CHAPTER 39

EQUILIBRIUM FLOW AREAS OF TIDAL INLETS ON SANDY COASTS

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ABSTRACT

The flow area of inlets on sandy coasts is a unique function of the tidal prism when equilibrium has been achieved. The size of material, the presence or absence of jetties, and the magnitude of general littoral drift does not appear to affect this equilibrium flow area within the accuracy of the data available.

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In the summer of 1929, the writer made a reconnaissance of the beaches and harbors of the Pacific Coast of the United States for the predecessor organization of the U. S. Beach Erosion Board. In the years preceding this study, many tidal inlets on the North Pacific Coast had been improved for navigation by constructing jetties, and the progress of these inlets towards stabilization was being followed through frequent hydrographic surveys, which were available for study. The obvious fact that large inlets were found at large bays and small inlets at small bays suggested the possibility that there might be a unique relationship between entrance area and tidal prism. The data then available[1] showed good agreement with equation (1)

$$A = 4.69 \times 10^{-4} P^{0.85} \qquad (1)$$

Here, A (ft^2) is the <u>minimum</u> flow cross-section of the entrance channel (throat) measured below mean sea level and P (ft^3) is the tidal prism corresponding to the diurnal range of tide. (As quoted originally, $A = 1000\,T^{0.85}$ where T, the prism, is feet of range times square miles of tidal area.)

The data then available agreed closely with equation (1) but the agreement was regarded as fortuitous for the following reasons:

a) The tidal prism was computed as the product of the tidal area at HW shown on the USC&GS charts times the diurnal range in the ocean at the inlet. The tidal prism was approximate.

b) There was no apparent effect of the size of bottom material in the inlet channel on the inlet flow area.

c) Jettied and unjettied entrances followed the same curve.

d) The data pertained, with one exception, to the Pacific Coast where the tide shows a marked diurnal inequality and only a small variation in range.

The writer believed at the time that precise and extensive data would demonstrate the influence of the factors just mentioned and that eq (1) was merely an approximation of a relationship which would depend uoon material size, degree of exposure to wave action, jetty protection, and possibly other quantities as parameters.

Casual comparison by a number of writers of data on other inlets has shown a surprisingly small deviation from eq (1) for large and small inlets, with and without jetties, on the Atlantic, Gulf and Pacific coasts. The phenomena involved seemed too complex to yield so simple a relationship and the present study was undertaken to eliminate data of uncertain accuracy and to discover any consistent influence of the factors mentioned above. Clearly, the nature of such data makes appraisal of the accuracy dependent on judgement but a few considerations could be applied, namely:

1) When the tide range is approximately constant around the shores of the bay and the low water area seventy-five percent or more of the high water area, the prism can be computed with an accuracy of ± 10 percent.

2) When the tidal range in the bay is markedly less than at the entrance, as in the case of fire Island Inlet, accurate determination of the tidal prism must be based upon a detailed summation of the area, range, and phase relationships or upon flow measurements at the entrance.

3) The high water area is usually delineated accurat y on the charts, but the low water is frequently ill-defined.

4) Surveys are usually made for navigation purposes and are incomplete outside the navigable areas.

Appraisal of the available data in the light of these considerations yielded the data shown in Table II which is believed to be accurate within ± 10 percent in flow area and ± 15 percent in tidal prism.

The inlets without jetties, ranging from Delaware Bay with a tidal prism of 1.2×10^{11} ft^3 to estero Punta Banda, 3.0×10^8 ft, follow the linear relationship

$$A = 2.0 \times 10^{-5} P \qquad (2)$$

Reliable data on smaller inlets have not yet been obtained. With the exception of Delaware Bay, these inlets without jetties also follow Eq 1, down to a tidal prism of 1.1×10^7 ft^3.

During either phase of the tide, the volume of water accumulated in, or discharged from, the bay is the intergral over the duration of the instantaneous flow area, a, and the velocity averaged over this area:

$$Volume = \int_0^t a \cdot v \, dt \qquad (3)$$

$$a = f_1(z)$$

$$v = f_2(h, z, t)$$

t = elapsed time

a = instantaneous area

v = velocity averaged over area a

h = tide range

z = surface elevation

T = duration of tidal cycle of ebb and flood

V_{max} = maximum value of v

Making the assumption that the flow area is constant and equal to A, the minimum area below MSL, that the function of time is only for a particular tide range, and that the duration of flood and ebb are equal,

$$v = V_{max} \cdot \sin \frac{2\pi t}{T}$$

$$Volume = \frac{A \cdot V_{max} \cdot T}{\pi} \qquad (4)$$

If eq (4) is compared with eq (2), assuming that T = 44,700 seconds, the maximum velocity, averaged over the flow area A is approximately V_{max} = 3.5 ft/sec. If the average depth over the area A is large as compared with the range of tide, the observed velocity should equal this figure. Delaware Bay, the largest of the inlets included in this study meets these conditions; the velocity at strength of flow reported by the USC&GS is 3.55 ft/sec. At smaller inlets, the variation of flow area with tide stage is appreciable and the phase relationship between velocity and area is more complex.

The three inlets with single jetties(triangles in fig 1), considered separately, would yield a relationship between tidal prism and flow area differing from eqs (1) and (2) but it is also true all three points fall close to both of these curves. The data on inlets with two jetties in equilibrium agreed closely with eq (1); there was no reason to modify this equation to represent the data. The range of tidal prism represented by these data is from 3.8×10^{10} ft^3 (Columbia River Entrance) to 1.1×10^7 (Pendleton Boat Basin).

There is no obvious reason that the tidal prism - entrance area relationship in equilibrium should have any particular functional form such as eq (1) or eq (2). Fig 2 shows the same data points as Fig 1 but the functional relationship shown there has been faired through the points without assuming that the relationship has any particular form; greater precision in establishing the functional relationship of Fig. 2 seems unjustified in view of the scatter of the data, but it should be noted that nearly all of the points agree with the curve within the probably accuracy of the data.

Fig 3 shows the gross configuration of a tidal inlet which has very nearly ideal proportions: a crescent-shaped bar seaward having a center of curvature near the throat section, a swash channel alongshore at each end of the bar, and a controlling depth over the bar much smaller than at the throat section. The currents on the flood tide are shown schematically in Fig 3a, with the flow converging from all seaward directions towards the entrance. Fig 3b shows schematically the currents existing seaward of the entrance during the ebb tide; here, the momentum of the flow through the entrance forms a jet directed seaward, and the lateral mixing of this jet induces an eddy on each side. These idealized diagrams show that the currents near the shore are directed toward the entrance from both sides, on both the flood and ebb tides. Figs 3a and 3b show the current situation resulting from tide alone without the effect of currents induced by local winds, by wave action, or by oceanic circulation; these effects are superimposed on the pattern shown in Fig 3.

Added to this pattern of tidal currents in Fig 3 is the effect of refraction of the waves by the crescent-shaped bar and by the tidal currents. Refraction tends to bend the wave crests to become parallel to the bottom contours, thus focusing them on the entrance and inducing currents in the surf zone towards the entrance from each side. The ebb current, running against the wave crests adds somewhat to this focusing action while the flood currents tend to counteract it. In addition to inducing currents in the surf zone, the breakers throw sand in suspension to be transported by whatever current exists there. Thus it appears that there is, under the action of waves approaching perpendicular to the shore, sand movement along the shore from both sides towards the entrance on both the flood and ebb phases of the tide. Tidal currents through the inlet must sweep this littoral drift away if the channel is to remain open, moving this sand either into the bay or seaward to the bar or in both directions. When the tide exhibits a diurnal inequality with the long-runout following higher high water, as on the Pacific Coast of the United States, the ebb currents probably predominate and move the littoral drift seaward. However, along the Gulf Coast the diurnal inequality results in flood currents which are predominant, thus tending to accumulate the littoral drift inside the bay, a situation which may account for the instability of these entrances prior to stabilization by jetties and dredging.

The transportation of sand by currents alone is characterized by a critical bottom velocity below which no motion occurs, by a rate of bed motion which increases exponentially with velocity above the critical value, and by a higher critical velocity above saltation or suspension develops. Near a tidal entrance, sand movement at the bottom is further complicated by the effect of oscillatory currents due to waves and by irregularity of the bottom. Quantitative prediction of the capacity of the tidal currents to move sand away from the inlet and of the predominance of either the floor or ebb currents would be extremely tedious if not impossible to accomplish. In this study it was assumed that the higher ranges of the tide would dominate and either the diurnal range or the spring range was used in computing the tidal prism, for the practical reason that they are readily available. The agreement shown in Fig 1 indicates that this range of tide is reasonably representative of the capacity of the tidal currents to maintain the channel.

The capacity of the tidal currents to maintain an inlet open is perhaps best represented in terms generally applicable by the maximum rate of flow ($A \cdot V_{max}$) but this quantity has not often been measured directly because it requires extensive current measurements to obtain a representative average value. Apparently, quoted values of maximum flow have been calculated from the tidal prism and not measured.

The flow phenomena described, which establish the equilibrium configuration of an inlet, appear to make meaningless use of the tractive force applied by the tidal currents as the criterion of inlet area.

The flow areas of Jones Inlet and Fire Island Inlet were obtained by Dr. T. Saville from surveys made by the Long Island State Park Commission prior to the construction of jetties. The figures quoted were the average of the flow areas at the same cross-section taken from several surveys. The littoral drift here is from the east and the easterly side of both inlets overlaps the west side. Heavy wave action at these locations would drive sand across the eastern spot towards the channel and would probably leave a reduced flow area after each storm. Surveys are made normally in the summer season of relatively calmer wave action when the flow area would approximate its equilibrium value. The flow areas averaged were measured at the same cross-section, which may not have been the minimum area at the time of the survey. Considering these circumstances, it is believed that the data on these inlets, quoted in Table I, is within the accuracy criteria stated previously. Noteworthy is the fact that the flow area after the construction of the jetty at Fire Island Inlet differs by less than 5 percent from the area shown in the Table, before the jetty was built.

The system of littoral currents near an entrance shown in Fig 3 tends to close an inlet- and this tendency would increase with an increase in the severity and duration of wave action, except that under very severe storm conditions the bar may be scoured away and the entrance enlarged. For each size of inlet, there may be some severity and duration of wave attack which will close an entrance against the scouring effect of the tidal currents. Data on this point are scarce but two locations not far apart on the Pacific Coast give an indication of this effect. Lake Earl, north of Crescent City, California, has an area of 1.4×10^8 ft^2; the tide diurnal range at this point is 6.9 ft and the potential tidal prism is 9.4×10^8 ft^3. Lake Earl is separated from the ocean by a very narrow beach; a channel to the ocean is normally opened up during the winter rainy season but closed in the summer. The beach separating Lake Earl from the ocean runs north-south and is exposed to the full intensity of wave action. The inlet to Drake's Estero, on an east-west beach in the lee of Point Reyes, is open continuously; its tidal prism is approximately 7.1×10^8 ft^3, less than the potential tidal prism of Lake Earl. Wave action at Drake's Estero is normally light, consisting of long swells refracted around Point Reyes. At times, however, this inlet is subjected to storm waves of short duration from the South which widen the entrance and alter the entrance channels. (Drake's Estero was not included in the tabulated data because the flow area was not known.)

The Boat Basin at Camp Pendleton has a tidal prism of $1.14 \times 10^7 ft^2$.

This tiny inlet is an entrance within an entrance, being located within the area protected by the converging jetties of Oceanside Harbor and subjected to the mild but continuous action of only long, low waves diffracted and refracted inside the jetties. The maximum average velocity computed from eq 4 is 1.7 ft/sec.

Galveston Entrance on the Gulf Coast shares a tidal prism with San Luis Pass, which has a flow area 25 percent as large as Galveston. In the Table, the flow area shown is the summation of the areas of the two channels and the prism is the total tributary to both.

The data presented pertain to inlets which are believed to have reached a state of equilibrium at the time of the survey. During periods of abnormal wave action, the increased littoral sand movement towards the entrance tends to reduce the flow area but the counter balancing scour of the tidal currents, being controlled by the tidal cycle, remains unchanged and one would expect to find reduced areas following storms. On the other hand, long, high jetties, which extend seaward beyond the zone of active bottom sand movement, cut-off the alongshore drift and should tend to maintain a flow area larger than that corresponding to Fig 2 once the larger area has been dredged; in any event, jetties should reduce the rate of approach to equilibrium. Some of the scatter of the data is due to non-equilibrium conditions, which would tend to make the plotted flow areas too small for natural conditions and too large, if the deviation from equilibrium results from dredging.

CONCLUSIONS

The data cited pertain to inlets in equilibrium under tidal currents on the mainland coasts of the United States. Conclusions drawn from these facts are:

1. The equilibrium minimum flow area of an inlet, with or without jetties, is controlled by the tidal prism. A reduction of the tidal prism by sedimentation, vegetation, or artificial fill will reduce the flow area.

2. If the tidal area is connected to the sea through two or more inlets, closure of one or more of these channels will enlarge the flow area of the others.

3. Jetties not only stabilize the position of an inlet but also protect it against closure under wave action.

4. Very small inlets can be kept open by tidal currents, if they are protected against strong surf and littoral drift.

5. The <u>equilibrium</u> flow area of an inlet depends to a minor extent, if at all, on bed material size.

6. Tractive force does not appear to provide a meaningful criterian for the equilibrium conditions of tidal inlets.

REFERENCES

O'Brien, M. P. (1931). Estuary Tidal Prism Related to Entrance Areas: Civil Engineering, Vol. I, No. 8, p. 738. (1)

TABLE I

Inlet	Location	Tidal Prism on Spring or Diurnal Tide (P)(Ft^3)	Minimum Flow Area at Entrance Channel Below MSL(A)$(Ft)^2$	Δ(Eq 1-A_{max}) %	Remarks
No Jetty					
Delaware Bay	Atl	1.25×10^{11}	2.5×10^{6}	0	
Golden Gate	Pac	5.1×10^{10}	9.38×10^{5}	+4	
Willapa	Pac	2.50×10^{10}	3.94×10^{5}	+35	
North Edisto R.	Atl	4.58×10^{9}	9.95×10^{4}	-14	
Tomales Bay	Pac	1.58×10^{9}	3.6×10^{4}	-9	
Fire Island	Atl	2.18×10^{9}	3.56×10^{4}	+16	See (1) below
Jones Inlet	Atl	1.5×10^{9}	2.89×10^{4}	+3	See (2) below
Punta Banda	Pac	2.99×10^{8}	5.46×10^{3}	+13	
One Jetty					
Rockaway	Atl	3.7×10^{9}	8.6×10^{4}	-14	
Tillamook	Pac	2.11×10^{9}	3.69×10^{4}	+12	
E. Rockaway	Atl	7.6×10^{8}	1.15×10^{4}	+32	
Two Jetties		3.82 measured	4.70 calculated 4.68 measured		model
Columbia	Pac	3.82×10^{10}	5.08×10^{5}		
Grays Hbr	Pac	2.43×10^{10}	2.85×10^{5}		
Galveston	Gulf	1.59×10^{10}	2.2×10^{5}		See (3) below
Charleston	Atl	5.75×10^{9}	1.44×10^{5}		
Humboldt	Pac	4.38×10^{9}	7.55×10^{4}		
San Diego	Pac	3.38×10^{9}	6.17×10^{4}		
Coos B.	Pac	2.84×10^{9}	6.11×10^{4}		

TABLE I (continued)

Inlet	Location	P	A	%	Remarks
Umpqua	Pac	2.20×10^9	4.62×10^4		
Absecon	Atl	1.48×10^9	3.13×10^4		
Morichee	Atl	1.57×10^9	2.04×10^4		
Yaquina	Pac	7.73×10^8	1.98×10^4		
Nehalem	Pac	6.0×10^8	1.12×10^4		
Siuslaw	Pac	4.64×10^8	1.10×10^4		
Mission B	Pac	4.2×10^8	1.04×10^4		See (4) below
Coquelle	Pac	3.89×10^8	9.02×10^3		
Newport B	Pac	1.98×10^8	5.89×10^3		
Pendleton BB	Pac	1.14×10^7	4.64×10^2		See (5) below

1. Data by Saville - before jetties
2. Data by Saville - before jetties
3. Includes flow area and Prism of San Luis Pass
4. Data by D. Inman
5. Data by D. Inman

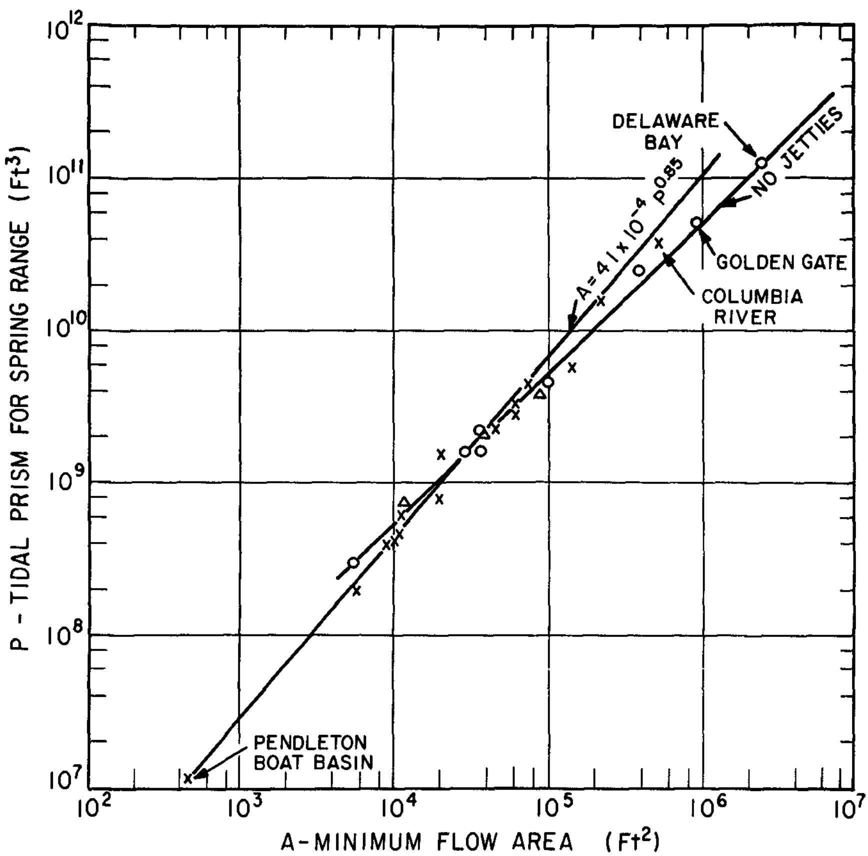
DELAWARE BAY
$A = 4.1 \times 10^{-4} P^{0.85}$
NO JETTIES
GOLDEN GATE
COLUMBIA RIVER
PENDLETON BOAT BASIN
P - TIDAL PRISM FOR SPRING RANGE (Ft³)
A-MINIMUM FLOW AREA (Ft²)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

Fig. 1.

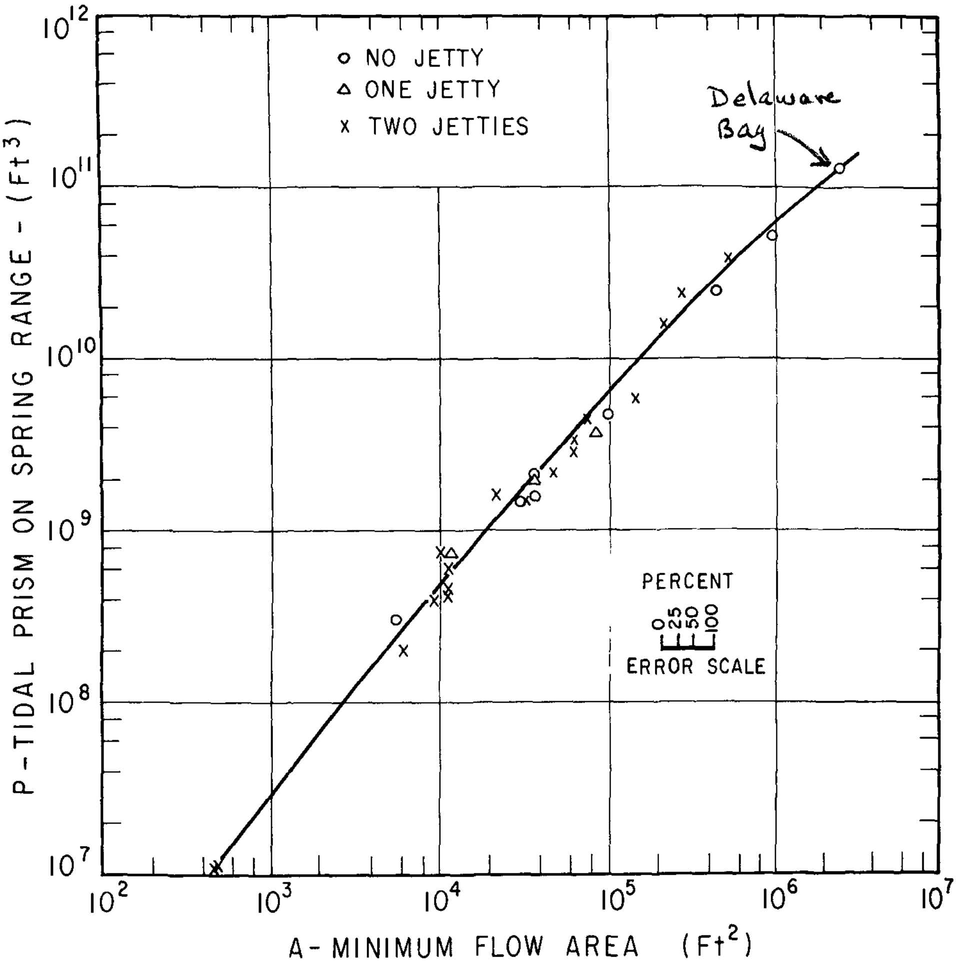
NO JETTY
ONE JETTY
TWO JETTIES
Delaware Bay
PERCENT
0 25 50 100
ERROR SCALE
P-TIDAL PRISM ON SPRING RANGE - (Ft³)
A-MINIMUM FLOW AREA (Ft²)
10^7 10^8 10^9 10^10 10^11 10^12
10^2 10^3 10^4 10^5 10^6 10^7

Fig. 2.

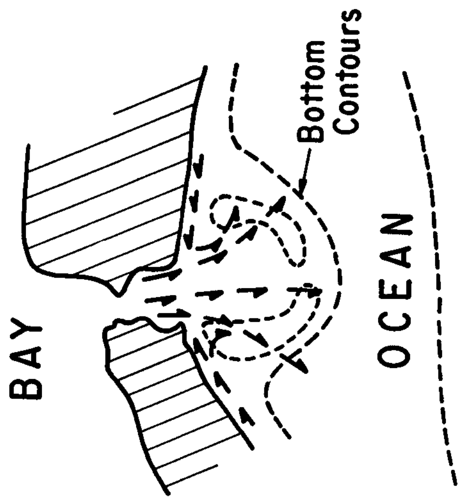

Fig. 3b.

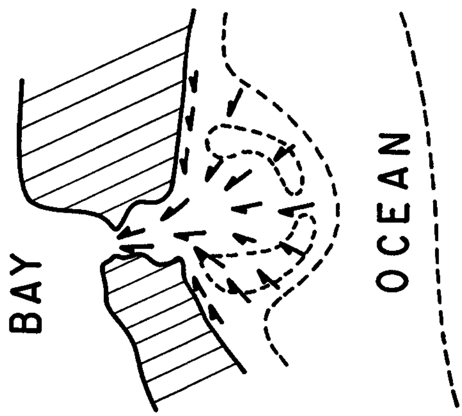

Fig. 3a.