TIDAL PRISM-INLET AREA RELATIONS FOR SMALL TIDAL INLETS

R.J. BYRNE, R.A. GAMMISCH and G.R. THOMAS

Virginia Institute of Marine Science
College of William and Mary
Gloucester Point, Virginia, 23062, U.S.A.

ABSTRACT

Fourteen tidal inlets within the lower Chesapeake Bay were studied to examine whether significant differences existed in their hydraulic behavior relative to the larger oceanic inlets hitherto studied. Measurements included simultaneous external and internal tides, gaging of discharge through a tidal cycle, measurements of inlet geometry, and basin area. The results indicate that: a.) smaller inlets ($A_c < 100\ m^2$) depart from the relationship between inlet throat area and tidal prism developed for oceanic inlets; b.) examination of inlet width versus depth indicates the departure from ocean inlet geometry occurs at A_c values between 100 and 500 m^2; c.) the maximum velocity in smaller inlets is significantly less than oceanic inlets (~0.35 vs 1.0 m/s); d.) tidal phase lags and tidal range ratio were generally equal. However, for conditions of significant tide range reduction, the low water phase lags more closely approximated the tide range ratio.

INTRODUCTION

It is generally recognized that inlets possessing a stable entrance cross-section reflect a dynamic balance between wave driven sand transport processes tending to close the entrance and the tidal flows tending to maintain the channel. A relationship between the tidal prism and the inlet throat cross-sectional area was presented by O'Brien (1969, and earlier); for inlets without jetties

$$A_c = 2.0 \times 10^{-5}\ \Omega\ ,\ \text{(FT)} \tag{1}$$

Jarrett (1976), analyzing a larger data set of inlets on the U.S. coasts, found differences between the Atlantic, Pacific and Gulf Coasts which he attributed to wave climate and tidal characteristics.

Rather than base the correlation upon the integral of the discharge, Bruun (1978, and earlier work) has related the throat area with maximum discharge as it, or the maximum velocity, more clearly designates the relevant bottom shear stress. For inlets of large depth relative to the tide range, Keulegan's analysis (1967) indicates the maximum discharge is proportional to the discharge. Thus, under simplified conditions, the two approaches are closely related. In both cases, the correlation between minimum flow area and the hydraulic parameter are taken to represent the condition of sedimentary equilibrium.

Departures from "equilibrium" conditions have also been considered by Escoffier (1940, 1977) and O'Brien and Dean (1972), who utilized the analysis of Keulegan (1967). Basically, the approach gives an estimation of the resulting maximum velocity due to a change in the inlet area which is then compared with the velocity associated with the corresponding "equilibrium" area as derived, under simplifying assumptions, from Equation 1 or similar plots. The procedure provides a basis for prediction as to whether the inlet area will tend to return to "equilibrium" or toward closure. It is important to note that the method depends upon the empirically derived relationship between flow area and hydraulic parameters.

PURPOSE OF THE STUDY

Most previous studies have focused on oceanic inlets with relatively large entrances (throat areas $> 10^2 m^2$) or in small models (throat areas $< 10^{-1} m^2$). This study focuses on natural tidal inlets, the dimensions of which fall between oceanic inlets and the model scale. Interest in this mid-range exists because of increasing demand to improve navigability into such inlet-basin systems fringing the Chesapeake Bay. Moreover, the model results of Mayor-Mora (1977) suggested that very small systems may depart from the relationships developed for oceanic inlets. Those results showed that for a given tidal prism, the inlet area was an order of magnitude higher than that predicted by extrapolation of the oceanic inlet data.

Fourteen tidal inlets without jetties, Figure 1, in the lower Chesapeake Bay were studied in 1978 and 1979. The cross-sectional area of the channel throats varied between 25 m^2 and 0.5 m^2 so the data set extends the observed range of natural inlets by two orders of magnitude. The data set for each inlet includes basin and "ocean" tides, discharge gaged through a full tide cycle, the geometrical characteristics of the inlet channel, and the planform characteristics of the basin. The exposure to wave action varied widely with the fetch ranging between fractions of a kilometer to tens of kilometers. To insure that true inlet systems were considered, only those entrances connecting to basins with a tide range reduction or inlets whose histories otherwise demonstrated a dynamic balance between littoral drift and tidal scour were selected. A complete description of the inlet-basin systems, including available aerial photography, is given in Byrne, et al. (1980).

This paper reports on: a.) the observed inlet area-tidal prism relationship; b.) the geometry of the inlet throat; c.) the observed maximum channel velocity; d.) the observed phase lags between ocean and basin tides.

METHODS

Tides. The external and basin tidal fluctuations were measured either with Fisher-Porter recording gages, recording bubbler gages, or graduated plastic tubes with a small oriface to filter out wind wave action. In most cases, the external and internal tide measuring devices were leveled to a common datum.

Discharge. Instantaneous tidal discharge was obtained as the sum of area weighted velocity readings from an array of current meter across the channel. The vertical position of the small ducted impellor meters (Byrne and Boon, 1973) was maintained at 0.6 the water depth and values determined were accepted as local vertically averaged mean velocity.

Throat geometry. Channel cross-section profiles were obtained with level and rod reference to the tide recorders.

Basin area. Basin area was determined from aerial photography or plane table mapping with separate consideration given to total basin area and the fraction filled by marsh. The area-height relationship of the basins is currently under study (see also Boon and Byrne, 1981).

DISCUSSION OF RESULTS

Tidal prism-inlet area relationship

The relationship between tidal prism and inlet area, for semi-diurnal tidal conditions, is shown in Figure 2 for 15 Chesapeake Bay inlets, the model results of Mayor-Mora (1977) with tide and waves, and 34 Atlantic coast inlets (without jetties) presented by Jarrett (1976). The least square fit for these data sets are, in metric units:

Jarrett data: $m = 34$

$$A_c = 6.954 \times 10^{-6}\ \Omega^{1.14} \qquad \text{corr. coeff. } (r) = 0.97 \tag{2}$$

Chesapeake Bay: $m = 15$

$$A_c = 9.902 \times 10^{-3}\ \Omega^{0.61} \qquad r = 0.87 \tag{3}$$

Mayor-Mora: $m = 17$

$$A_c = 7.61 \times 10^{-3}\ \Omega^{0.68} \qquad r = 0.95 \tag{4}$$

Chesapeake Bay plus Mayor-Mora: $m = 32$

$$A_c = 8.079 \times 10^{-3}\ \Omega^{0.64} \qquad r = 0.98 \tag{5}$$

For the Chesapeake Bay data set (Tables 1 and 2), the tidal prism could be calculated either from the product of the open basin area and the spring tide range or from the integrated discharge curves which were then linearly scaled to spring tide range.

The ratio of the two prism values was found to vary directly with the open water fraction of the total basin area. This result may be expected since the calculation of prism as the product of tide range and open water basin area neglects the actual basin area-height conditions of the system. The values plotted in Figure 2 are the tidal prisms calculated from the discharge.

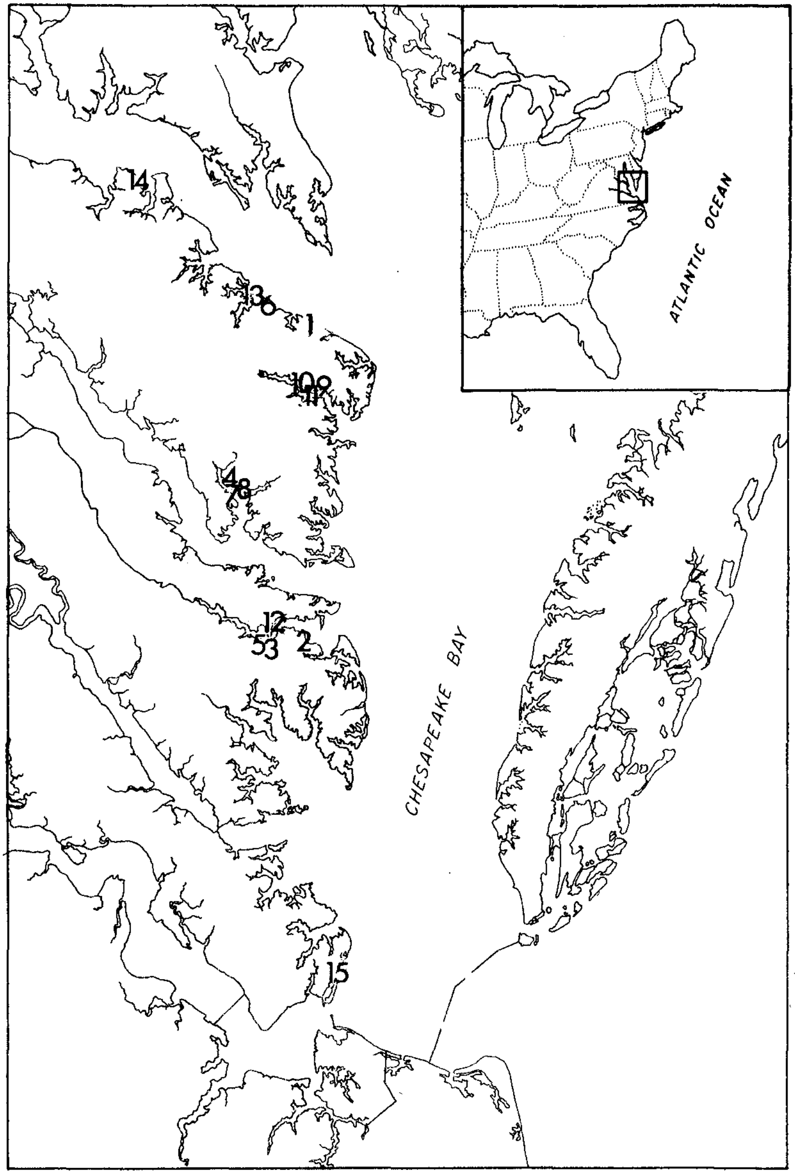

Figure 1. Location map; numbers identify inlets in Table 1.

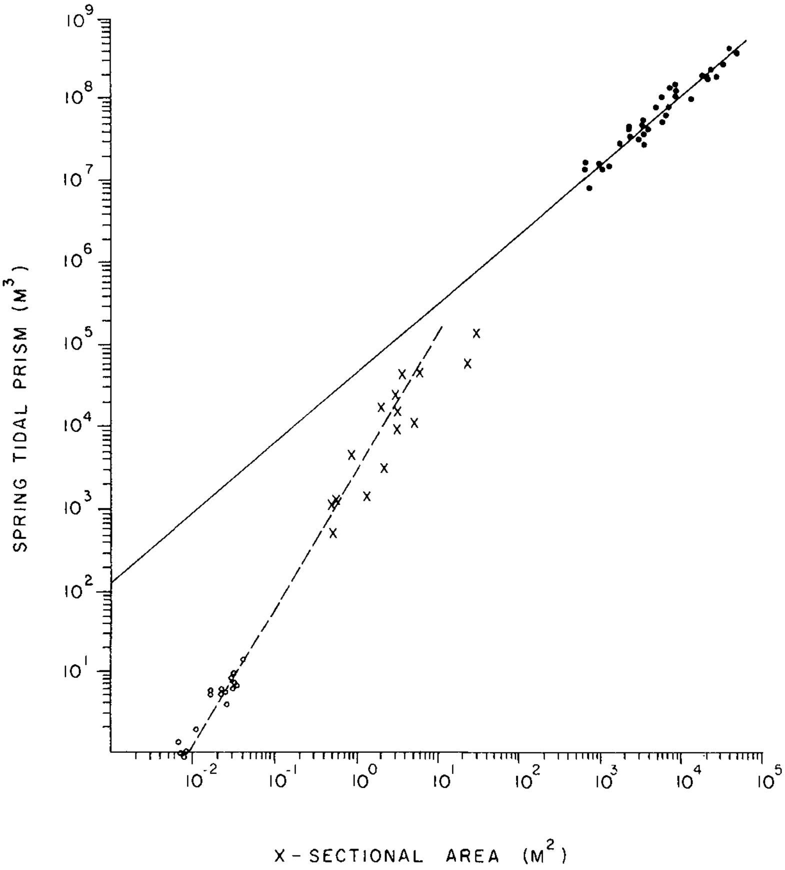

Figure 2. Tidal prism versus inlet throat cross-sectional area. Open circles are from Mayor-Mora (1977); closed circles are from Jarrett (1976); crosses represent Chesapeake Bay Inlets. All cases are inlets without jetties.

Table 1. Geometrical Characteristics of Inlet Systems.

NO.	INLET NAME	BASIN AREA PARAMETERS: TOTAL* (km^2)	BASIN AREA PARAMETERS: MARSH PLUS WATER (m^2)	BASIN AREA PARAMETERS: OPEN WATER (m^2)	BASIN AREA PARAMETERS: % OPEN	CHANNEL PARAMETERS: A_C (MTL) m^2	CHANNEL PARAMETERS: $\frac{A_H}{A_L}$	CHANNEL PARAMETERS: W (MTL) m	CHANNEL PARAMETERS: W/D
1	CUBITT	9.11	874,900	709,000	81	3.90	2.2	15.2	58
2	CHAPEL	2.89	166,700	118,700	71	3.20	2.6	6.6	14
3	WADINGER	2.71	48,690	25,693	53	3.46	5.2	11.3	36
4	JOHN	2.15	113,300	88,200	78	25.27	1.6	27.4	30
5	BOUNDARY	0.65	12,733	6,638	52	0.91	3.6	3.4	13
6	COD	0.34	62,100	62,100	100	2.13	3.2	4.2	8
7	PALMER	0.33	27,700	26,700	96	5.67	2.4	11.3	22
8	SCHOONMAKER	0.23	18,500	17,500	95	3.30	2.9	7.3	16
9	MARINA	0.23	8,253	7,319	87	2.32	4.3	8.2	29
10	HEADLEY	0.07	2,438	2,159	88	1.41	6.6	5.8	24
11	KILDUFF	0.06	2,966	1,419	48	0.50	9.5	2.7	15
12	LITTLE WILLIS	0.03	1,467	1,356	92	0.58	5.5	2.2	8
13	LITTLE COD	0.04	3,894	3,203	82	(0.56)+	-	(1.5)	4
14**	CABIN POINT	2.97	450,000	120,000	27	(6.4)	-	(16.7)	44
15	SALT PONDS	4.04	530,000	200,000	38	(31.0)	-	-	-

*Area of total drainage system, upland plus tidal basin.
**From Seelig, W.H., 1976.
+(), estimates.

Table 2. Hydraulic Characteristics of the Inlet Systems.

INLET NO.	TIDAL PRISM (SPRING) m^3	OCEAN SPRINC TIDE RANGE m	AVE. SPRING TIDE Vmax m/s	DIMENSIONLESS DURATION OF TIDE ebb	flood	TIDE RANCE RATIO Rb/Ro	PHASE LAC cos ε ebb	flood
1	4.25×10^4	0.43	0.19	0.70	0.30	0.16	-	-
2	2.40×10^4	0.43	0.46	0.66	0.34	0.34	0.34	0.39
3	1.57×10^4	0.49	0.36	0.66	0.34	0.83	0.88	0.80
4	6.03×10^4	0.49	0.16	0.50	0.50	1.04	0.99	1.00
5	4.46×10^3	0.49	0.36	0.57	0.43	0.84	0.89	0.99
6	1.71×10^4	0.43	0.56	0.66	0.34	0.68	0.69	0.95
7	1.08×10^4	0.49	0.30	0.54	0.46	1.04	1.00	1.00
8	9.09×10^3	0.49	0.31	0.48	0.52	1.06	1.00	1.00
9	3.05×10^3	0.43	0.40	0.68	0.32	0.61	0.75	1.00
10	1.40×10^3	0.43	0.12	0.55	0.45	0.97	1.00	1.00
11	1.12×10^3	0.43	0.28	0.68	0.32	0.86	0.85	1.00
12	1.22×10^3	0.49	0.35	0.52	0.48	1.00	1.00	1.00
13	5.23×10^2	0.43	-	0.67	0.33	0.38	0.98	0.82
14	4.60×10^4	0.61	-	-	-	-	-	-
15	1.37×10^5	0.85	-	-	-	-	-	-

Mayor-Mora's experiments were conducted with combined scaled tidal action and waves. Tidal prism was calculated as the product of basin area and tide range. Since a natural quartz sand distribution d_{50} = 0.34 mm) was used, scale effects may be important.

Review of extant aerial photography indicates that the Chesapeake Bay inlets included in this study have existed for at least a decade which suggests they are not ephemeral. When only a single survey is performed on an inlet, the observed correspondence between inlet channel area and hydraulic parameters (prism, discharge, etc.) is assumed to approximate the condition of sedimentary equilibrium. Modulations around an average equilibrium flow area occur with changes in wave conditions and tidal height variations but recovery from extreme events may take only days (Byrne, et al., 1974). The inlet sites herein presented are exposed to relatively weak littoral drift so disturbances from "equilibrium" may require longer recovery times. Moreover, those systems with relatively large upland drainage basins (i.e. No. 1, Cubitt Creek) may have periodically large freshwater outflow which temporarily enlarge the channel throat area.

Given the assumption that the inlets studied do approximate conditions of sedimentary equilibrium, the results displayed in Figure 2 indicate the inlet area-tidal prism relationship deduced for oceanic inlets does not apply to smaller natural inlets. Inspection of the plotted points and the least squares analyses suggests that the transition zone between the oceanic and smaller inlets occurs near $A_c \simeq 100\ m^2$ to $500\ m^2$.

Geometry of the inlet throat

Oceanic inlets are generally considered to be hydraulically wide (hydraulic radius ≃ mean depth). However, for smaller channels to remain stable, the cross-section must become more efficient. For example, for the oceanic inlets plotted in Figure 2 (Jarrett, 1976), the average value of W/R = 337 whereas the average value of W/D = 23 for the smaller Chesapeake Bay inlets herein reported. A dimensionless downstream view of channel geometry, scaled to a reference semi-circular cross-section, is shown in Figure 3. For comparison, a channel cross-section from Mayor-Mora's model results are included.

The departure of the width-depth characteristics of mid-range and model inlets from the ocean inlets is shown in Figure 4 (Mehta, 1976; Winton, 1979). While there is appreciable scatter in the data, the departure zone between the trend of the larger oceanic inlets alone and that of a smooth curve through all of the data appears to lie at an inlet area of about 100 to 500 m^2, the same zone observed in the inlet area-tidal prism plot (Fig. 2).

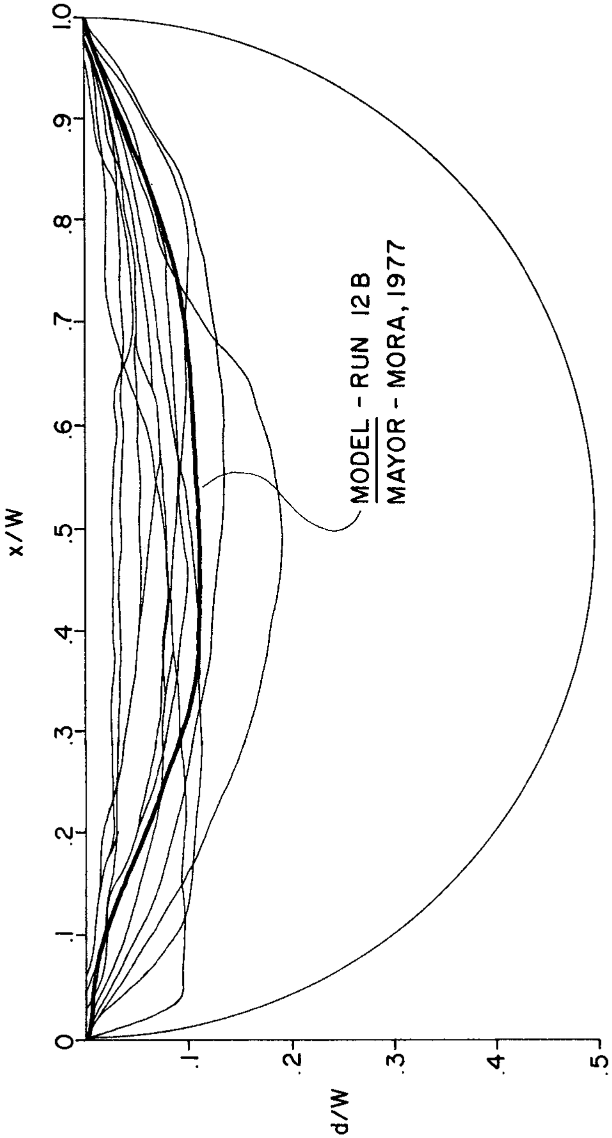

Figure 3. Dimensionless inlet throat geometry.

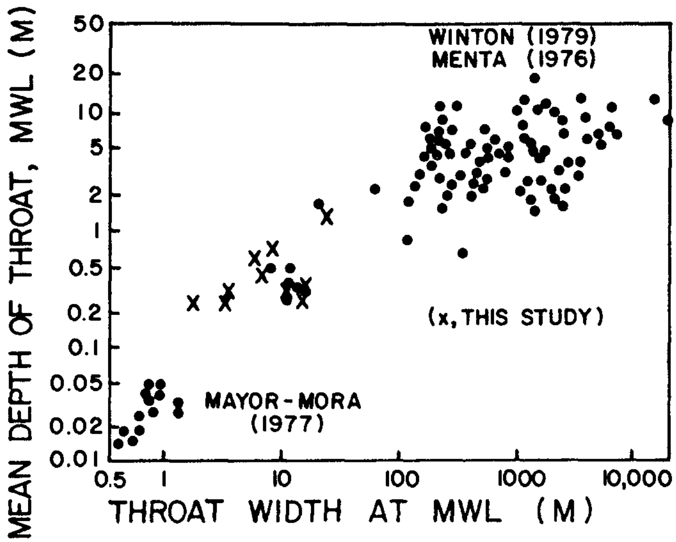

Figure 4. Width-depth relationship for inlets without jetties. After Winton, 1979.

Maximum velocity versus inlet area

As previously mentioned, the scouring capacity of the tidal current to maintain the inlet entrance may be represented by the maximum discharge ($Q_{max} = A_c V_{max}$). If the constraints leading to a sinusoidal time variation in discharge are accepted, the "equilibrium" relationship between channel area and tidal prism may be used to calculate the corresponding Q_{max} or V_{max} (Keulegan and Hall, 1950; O'Brien, 1969; Bruun, 1974). Following O'Brien:

$$\Omega = \int_0^{T/2} a\ v\ dt \ ,$$

and if $$v = V_{max} \sin \frac{2\pi t}{T} \ ,$$

then $$\Omega = \frac{A_c\ V_{max}\ T}{\pi} \text{ or } Q_{max} = \frac{\pi\Omega}{T} \ . \qquad (6)$$

Equation 6 may be expected to hold when $A_c \simeq$ constant, and by definition, the duration of the ebb and flood currents are equal.

Combining Equations 1 and 6 and with T = 12.4 hours, O'Brien found V_{max} = 1.06 m/s (3.5 fps). This value corresponds rather closely with values of V_{max} = 1.0 $\pm$ 15% m/sec reported by Bruun (1967) and Jarrett (1976) for a number of oceanic inlets.

Keulegan and Hall (1950) tested Equation 6 against gaged discharge at four oceanic inlets and concluded that a coefficient was required to account for deviations from a sinusoidal discharge ($Q_{max} = C(\pi\Omega/T)$, C = 0.86). In his later theoretical development of inlet hydraulics for conditions of constant basin and channel areas, Keulegan (1967) found that the coefficient, C , may vary between 0.8 and 1.0.

The purpose of this section is to examine the relationship between V_{max} and A_c for the smaller tidal inlets studied. As shown in Table 1, the channel cross-sectional area changes appreciably during the tidal cycles giving rise to distortions in the velocity time history. For comparative purposes, Figure 5 presents the measured values of V_{max} with those calculated from Equation 6 for a smooth curve drawn through the combined data in Figure 1. That segment of the V_{max} versus A_c curve derived from the Jarrett (1976) data ($A_c > 10^2$m) indicate a decrease in V_{max} as A_c increases. This result would arise as well from the application of Equation 6 to Equation 2 since the exponent in Equation 2 is greater than 1. This is likely to be an anomaly arising from a limited data set.

Three data sets are presented in Figure 5. Data associated with channel areas less than 10^{-1}m^2 are V_{max} values averaged for flood and ebb from the model results from Mayor-Mora. The mid-range inlets of

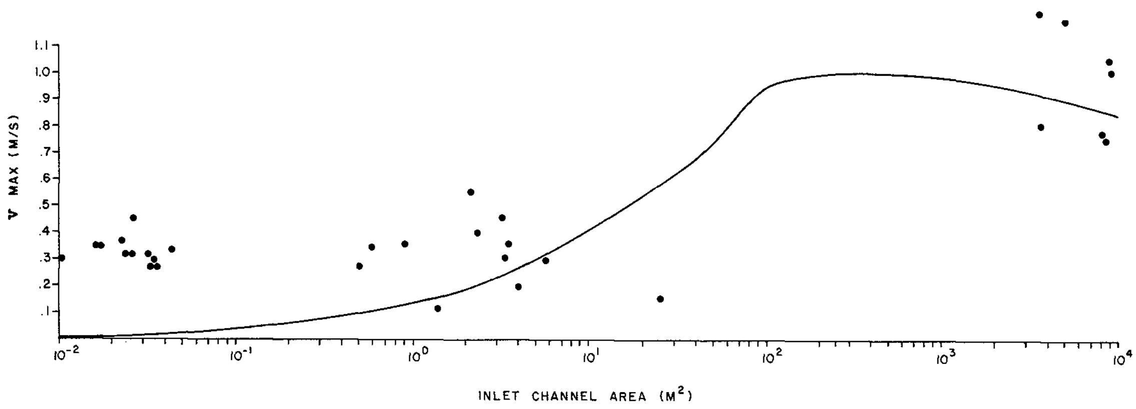

Figure 5. Observed maximum velocity versus throat cross-sectional area, A_C. Solid line is derived from smooth curve through points in Figure 2 and application of Equation 6. Data points for $A_C > 10^2$m from Jarrett (1976), points for $A_C < 10^{-1}m^2$ from Mayor-Mora (1977).

Chesapeake Bay ($10^{-1}m^2 < A_c < 10^2m^2$) represent the ebb and flood averaged values of V_{max} after adjusting to spring tide conditions with $V_{max}/\sqrt{ga_o}$ as the scaling parameter (Table 2). The unadjusted V_{max} values were taken from curves of $\overline{v}(t) = q(t)/a_c(t)$ for each inlet. The data for $A_c > 10^3m^2$ are taken from Jarrett (1976) for inlets on the Atlantic U.S. Coast.

Inspection of Figure 5 indicates that V_{max} for the model and mid-range (Chesapeake Bay) inlets cluster around the value of $V_{max} \simeq 0.35$ m/s. This may represent a limiting condition for the active transport of medium to fine sand sized sediments in the entrances and thus act as the limiting V_{max} for stable inlets.

Phase lags and durations of flow

The analysis of Keulegan (1967) indicates that for a sinusoidal "ocean" tide and a horizontal water surface response in the basin (basin small relative to tide wave length), the tide range ratio (R_o/R_b) should equal the cosine of the phase lag between the times of high (low) water in the "ocean" and those of the lagoon. Keulegan's analysis was based, as well, on the assumption that the inlet depth was large relative to the tide, and that the inlet hydraulics were controlled by local head differences rather than a progressive wave through the entrance. O'Brien and Clark (1973) attempted to test the theoretical expectation for U.S. inlets using available current and tide data. Recognizing the appreciable scatter in the date, they concluded that for smaller entrances $(A_c/(\frac{1}{2}R_o)^2 < 10^4)$ the theoretical expectation was reasonably approximated.

For small tidal inlets, the channel cross-sectional area may vary significantly during the tidal excursion which results in a distortion of the velocity time history such that a longer ebb flow duration over a reduced flow area is required to balance an equivalent tidal prism. Such were the conditions considered by Mayor-Mora in model experiments. He found the ebb flow durations to be greater than the flood durations and, correspondingly, that the phase lags between high waters were shorter than predicted in the Keulegan analysis while the low water lags were longer.

The mid-range inlets herein reported have significant variation in entrance channel area during the tidal excursion (high water area to low water area ranging between 1.6 to 9.5, Table 1). Accordingly, the observed distortions in the ebb and flood flow durations may be expected (Table 2). However, variations in the basin area with tidal stage induce an opposing effect leading to longer flood durations (Mota-Oliveira, 1970; Boon and Byrne, 1981).

Given the distorted durations of flow, Seabergh (1979) indicates that the phase lags may be weighted by the duration of ebb and flood flow:

$$\varepsilon = \frac{\Delta t \text{ between basin and ocean high (low) tide}}{\text{duration of flood (ebb) flow}} \times 180^{\circ}$$

Inspection of Table 2 indicates there is generally good agreement between the tide range ratio, R_b/R_o , and cos ε. In those cases where there is substantial reduction of the basin tide range (inlets 2, 3, 5, 6, 9, 11), the ebb phase lag more closely corresponds to the resultant tide range ratio. Inlet 13 is an anomalous case arising from the fact that this entrance, crossing the foreshore of a beach, becomes perched at low tide which controls the basin tide range.

CONCLUSIONS

1.) The data on smaller tidal inlets indicate significant departures from the oceanic inlets in the relationship between throat cross-sectional area and tidal prism. For the cases studied, namely inlets on the Atlantic United States coast subject to semi-diurnal tides, the departures appear to exist for inlet areas less than 500 m^2.

2.) Examination of the relationship between inlet width and depth also suggests a departure between the oceanic inlets and the smaller natural and model inlets at throat area values between 100-500 m^2.

3.) Within smaller tidal inlets characterized by large flow area variations with tidal stage, the maximum velocity is significantly lower than that observed in the larger inlets (0.35 m/s *vs* 1 m/s). It is suggested that these low maximum velocities may represent the limiting condition of inlet stability.

4.) The idealized relationship (Keulegan, 1967) between the tide range ratio and tidal phase lag,

$$R_b/R_o = \cos \varepsilon$$

was found generally to hold when the time lag between "ocean" and basin tides were scaled by the duration of ebb or flood flow. When there was substantial reduction in the basin tides, the low tide phase lags more correctly predict the tide range ratio. This is probably due to the higher inlet impedance at low tide.

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SYMBOLS

A_c	Inlet throat cross-sectional area at mean tide level (MTL)	m
$A_H(L)$	Inlet throat cross-sectional area at high (low) water	m
a	Instantaneous channel area	m
a_o	Amplitude of "ocean" tide	m
D	Inlet throat mean depth at MTL	m
d	Local channel depth, as f(x)	m
Q_{max}	Maximum of discharge	m^3/s
R	Hydraulic radius at MTL	
$R_o(b)$	Tide range in ocean (basin)	m
T	Period of tide	hrs
V_{max}	Maximum velocity averaged over flow area	m/s
v	Instantaneous velocity averaged over flow area	m/s
W	Inlet throat width at MTL	m
x	Local distance across channel	m
ε	Phase lag between external and internal high (low) tides	hrs
Ω	Spring tidal prism	m^3

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