CHAPTER 112

CAPACITY OF INLET OUTER BARS TO STORE SAND

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ABSTRACT

Inlets act as large sand sinks for sand derived from adjacent beaches. An attempt to quantify the amount of sand in an outer bar is made with the major governing parameter of inlet hydraulics, tidal prism. In areas of high wave activity there appears to be a well defined limiting relationship to the amount of sand stored in the offshore bar as a function of tidal prism. In areas where inlets are exposed to lower wave activity, more scatter is noted in this correlation.

Relationships for estimating the equilibrium storage volume of sand in the outer bar/shoal of newly cut inlets on highly exposed, moderately exposed, and mildly exposed coasts (where degree of exposure relates to wave action offshore) are proposed for use in estimating quantities of sand which will eventually be lost to adjacent beaches.

A conclusion of the study is that more sand is stored in the outer bar of a low energy coast than in the outer bar of a high energy coast. An upper limit to outer bar storage in low energy zones may be a function of additional parameters other than tidal prism such as longshore energy flux at the inlet site and inlet history.

INTRODUCTION

A commonly recurring problem of importance to coastal engineers is evaluating the number of inlets which a given length of shoreline can maintain in terms of inlet stability, and the degradation which a given inlet will cause to the surrounding shoreline. A considerable amount of research effort has been placed on the hydraulic aspects of inlet design and is discussed in References (1,2,3,4,5, and 6). Little research though has been done on the effects of inlets on adjacent shorelines (7). It is apparent that these effects are considerable when a correlation of shoreline erosion rates and locations of tidal inlets are made. In Florida, shoreline recession rates in the near vicinity of inlets are one to two orders of magnitude higher (10-70 feet per year) than average shoreline recession rates away from the influence of inlets (1-3 feet per year) (8). It is apparent that these inlets act as sand sinks in their capacity to absorb tremendous quantities of sand in both their outer bars and their inner shoal areas. Unfortunately this sand is derived from adjacent beaches and causes a consequental degradation to those beaches. An idea as to the magnitude of the inner shoal volumes of

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sand trapped by an inlet is given in Table 1. The data in this Table are calculated from comparative surveys of the inlets over the period of years noted. It appears that the inner shoals of inlet systems may reach an equilibrium shoaling volume (Reference (10)) after a given period of time, therefore decreasing the erosional influence on adjacent shorelines (assuming no dredging of inner shoals takes place).

It seems reasonable to assume at first that such a process might occur on outer shoal/bars of inlets also. If an inlet is to be cut in a barrier island system, it is desirable to have an estimate of this sand volume which will eventually be lost from the surrounding beaches to the outer bar/shoals and to the inner shoals of the inlet. The present paper discusses a correlation between the amount of sand stored in the outer bar of an inlet and the inlet tidal prism or the inlet channel cross section. Assuming one can properly estimate the inlet hydraulics and equilibrium cross-sectional area which an inlet will take, this correlation should allow a coastal engineer to obtain a rough approximation of the final consequences which the opening of an inlet will have on adjacent shorelines.

METHODOLOGY

Calculation of Sand in Outer Bar/Shoals

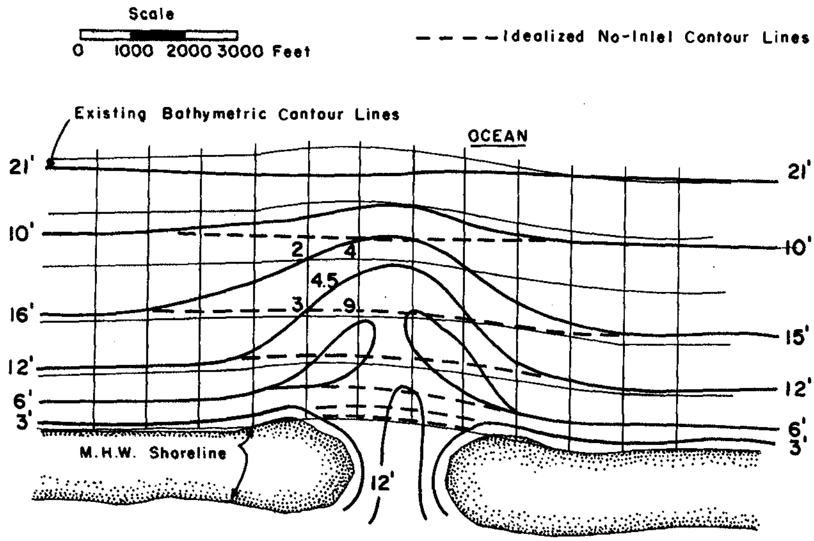
The procedure followed in calculating the volumes of sand residing in the outer bar/shoals of inlets is covered in depth in Reference (7). A summary of the methodology follows.

The parallel contour lines upcoast and downcoast of an inlet away from the influence of the inlet, were assumed as the natural topography of the coast without the inlet. This idealized "no-inlet" hydrography was then superimposed on a chart of the actual hydrography for the inlet. Depth differences between the actual existing bathymetry and the idealized "no-inlet" bathymetry were then calculated at the intersections of a grid system and averaged for each grid square and summed to give a volume of sand in the outer bar. The procedure for calculation is summarized in Figure 1 from Reference (7). As the procedure is somewhat subjective, the total difference in sand volume between the idealized "no-inlet" shoreline and the existing inlet shoreline was calculated two or more times for each inlet system with acceptable answers showing less than 10% deviation in the bar/shoal sand storage volumes calculated. Volumes of sand in outer bar/shoals of inlets on the lower East Coast of Florida were very hard to estimate in this manner due to complicated offshore reef structures in the nearshore zone and in all but one case were eliminated from further consideration. Volumes of sand stored in the outer bar/shoals of 44 inlets around the sandy portion of the United States coastline were calculated in the above manner and are presented in Table 2.

As an indication of how extensive some inlet outer bar/shoal systems are, Figure 2 shows an inlet outer bar/shoal system for St. Mary's River Entrance. St. Mary's River Entrance on the Florida-Georgia border has shoals extending over five nautical miles offshore (from the updrift coastline). This inlet has one of the largest offshore bar/shoal systems

Table 1. Volumes of Material Deposited in Inlet Bay Shoals

Inlet	Calculated Volume of Shoaled Material in Bay Shoals (cubic yards)		Period of Survey	Inlet History
Redfish Pass, Florida	3.75×10^6	(130,000/year)	1879 - 1956	Inlet opened in hurricane in 1926
Fort Pierce Inlet, Fla.	7.49×10^6	(160,000/year)	1879 - 1930	Inlet opened by man in 1921
St. Lucie Inlet, Fla.	7.46×10^6	(210,000/year)	1882 - 1930	Inlet opened by man in 1892
Sebastian Inlet, Fla.	2.58×10^6	(180,000/year)	1882 - 1938	Inlet opened by man in 1924 - has had a history of natural closure
Clearwater Pass Entr., Fla.	5.09×10^6		to - 1950	Inlet historically open
Carolina Beach Inlet, N.C.	4.00×10^6	(235,000/year)	1952 - 1969	Inlet opened in 1952 Reference (9)



Procedure

1. Construct Idealized No-Inlet Contour Lines

2. Impose 1000 foot square grid system on chart and calculate differences between actual depth and idealized no-inlet depth at grid line intersections (see example block)

3. Average depth differences at intersections and record in center of block (see example block)

4. Compute volume of sand in outer shoal by summing averaged block depth differences and multiply by 10^6 feet^2

Figure 1. Steps in Calculation of Accumulated Volume of Sand in the Outer Bar. Procedure Illustrated for Idealized Inlet. From Reference (7).

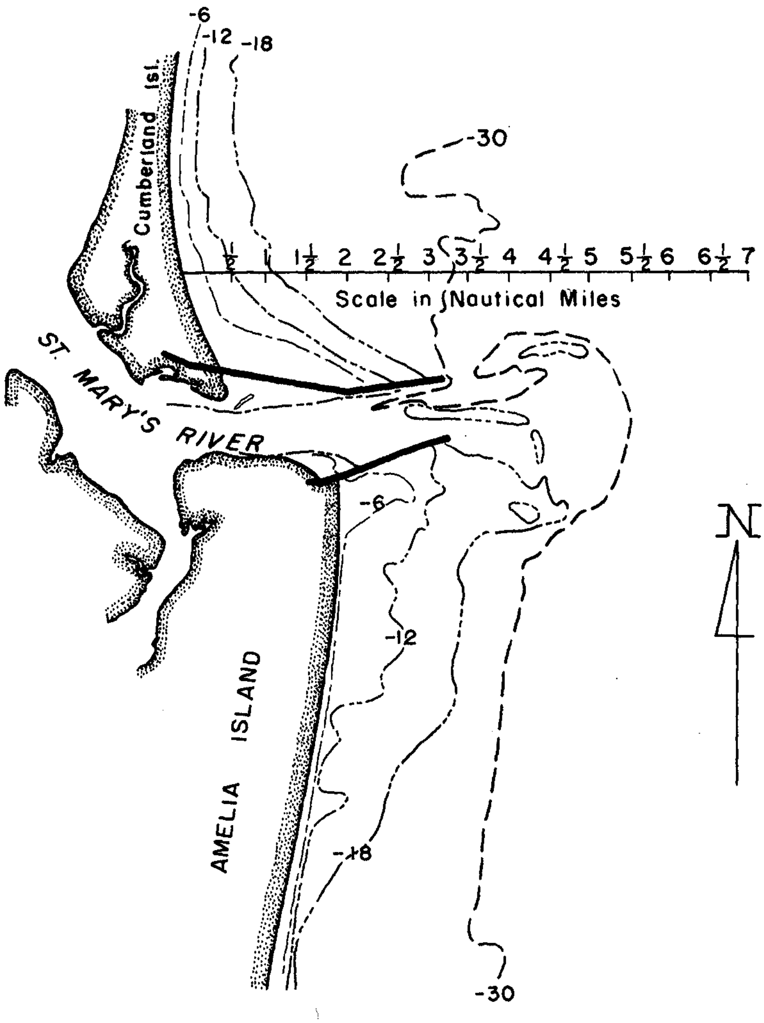


Figure 2. St. Mary's River Entrance.

of inlets investigated in Florida with over 136 million cubic yards of sand stored in it. The heavily developed area to the south of this inlet has historically suffered from erosion.

Tidal Prisms

Tidal prism measurements came from References (11,12,13,14, and 15). In most all of the cases the tidal prisms were either measured from current data taken at the throat of the inlet or by the "cubature method". Jarrett (14) discusses the cubature method in detail. In most all cases the date when the prism was measured corresponded to the survey date from which the estimate of outer bar sand volume was made.

Tidal prisms for the 44 inlets in which sand volumes have been calculated are presented in Table 2.

Channel Cross Section Areas

Channel cross section areas came from References (11,12,13,14, and 15) and from some additional measurements by the authors. In most all cases the cross section used was that at the throat area as defined in Reference (11), and were taken from the same survey as the inlet outer bar. Channel cross sectional areas are presented in Table 2.

Coastal Energy Regime

To suitably classify the data on inlets into some organizational scheme with regard to wave energy acting on the outer shoals of the inlets it was necessary to use some type of coastline parameters which gives a rough quantitative description of the energy potential available to modify the outer shoals of inlets. The parameters chosen were wave height, wave period, and nearshore continental shelf slope. Wave heights and wave periods available were average wave heights from wave gages in the nearshore zone (15 to 20 feet below MLW) from the Coastal Engineering Research Center wave gage program. As these wave heights already have the measure of continental shelf slope implicit in them (energy has been dissipated over the shelf up to the wave gage depth), the basic measure of wave energy used to separate energy environments was the parameter H^2T^2 (wave height^2 x wave period^2). On mildly exposed, moderately exposed, and highly exposed coastlines, this parameter was arbitrarly chosen to range from 0-30, 30-300, >300 respectively. This classification lumps the South Carolina, Texas, and lower Gulf Coast of Florida inlets into the mildly exposed coast range; the East Coast, and Panhandle of Florida (Gulf Coast) inlets into the moderately exposed coast range; and the Pacific Coast coasts into the highly exposed coast range. The (wave energy) parameter H^2T^2, and the offshore distance to the 5 and 10 fathom depth curves are given for various coastal segments in Table 3.

RESULTS

The data used in the correlations of tidal prisms with outer bar/shoal sand storage volumes are given in Table 2. Correlations were made for three coastal energy level groupings and for all inlets combined using

Table 2. Tidal Prism-Outer Bar Storage Volume Relationship

Inlet	Tidal Prism (ft^3)	Measurement Date	Outer Bar Volume (yd^3)	Survey Date	Cross Section Area at Throat (above MSL) (ft^2)
Little Egg, N.J.	17.2×10^8 (S)	1935	45.0×10^6	*	38.3×10^4
Brigantine, N.J.	5.23×10^8 (S)	1936	6.70×10^6	*	1.22×10^4
Great Egg Harbor Ent., N.J.	20.0×10^8 (S)	1936-37	24.2×10^6	*	7.01×10^4
Hereford, N.J.	11.9×10^8 (S)	1937	25.0×10^6	*	3.57×10^4
Oregon Inlet, N.C.	39.8×10^8 (S)	1965	27.2×10^6	*	6.66×10^4
Beaufort, N.C.	50.5×10^8 (S)	1935-36	45.4×10^6	*	8.66×10^4
Carolina Beach Inlet, N.C.	5.25×10^8 (S)	1967	3.51×10^6	1967	0.76×10^4
Stono Inlet, S.C.	28.6×10^8 (S)	May, 1934	93.2×10^6	*	5.43×10^4
North Edisto River, S.C.	45.8×10^8 (S)	Ref. (12)	216.0×10^6	*	9.95×10^4
Nassau Sound, Fla.	22.0×10^8 (S)	1934	53.2×10^6	1953-54	7.25×10^4
St. Augustine Inlet, Fla.	13.1×10^8 (S)	1957	106.0×10^6	1954-57	2.65×10^4
Barnegat Inlet, N.J.	6.25×10^8 (S)	1936	13.1×10^6	*	1.48×10^4
Indian River Inlet, Del.	5.25×10^8 (S)	1948	3.11×10^6	*	$.966 \times 10^4$
Winyah Bay S.C.	30.2×10^8 (S)	1935	73.6×10^6	*	7.86×10^4
St. Marys, Fla.	47.7×10^8 (S)	1937	136.0×10^6	1954-55	14.4×10^4
St. John's River, Fla.	17.3×10^8 (S)	1958-59	90.2×10^6	1967	5.73×10^4
Jupiter Inlet, Fla.	1.11×10^8 (S)	1967	0.97×10^6	1967	$.291 \times 10^4$

Table 2 (Continued)

Inlet	Tidal Prism (ft^3)	Measurement Date	Outer Bar Volume (yd^3)	Survey Date	Cross Section Area at Throat (aboveMSL) (ft^2)
Bakers Haulover, Fla.	3.6×10^8 (S)	1928	0.29×10^6	1928	$.438 \times 10^4$
Captiva Pass, Fla.	19.0×10^8	Aug. 1960	12.34×10^6	1956	2.87×10^4
Boca Grande, Fla.	126.0×10^8	1959	$175. \times 10^6$	1956	16.6×10^4
Gasparilla Pass, Fla.	4.7×10^8	Nov. 1958	6.90×10^6	1956	1.33×10^4
Midnight Pass, Fla.	2.84×10^8	Mar. 1955	0.63×10^6	1954	$.322 \times 10^4$
New Pass, Fla.	4.00×10^8	Sept. 1953	6.60×10^6	1954	$.637 \times 10^4$
Longboat Pass, Fla.	4.90×10^8	Oct. 1953	7.78×10^6	1954	1.14×10^4
Ponce de Leon, Fla.	5.74×10^8 (S)	1936	19.0×10^6	1924	1.15×10^4
Sarasota Pass, Fla.	7.6×10^8	Mar. 1955	18.7×10^6	1954	2.31×10^4
Pass-a-Grille, Fla.	14.2×10^8	1950	23.5×10^6	1952	3.5×10^4
John's Pass, Fla.	5.03×10^8	1951-52	6.30×10^6	1952	$.886 \times 10^4$
Clearwater Pass, Fla.	6.8×10^8	June. 1951	3.00×10^6	1950	2.23×10^4
Dunedin Pass, Fla.	3.76×10^8	1959	8.5×10^6	1950	1.44×10^4
East (Destin) Pass, Fla.	15.7×10^8	1938	4.90×10^6	1941-47	1.72×10^4
Pensacola Bay Entr., Fla.	94.5×10^8	Apr. 1940	49.1×10^6	1940	11.2×10^4
Mobile Bay Entr., Ala.	$200. \times 10^8$	June. 1935	$1173. \times 10^6$	*	31.5×10^4
Venice Inlet, Fla.	0.74×10^8	May. 1955	0.89×10^6	1954	$.236 \times 10^4$

Table 2 (Continued)

Inlet	Tidal Prism (ft^3)	Measurement Date	Outer Bar Volume (yd^3)	Survey Date	Cross Section Area at Throat (above MSL) (ft^2)
Galveston Entr., Texas	59.4×10^8	1934	$127. \times 10^6$	*	19.7×10^4
Aransas Pass, (Rockport) Texas	17.6×10^8	Ref. (15)	25.9×10^6	*	1.6×10^4
Redfish Pass, Fla.	5.67×10^8	Ref. (15)	4.25×10^6	1956-60	1.19×10^4
San Francisco, Ca.	$510. \times 10^8$	Ref. (12)	$1055. \times 10^6$	*	93.8×10^4
Tillamook Bay, Oregon	21.1×10^8 (D)	Ref. (12)	22.07×10^6	*	3.69×10^4
Grays Harbor, Washington	$170. \times 10^8$ (D)	Ref. (13)	$342. \times 10^6$	*	29.1×10^4
Columbia River, Oregon	$382. \times 10^8$ (D)	Ref. (13)	$1006. \times 10^6$	*	50.8×10^4
Nehalem River, Oregon	5.66×10^8 (D)	Ref. (13)	4.2×10^6	*	$.964 \times 10^4$
Umpqua River, Oregon	22.0×10^8 (D)	Ref. (12)	33.7×10^6	*	4.62×10^4
Coos Bay, Oregon	25.1×10^8 (D)	Ref. (13)	36.2×10^6	*	5.65×10^4

* Outer bar volume computed from Nautical chart of latest issue (Survey date unknown)

(S) Refers to Spring Tidal Prism (D) Diurnal Tidal Prism

Table 3. Classification of Coastline by Offshore Slope and Wave Energy

Coastal Area	Distance to: (in Nautical Miles) 5 fathom curve	10 fathom curve	Avg. Wave Ht. H (feet) *	Avg. Wave Period T. (seconds) *	H^2T^2 (ft^2 - sec^2)
New Jersey/Delaware	½ - 1/½	1 - 3	1½ - 2½	6½	169
North Carolina	¼ - ½	10 - 15	2 - 4	5	225
South Carolina	5 - 8	18 - 22	½ (Georgia)	5	1.6
Upper Florida (East Coast)	½ - 2½	11 - 17	2	5	100
Lower Florida (Gulf Coast)	2 - 5	11 - 20	1	4	16
Panhandle Florida (Gulf Coast)	¼ - 1	1 - 2	1½ - 2	4	49
Texas	1 - 3	5 - 8	1 - 1½	4	25
Oregon/Washington	½ - 1	1 - 2½	3 - 5	9	1296

* These are rough averages from gage(s) located in the nearshore zone of the areas noted and may vary considerably depending on a variety of factors (information from Coastal Engineering Research Center wave gage program).

an equation:

$$\forall = aP^b \tag{1}$$

where

$\forall$ = volume of sand stored in the outer bar/shoal of the inlet (in cubic yards of immersed sand),

P = tidal prism of inlet (in cubic feet),

a,b = correlation coefficients.

Linear regression was used to obtain the coefficient b for the case of highly, moderately, and mildly exposed inlets and for the case of all 44 inlets combined. For these four cases the coefficient b equals:

Highly Exposed Inlets	b = 1.23
Moderately Exposed Inlets	b = 1.08
Mildly Exposed Inlets	b = 1.24
All Inlets	b = 1.26

As there was no significant difference in the exponental correlation coefficients, the value b = 1.23 corresponding to high energy coast (Highly exposed) inlets was used for the correlations with all inlet groupings. The justification for this somewhat arbitrary fixing of parameters was that a minimum of scatter existed in the correlation of the Pacific Coast Inlets (Figure 3). The minimum scatter in this plot over two orders of magnitude is somewhat suprising in view of the many parameters which should be of importance in inlet outer bar shoaling such as inlet history, available longshore energy flux, and physiography of the inlet-coastal location. The reasons for this minimum scatter in the Pacific Coast inlets studies may be more apparent upon considering the variables causing sand shoaling in outer bars.

The mechanism whereby sand is fed to the outer bar is twofold. Ebb tide flows tend to drive the material offshore which is being fed to the inlet by longshore currents, and wave activity on the outer bar tends to drive the material back to shore while at the same time feeding sand to the inlet in adjacent longshore current systems. The inlet outer bar/shoal is self perpetuating in the sense that longshore currents feed sand to the inlet system which causes the outer bar to grow which in turn causes wave refraction and sheltering effects at the inlet promoting a continued flux of sand toward the inlet over an increasing area (16).

Inlet history is important too. Should the inlet close or the tidal prism be reduced drastically (due to modifications of the inlet inner bay system) much of this material would be driven back to the beaches. The principal author has noted this occurrance in two locations on both the East Coast and Gulf Coast of Florida. In the case of the Pacific Coast inlets studies, all of the inlets have been open over recorded history.

Physiography must play an important part also. The authors have

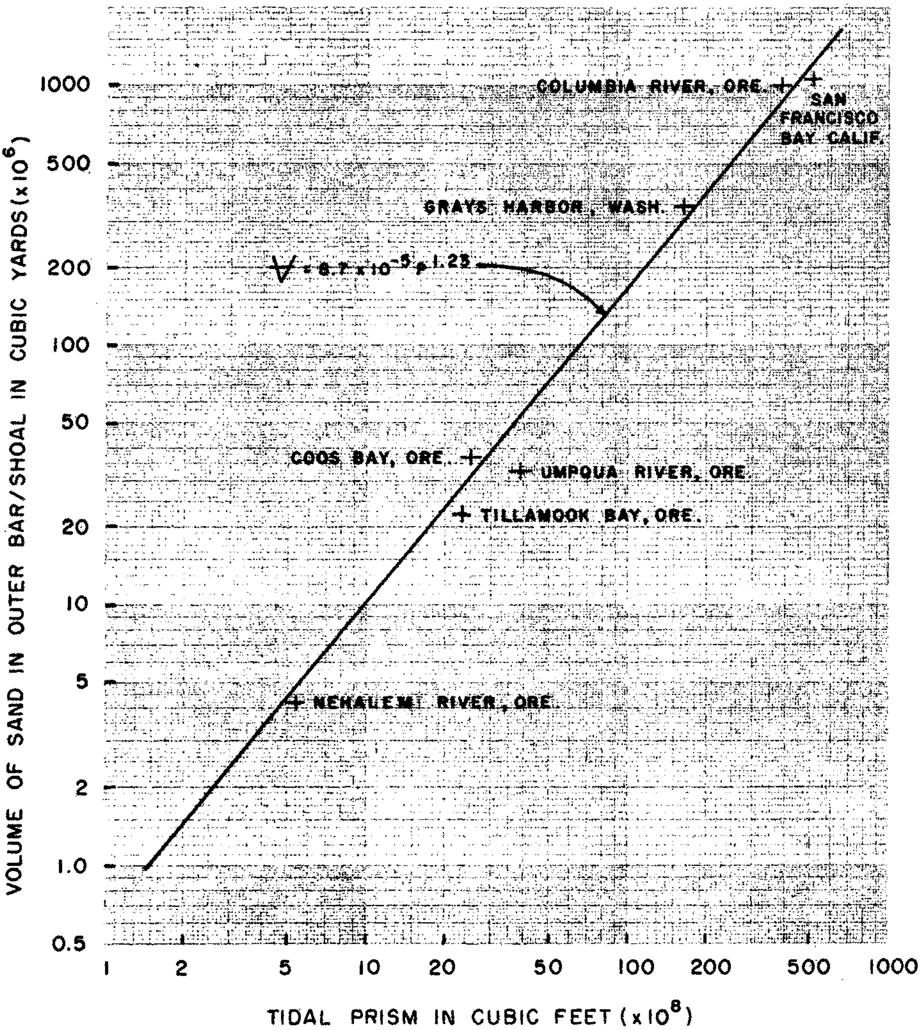


FIGURE 3. Tidal Prism-Outer Bar Storage Relationship for Highly Exposed Coasts.

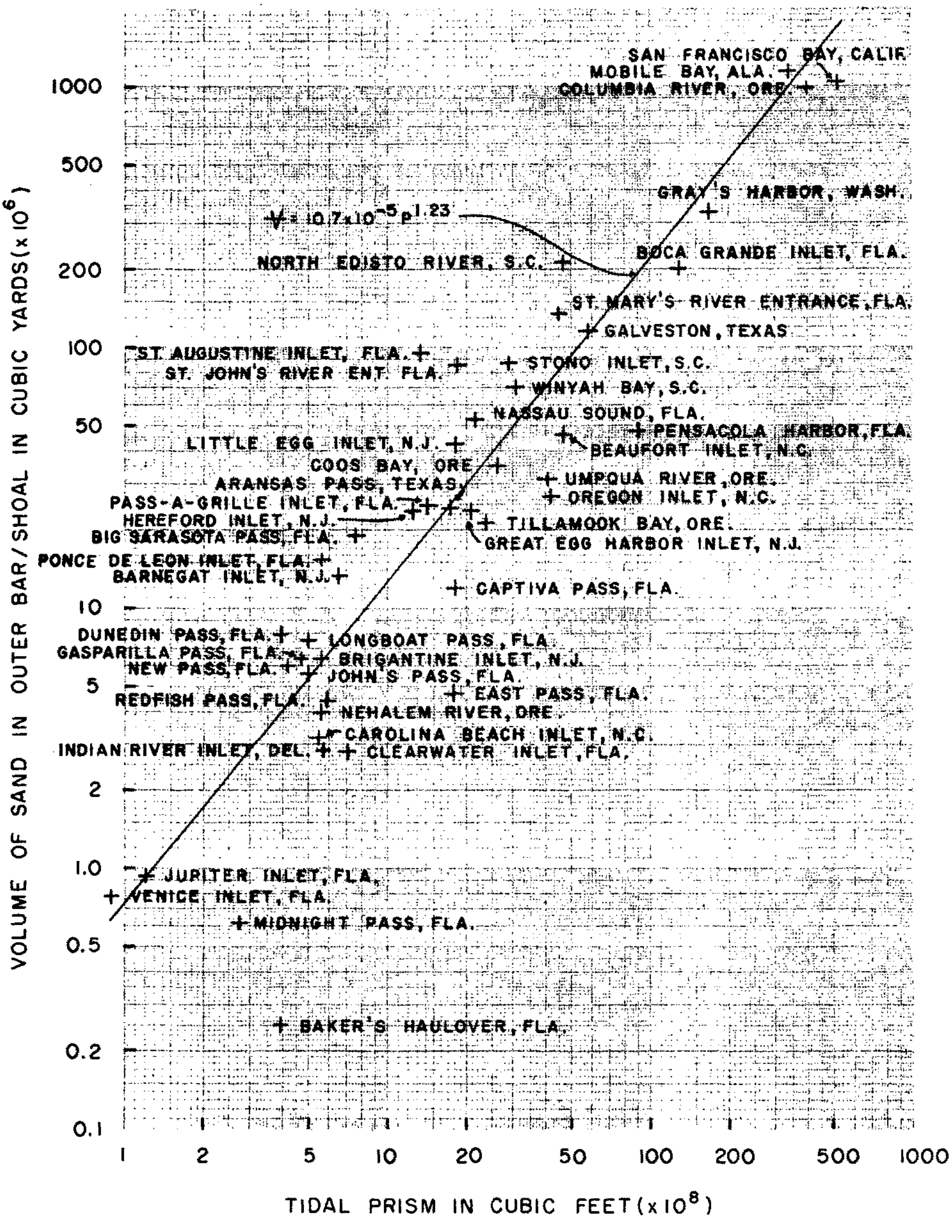


FIGURE 4. Tidal Prism-Outer Bar Storage Relationship for Inlets on Sandy Coasts.

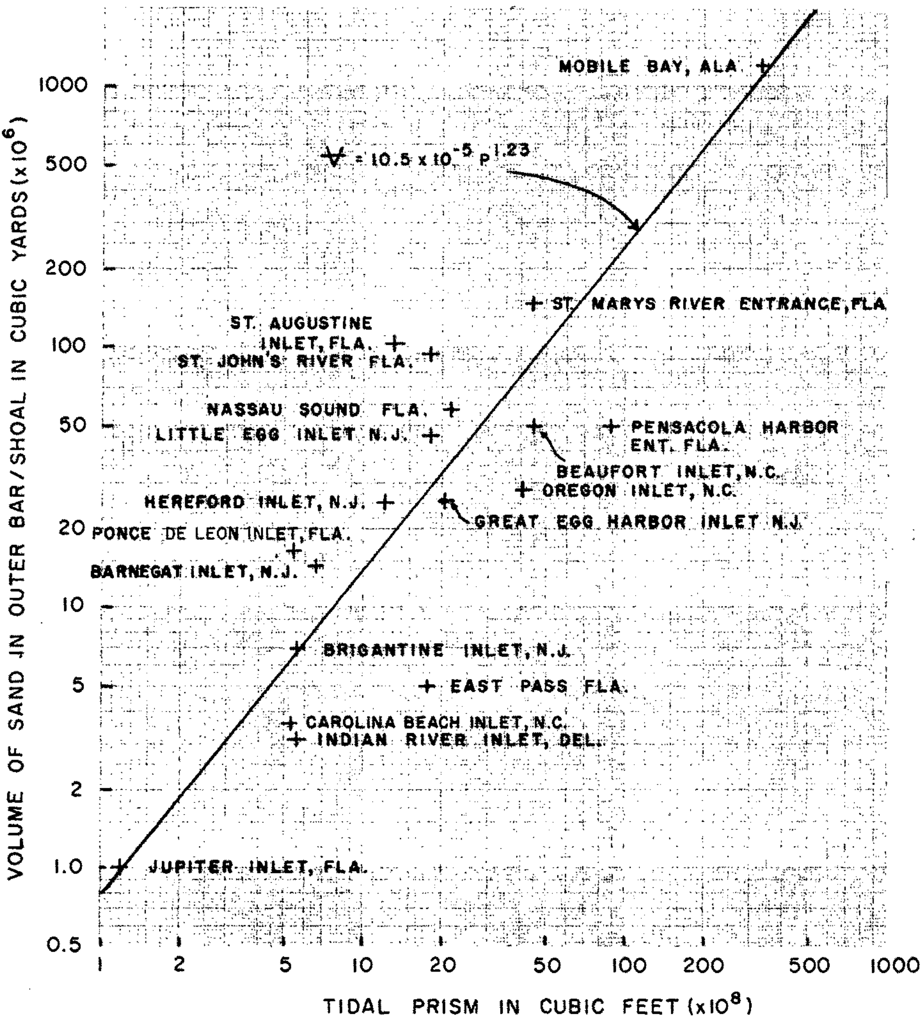


FIGURE 5 . Tidal Prism-Outer Bar Storage Relationship for Moderately Exposed Coasts.

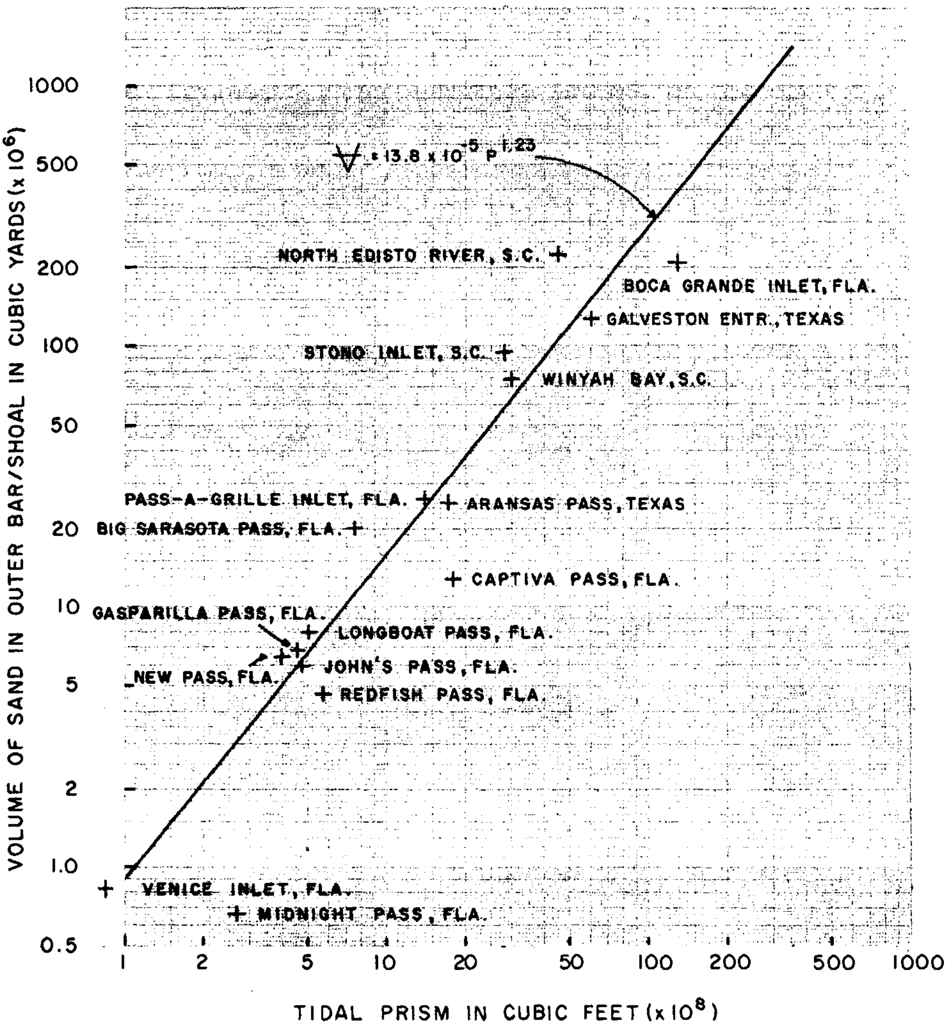


FIGURE 6 . Tidal Prism-Outer Bar Storage Relationship for Mildly Exposed Coasts.

noted that inlets which are estuarine (i.e., estuaries), have significantly smaller inner shoals most likely due to the predominance of ebb flow during landward flooding periods. The Pacific Coast inlets used for the highly exposed coast correlation are alike in that they are estuary systems.

Thus, the Pacific Coast inlets are physiographically similar, historically open, and have similar (in a gross sense) longshore energy flux levels; and, therefore, should experience less scatter.

Using the exponential correlation coefficient b = 1.23, analysis was made to determine the correlation coefficient a and the corresponding volume - prism relationship for the three groupings of inlets and for the 44 inlets combined. The corresponding equations are shown below:

Highly exposed coasts (7 inlets)	$\not{V} = 8.7 \times 10^{-5} P^{1.23}$	(2)
Moderately exposed coasts (18 inlets)	$\not{V} = 10.5 \times 10^{-5} P^{1.23}$	(3)
Mildly exposed coasts (16 inlets)	$\not{V} = 13.8 \times 10^{-5} P^{1.23}$	(4)
All inlets (44 inlets)	$\not{V} = 10.7 \times 10^{-5} P^{1.23}$	(5)

The plots of the prism-outer bar storage volume for the various inlet groupings are given in Figures 3, 4, 5, and 6. Three inlets were not used in any of the inlet groupings although they were used in the "all inlet" correlation. These inlets and the reasons for non-inclusion in the groupings are shown below:

1. Baker's Haulover Inlet - The inlet was created in 1923 with very short jetties which were destroyed in the hurricane of 1926 along with the occurrence of major modifications on the inlet. The inlet was rebuilt in 1928 shortly before the survey data in Table 2 was taken, therefore the outer bar would be expected to be far below any equilibrium value.

2. Clearwater Pass (formerly Little Pass) see below

3. Dunedin Pass (formerly Big Pass) Major modifications have occurred in the Clearwater Harbor area, drastically changing the inlet hydraulics of Clearwater Pass and Dunedin Pass to the North. The outer bars have responded to the tidal prism changes accordingly but may not as yet have reached an equilibrium for the new tidal prisms of the inlets as changes in the sedimentary structure of an inlet lag changes in tidal hydraulics.

As inlet channel cross-sectional area shows a definite correlation with tidal prism (11, 12) and is an easier quantity to measure than tidal prism, a correlation was also made with the available data for bar volume — channel cross-sectional area relationships. Correlations were made for the three coastal energy level groupings and for all inlets combined using an equation:

$$\not{V} = a' A^{b'} \qquad (6)$$

where

$\forall$ = volume of sand stored in outer bar/shoal (as before),
A = inlet channel cross-section area at throat (in square feet),
a',b' = correlation coefficients

Linear regression was again used to obtain the coefficient b' for all cases and is tabulated below:

Highly Exposed Inlets	b' = 1.28
Moderately Exposed Inlets	b' = 1.23
Mildly Exposed Inlets	b' = 1.28

The value b' = 1.28 corresponding to the highly exposed and mildly exposed inlets was used for the correlations with all inlet groupings, and analysis was made for the coefficient a'. The corresponding equations for all inlet groupings are shown below:

Highly exposed coasts (7 inlets) $\forall = 33.1A^{1.28}$ (7)
Moderately exposed coasts (18 inlets) $\forall = 40.7A^{1.28}$ (8)
Mildly exposed coasts (16 inlets) $\forall = 45.7A^{1.28}$ (9)

The plots of the cross sectional area-outer bar storage volume for the various groupings are not shown, but prove to have considerably less scatter than the tidal prism - outer bar storage volume plots. Under a given set of conditions either tidal prism measurements or inlet cross-sectional measurements could be considerably unrepresentative of the "equilibrium" conditions, hence, both the volume - prism and volume-cross section relationships should be considered when obtaining an estimate of the sand storage capacity of an outer bar system.

CONCLUSIONS

The volume of sand stored in the outer bar/shoals of inlets shows a strong correlation with the tidal prism, and also, as would be predicted by the pioneering work of O'Brien (11,12), a strong correlation with cross sectional inlet throat area also.

Although a great deal of scatter exists in the data, the trend of increasing outer bar/shoal storage with increasing tidal prism exists over two orders of magnitude as shown by the included inlet data.

A correlation was made of these parameters and it was found that more material was stored in the outer bar/shoals of low (wave) energy coasts then high (wave) energy coasts. This is because there is more available (wave) energy to drive the sand back to shore in high energy environments after being deposited as a shoal.

A number of parameters other than tidal prism (or cross-sectional area) and wave energy also play a large role in sand trapping on outer bar/shoals. Two important parameters which have not been explicitly considered in the present analysis are longshore energy flux which moves the sand to the inlet where the ebb tidal current can deposit it on the outer bar, and size distribution of littoral material which limits the ability of the material to movement away from the surf zone. Further research is needed to better define how these parameters control the influence of outer bar sand storage.

Further work is also needed on the inner bay or lagoon shoal storage volumes and on the potential of any given inlet to trap sand in its interior shoal system.

ACKNOWLEDGMENTS

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