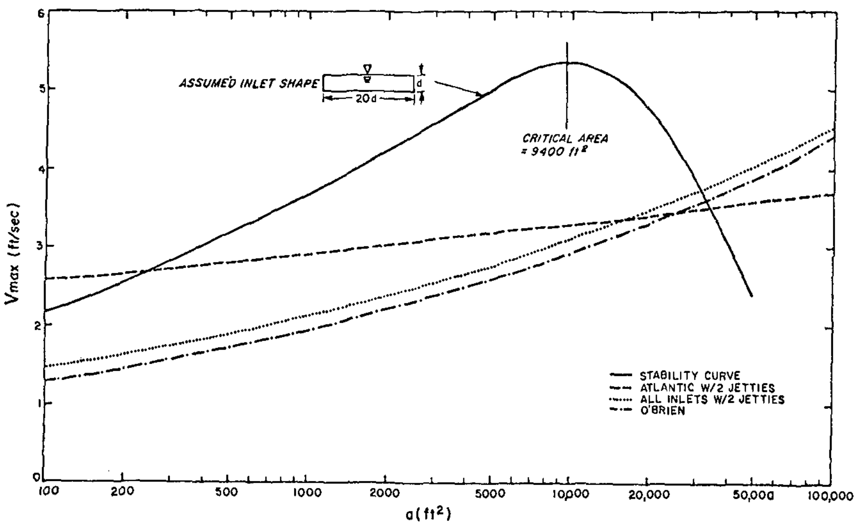

Figure 9 Stability and Prism-Area Curves for Indian River Inlet

Overall, the results of the stability and prism-area concepts reveal that neither of the inlets is presently in equilibrium. For Roosevelt Inlet a tendency for reduction in area is evident, mostly through a decrease in width from the developing sand lobes along the banks. At Indian River Inlet a tendency for cross sectional enlargement is expected to continue, mostly through a general deepening.

A true equilibrium will only exist if there is a zero mass transport through the system. The cross sectional enlargement at Indian River Inlet and decrease at Roosevelt Inlet are possibly natural adjustments to gradually alter the respective flow regimes at each inlet to reach a zero net flow condition.

CONCLUSIONS

1. Downdrift erosion is the major problem that developed after the stabilization of each inlet. In both cases sediments easily enter the inlet channel where they are transported to developing shoals with no apparent natural return to the littoral system. Sand primarily enters Indian River Inlet through the overtopping of the impounded south jetty. At Roosevelt Inlet sediments are readily transported past the badly deteriorated steel sheet pile structures.

2. The results of a one-dimensional hydraulic model, as well as field measurements, predict the presence of a mean southerly flow through the canal and bay system which connect Roosevelt and Indian River Inlets. This flow is believed to cause a major bias in the tidal power available for sediment transport at each inlet (6 to 1 at Roosevelt Inlet), thus significantly influencing the depositional characteristics at both locations.

3. The tidal power bias, as well as stability and equilibrium analyses, indicates that at Roosevelt Inlet a tendency toward closure is evident; whereas, Indian River Inlet seems quite stable against such an occurrence.

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ACKNOWLEDGMENTS

These studies were supported by the Office of Sea Grant Programs under grants to the University of Delaware.