A COASTAL INLET WITH FIXED BED AND MOBILE SIDES

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1. INTRODUCTION:

The coastal inlet dealt with in this paper has a fixed bed of exposed rock and mobile side boundaries of sand that overlies the bed rock platform.

The work was undertaken to investigate the response of the throat section to natural hydraulic and meteorological events and to observe the nature and rate of recovery of the inlet after the more extreme events. These events included sea and swell states, wind, freshwater flood flows and short term changes in mean sea level (storm surges or meteorological tides). The three year study involved the inlet at the mouth of the Barwon River, Victoria, Australia (see Figure 1). The work forms part of a continuing study to assess the impact of engineering works on the stability of the estuary and inlet, and was required to assist in delineating the natural inlet variability from that due to engineering works. The study described here looked specifically at the inlet throat section which refers to the short narrow waterway connecting the estuary with the sea. The inlet throat section at Barwon Heads is well defined and is shown in Figure 1.

The inlet itself is free of training walls and is normally flanked by sandy beaches. However, the depth of the inlet is limited by a bed of rock (see Figure 2), there being, in effect, unlimited mobility on a side boundary only. The study therefore included

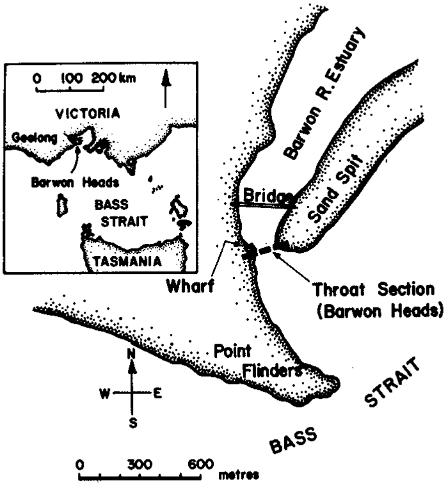

FIGURE 1: LOCALITY SKETCH

an investigation to see if such an inlet conformed to equilibrium criteria developed from inlets with unrestricted bed mobility.

Some results of previous investigations on the estuary and inlet were reported by Nelson (1977).

2. DESCRIPTION OF INLET:

The Barwon Heads inlet is located west of Port Phillip Heads and is backed by an estuary 9 km long, joining Lake Connewarre with the sea. The lake is 9 km^2 in area. The tidal limit lies on the river 1.5 km upstream of the lake. The tide at the inlet is semidiurnal with significant diurnal inequality. The mean spring tide range at the inlet (astronomical tide) is 1.56 m and in the lake is 0.15 m. Superimposed on this astronomical tide is a significant meteorological tide range observed to be at least 0.8 m. An investigation of the meteorological tide has been reported elsewhere (Keats, 1979). During the three year study the maximum and minimum still water levels observed on the gauge at the inlet were 2.48 m and 0.02 m respectively. The mean sea level for the three year period of study was 1.03 m on the gauge.

The total catchment area above the inlet is 4400 square kilometres with an average annual catchment rainfall of about 660 mm, of which only 80 mm per year, on average, passes the catchment outlet as runoff. Higher runoff proportions occur during heavy storm or prolonged wet periods. Most flood flows occur as a result of heavy winter and early spring rainfalls.

For at least 80 per cent of the time the inlet experiences insignificant freshwater inflows. The peak tidal discharges at the inlet during these dry periods range from 230 m^3/s (measured) on a mean spring tide range to 80 m^3/s (measured) on a neap tide.

The tidal prism of the inlet, as determined by continuous monitoring of discharge over a tide cycle, is 2.3 million cubic metres for a mean spring tide range.

Winds in Bass Strait have a predominant westerly component and therefore, sea states from the south west predominate in the region of Barwon Heads. Swell from the south west is also dominant and originates in the Southern Ocean. The result is a net littoral transport along the coast from west to east in the region of Barwon Heads.

Sand samples taken from the inlet from time to time indicate a median diameter of 0.20 mm to 0.25 mm.

3. DATA COLLECTION:

3.1 Tidal Discharges and Tidal Prism:

The tidal prism of the inlet was obtained by tidal gauging where continuous observation of velocities was made during a tide cycle at a cross section several hundred metres upstream of the throat section. Area velocity methods were used to convert this data to a relationship of discharge versus time, from which the tidal prism was readily obtainable. The measurements were made from a boat using a fan type current meter. Velocity measurement traverses were made over both width and depth and the process continually repeated. The exercise was done for several different tide ranges ensuring the availability of reliable data on tidal discharges and prism.

3.2 Inlet Throat Survey Data:

The variation with time of the area below mean sea level (Figure 4) was generated from regular surveys of the inlet throat section, supplemented by visual assessments made during intermediate inspections. The latter were generally made following extreme events or during weekly maintenance visits to the tide recorder located at the cross section. All surveys were made at the same cross section located as shown in figure 1. The cross section was retrievable from fixed markers and was always at the point of minimum width no matter what the overall geometric characteristics of the inlet were at any point in time. The survey of other cross sections from time to time confirmed that this point of narrowest width was in fact the point of minimum cross section area. An echo sounder was used to obtain bed levels in submerged regions and normal level survey methods used for above water regions. Surveys were undertaken, where possible, at or near low tide when sea and swell penetration were minimum. The mean sea level used was the average for the 3 years of the study, namely 1.03 metres on the Barwon Heads tide gauge.

3.3 Bed Rock Levels:

Bed rock levels are shown in figure 2. Where natural surface was above low tide level, rock levels were obtained using a mobile drilling rig. Rock levels in the channel were obtained using steel rod probing techniques immediately after floods when most of the underwater rock was cleared of sand and exposed by the flood.

3.4 Barwon River Freshwater Flows:

River flow (figure 4) was monitored using a rated river flow station at Geelong. River levels were obtained using a staff gauge, read at least once daily, and more frequently, as required during floods. River levels were converted to river discharges using a rating curve generated from a total of 40 river discharge gaugings, covering the whole range from near zero flow up to a maximum measured discharge of 735 cubic metres per second. The highest estimated discharge at Geelong during the three year investigation was 580 cubic metres per second (figure 4) and therefore no extrapolation of the rating curve was required.

3.5 Surface Winds and Sea State:

Regional surface wind velocities and direction (figure 4) were estimated indirectly from isobaric pressure gradients. The data was extracted from Australian Region, Sea Level Synoptic Charts at six hourly intervals for the duration of the study. The charts used were those corresponding to 0000, 0600, 1200 and 1800 hours G.M.T. Average offshore regional winds were thought to have more meaning in this study as sea state activity can be inferred from it. No recorded offshore wave data was available and since wave action and associated littoral drift has an important influence on inlet geometry, it was necessary to identify severe sea state occurrences and its general direction. These can be identified from the graph showing average daily wind vectors. Prevailing sea state conditions and direction over longer periods can be inferred from the graph showing average monthly wind vectors.

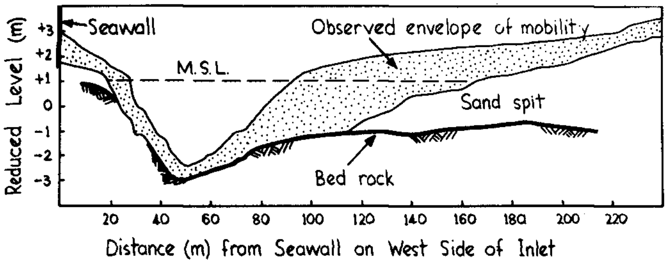

FIGURE 2: INLET THROAT CROSS SECTION

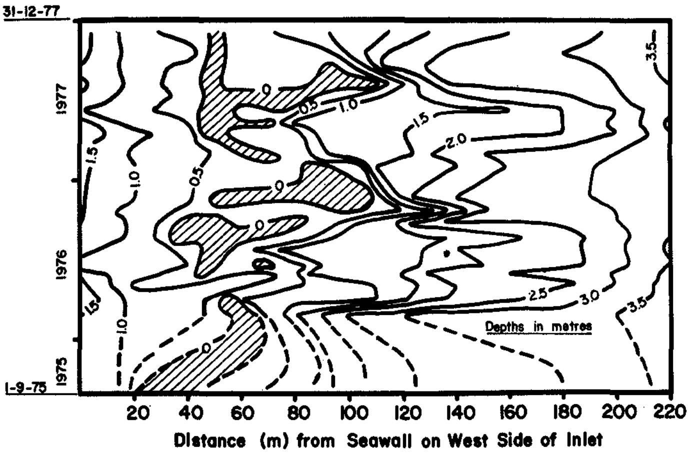

FIGURE 3: DEPTH OF SAND OVER BED ROCK

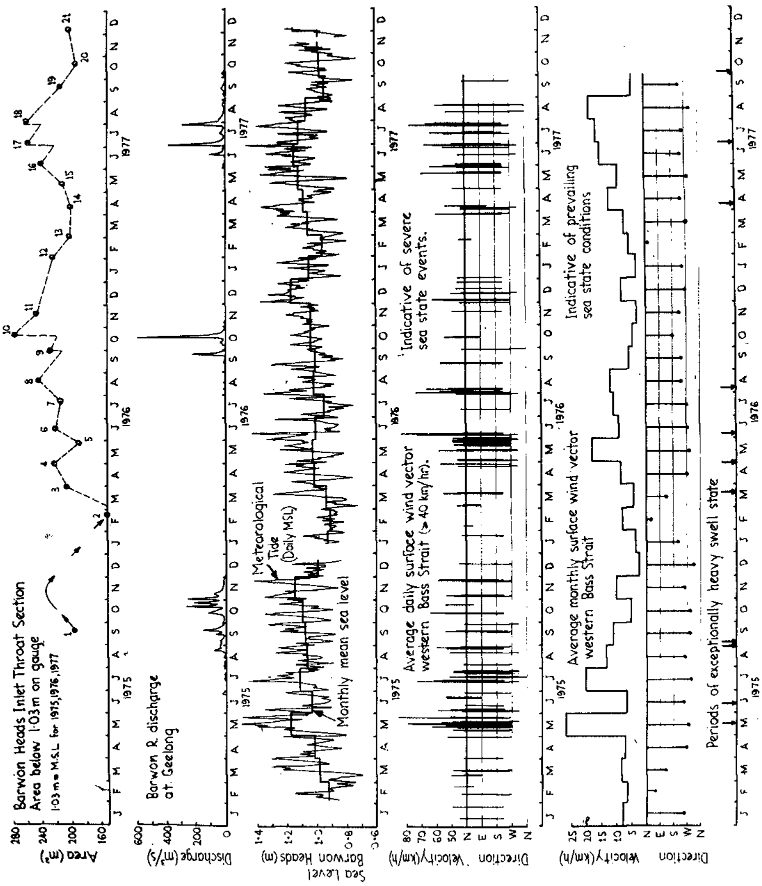

FIGURE 4: CHRONOLOGICAL SUMMARY OF DATA RECORD

TABLE 1

SUMMARY OF INLET DATA

Cross Section No.	Date of Survey	Area (A) Below MSL (m^2)	Width (w) at MSL (m)	Hydraulic Radius (R) at MSL (m)	W/R at MSL
1	19. 9.75	195	91	2.0	45
2	22. 2.76	149	71	2.1	34
3	30. 3.76	205	128	1.8	72
4	30. 4.76	222	128	1.7	76
5	28. 5.76	188	108	1.7	64
6	16. 6.76	220	124	1.7	74
7	23. 7.76	213	118	1.7	69
8	19. 8.76	243	133	1.8	74
9	1.10.76	227	99	2.2	45
10	22.10.76	276	126	2.1	59
11	19.11.76	246	101	2.2	45
12	2. 2.77	223	115	2.0	57
13	2. 3.77	200	116	2.0	59
14	13. 4.77	200	131	1.6	84
15	11. 5.77	210	140	1.4	97
16	8. 6.77	240	144	1.6	90
17	7. 7.77	258	131	1.9	69
18	5. 8.77	260	110	2.3	48
19	21. 9.77	214	88	2.4	37
20	19.10.77	192	88	2.1	41
21	6.12.77	202	114	1.7	66

Two wind recording stations do exist within a 16 km radius of Barwon Heads, one on the coast and one inland, but these are influenced by diurnal and topographic effects and would not be indicative of the offshore regional influences responsible for sea state conditions.

The data in figure 4 demonstrates the predominance of westerly winds. The only months during the study where an easterly component predominated over a westerly component were February and March.

3.6 Swell State:

The data in figure 4 were obtained from visual estimates made by the lighthouse keeper at Point Lonsdale, 10 km to the east of Barwon Heads. The estimates were for swell conditions and not sea conditions, a distinction which was made by the observer. The reliability of the data was dependent on the experience of the observer.

3.7 Sea Levels:

These were obtained from a tide recorder located at the throat inlet section for the duration of the three year study. The data was recorded in analogue chart form and digitised manually at one hourly intervals for computer analysis. The daily mean sea levels (meteorological tide) shown in figure 4 demonstrate that high levels (storm surges) were associated with strong and sustained westerly winds and unusually low levels were associated with easterly gales. A study of weather and associated sea levels at Barwon Heads has been reported elsewhere (Keats, 1979). Generally speaking the average monthly mean sea levels were lowest in February.

4. INLET BEHAVIOUR:

4.1 General Variability:

The cross section area below mean sea level varied from a minimum of 149 m^2 to a maximum of 276 m^2. The envelope of sand surface elevation over the study period (figure 2) represents the prism of sand worked over during that period. The prism of sand below mean sea level was 171 m^3 per metre length of inlet and 331 m^3 per metre length of inlet for the whole cross section. The gross volume changes (absolute sum of the changes between each survey) were 501 m^3 per metre length of inlet below mean sea level and 912 m^3 per metre length of inlet for the whole cross section. Nevertheless, net changes within the cross section between the first and last survey were only small being +7 m^3 per metre length of inlet below mean sea level and +30 m^3 per metre length of inlet for the whole cross section.

The maximum depth of sand movement within the total cross section was 2.9 m. Bed rock was always exposed in the bottom of the inlet restricting the water depth that could be attained (figure 3). The maximum depth of the inlet, therefore, varied little. Major adjustments in cross section area were achieved by movement of the inlet's eastern boundary as the sand spit extremity forming that boundary, retreated or advanced over the bed rock.

The inlet itself remained fixed in general location, this being attributable in no small way to the influence of Point Flinders.

4.2 Inlet Area Enlargement:

Flood flows, even if relatively small, had a significant influence on the area below mean sea level. The two flood flows of 1976, which occurred within a four week period, increased the cross section considerably, mainly by removing sand from above the base rock on the east side of the inlet. At Geelong, the larger of these two floods had a return period of ten years and the smaller a return period of three. Enlargement was again detected during the two floods of 1977 which also occurred within a four week period. The enlargement was again effected by the removal of sand from above the base rock on the east side of the section. The larger of these two floods had a return period at Geelong of five years and the smaller flood a return period of four years. The results are not inconsistent with a relationship where the inlet throat area after a flood is highly dependent on the magnitude of the flood peak such that the larger the flood peak the larger the resulting cross section area.

It should be understood that the peak flood discharge through the inlet occurs four to five days after the storm which produced it. Therefore it need not be coincident with extremes of other parameters such as gale force winds, high seas and high daily mean sea levels, which may have accompanied the storm responsible for the flood flows. The flood peaks shown for Geelong in figure 4 would have occurred two to three days after heavy rainfall on the upper catchment. The peak flows through the inlet at Barwon Heads would have occurred about 36 hours later again and would have been attenuated considerably below the peak at Geelong. Investigations undertaken so far, indicate that major flood peaks at Barwon Heads are at least 20 to 30 percent less than those observed at Geelong.

Other inlet enlargements did occur during periods well isolated from flood events, when river flows approached cease to flow conditions. Typically, these were periods which experienced -

a. High daily mean sea level events (storm surges).

b. Prolonged west to south west wind events where the average daily surface wind speed in Bass Strait exceeded 40 km per hour for 5 or more consecutive days. This also implies prolonged periods of high sea state from the south west.

c. Exceptionally heavy swell events from the south to west quarter.

Those periods immediately preceding cross sections 6, 8 and 16 fall into this category.

Enlargement during severe storm periods is contrary to expected behaviour. Most investigators report inlet channel reduction during such periods because of increased littoral drift rates. One possible explanation is that during exceptionally high tides, significant amounts of sea and swell do penetrate to the throat region and impinge on the sea wall on the Barwon Heads side of the inlet. This is particularly so during south westerly gales when high tide still water levels of 2.4 m are not uncommon and this is often sufficient to submerge the base of the sea wall on the west side of the inlet. The waves are reflected from the wall obliquely across the inlet, interacting with the incident waves, creating severe turbulence in the shallower edge regions on both sides of the estuary. The turbulence would tend to keep sand in suspension, it then being moved out of the region by prevailing tidal currents.

One enlargement that does not fit the patterns previously described is that resulting in cross section 3. The river was near cease to flow condition and strong winds from the south west exceeded average daily values of 40 km/hr in only one storm that lasted for only two consecutive days. There was, however, an earlier easterly gale when average daily surface winds exceeded 40 km/hr for two consecutive days. Despite the fact that this was only a two day event, and that daily mean sea levels were unusually low, the inlet's greater exposure to the easterly direction, combined with the later south westerly storm, must have enabled enough wave energy to reach the inlet to create sufficient turbulence to remove sand from the region.

4.3 Inlet Area Reduction:

The data record shows that periods of reducing cross section area are typically those which -

a. Follow the winter and spring flood periods.

b. Have falling or more moderate monthly mean sea levels.

c. Are free of prolonged, extreme wind events when the daily average surface wind speed in Bass Strait exceeds 40 km/hr for three or more consecutive days. That is when more moderate sea states prevailed.

d. Are generally free of exceptionally heavy swell events.

These characteristics are evidenced in all three years of the data record following winter and spring floods. The fact that these four characteristics are linked together is not surprising because they are not mutually independent. Low river flows, less extreme mean sea levels and less severe sea and swell states are associated with more moderate wind and weather conditions (Nelson and Keats 1978).

The rate of area reduction can be both rapid and sustained following a flood period. After the floods of September and October 1976, the cross section reduced at a peak rate of 30 square metres per month for a 28 day period immediately following the flood and sustained an average reduction rate of 16 square metres per month for a 131 day period, to produce a total reduction of 76 square metres. Following the floods of July and August 1977 the cross section reduced at a peak rate of 28 square metres per month over a 47 day period immediately following the flood and sustained an average reduction rate of 26 square metres per month over a 74 day period to produce a total reduction of 68 square metres.

The bulk of the material responsible for the area reduction was, in both instances, deposited on top of the base rock on the east side of the cross section so that the east side boundary gradually encroached toward the centre of the section. This is contrary to the general west to east movement of littoral drift prevailing along the coast. Sand tracer experiments have not been made to determine the precise cause of this local behaviour but wave pattern observations suggest the following explanation. The predominant south westerly waves refract and diffract around Point Flinders resulting in a wave direction near the end of the sand spit favourable to the movement of material back into the inlet from the east side. This material would be that washed out by flood flows together with some which appears to be deposited on a shallow bank on the east side of the inlet after bypassing the inlet from west to east.

The inflow of material from the east side and its deposition in the throat section only occurs during milder wave conditions. Severe and prolonged south west gales and their associated abnormally high sea levels cause the opposite effect as described in section 4.2.

4.4 Overall Influence of Floods:

Figure 5 is a plot of inlet throat area below mean sea level against peak river discharge at Geelong immediately preceding the inlet survey. Included is one survey taken after the flood of November 1978 which was the largest flood since 1952. While this is well isolated from the continuity of the main study period it is very valuable in assessing the inlet's response to flood flows. The area range shown on the zero discharge line, represents inlet surveys well isolated from flood events. It indicates the range of cross section area that can occur under the influence of varying wind, wave and meteorological tide conditions. Those points shown coupled with significant river discharges, demonstrate that the range of cross section area possible during flood flows is reduced, being minimised when the peak flood flows at Geelong are about 250 m^3/s to 300 m^3/s. For higher flows at Geelong the cross section area at the inlet is a function of the freshwater discharge only and independent of prevailing wind, wave and sea level conditions.

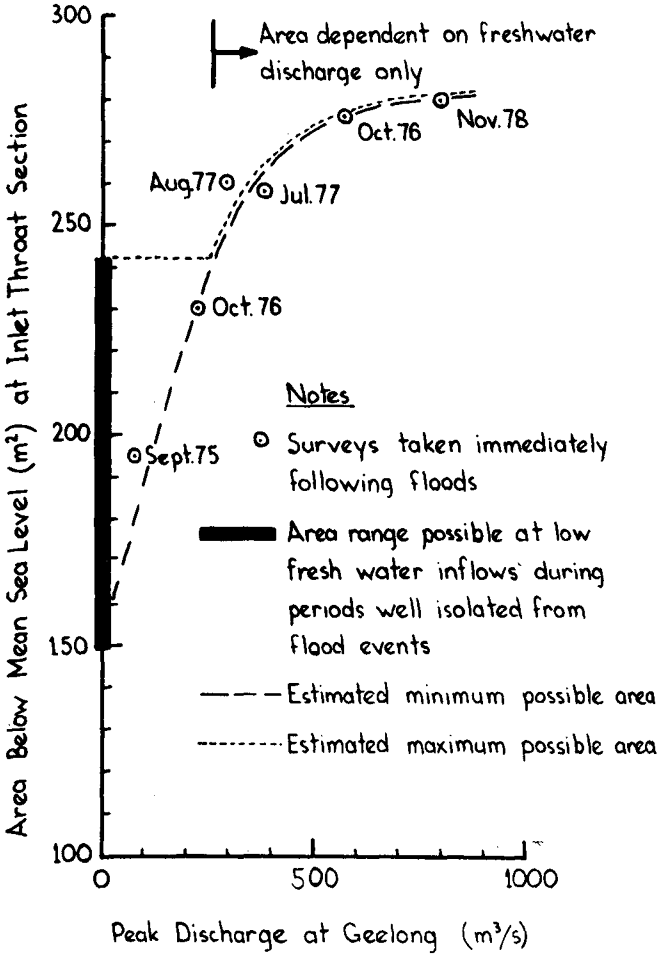

FIGURE 5: FLOOD FLOW INFLUENCE

5. EQUILIBRIUM CRITERIA CONSIDERATIONS:

Table 1 and figures 2, 3 and 4 demonstrate the geometric variability of the Barwon Heads inlet over the period of investigation. Of particular interest was the variability of the cross section area below mean sea level (1.03 m).

The mean area was 218 square metres with a standard deviation of 28 square metres representing 13 percent of the mean. The minimum observed area was 149 square metres and the maximum 276 square metres representing a range of from minus 32 percent to plus 27 percent of the mean. For comparative purposes discussed below, the standard deviation in log A was required and was determined to be 0.058. Investigators have found that the area below mean sea level depends primarily on the tidal prism of the upstream water body. Linear regression analysis on the logarithms of these two parameters yield equations of the form

$$A = bP^{c}$$

where A is the cross section area below mean sea level, P is the tidal prism and 'b' and 'c' are constants. Figure 6 shows a plot of data for eight North American inlets without training walls, published by O'Brien (1969). The cross section area at each inlet was generally estimated from one set of survey data. Data for the Barwon Heads inlet is also shown, based on the mean of twenty-one surveys. Linear regression analysis on the nine points yields equation (1).

$$A = 1.08 \times 10^{-4}\ P^{0.97} \qquad (1)$$

where A is in square metres and P is in cubic metres. A measure of the data scatter and the degree of uncertainty involved in using this equation is given by the standard error in log A which was 0.066. The standard error in log A must be used since the linear regression analysis was done on the logarithms of A and P. However, an indication of the physical significance is obtained by realising that a standard error of 0.066 in log A represents a range of from minus 14 percent to plus 16 percent about the most likely value of A.

The standard error associated with log A in equation (1) approximates the standard deviation associated with the 21 observed values of log A at Barwon Heads. It seems the entire uncertainty associated with equation (1) could be explained by the natural variability associated with each inlet. Therefore, attempts to reduce the uncertainty associated with equation (1) by investigating the influence of other parameters, such as grain size or by improving the accuracy, resolution and compatibility of the various data used to estimate areas and prisms at each inlet will, on their own, produce minimal rewards. They must be coupled with observations of the variability induced at individual inlets by varying hydraulic and meteorological conditions.

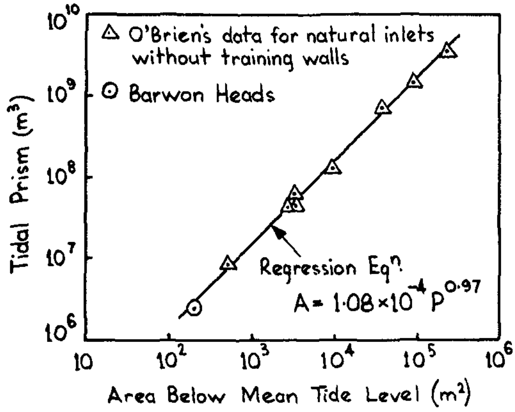

FIGURE 6: INLET AREA VERSUS TIDAL PRISM

The Barwon Heads data demonstrates that inlet area based on one survey (or even two or three surveys) can give quite misleading information as to the prevailing or average geometric characteristics. When a group of such data is assembled from different inlets (eg. O'Brien's data of figure 6), the degree by which the observed area varies from the mean will differ from inlet to inlet depending on the antecedent conditions experienced at each inlet prior to it being surveyed.

Of further interest in this study was whether an inlet like Barwon Heads conformed to equilibrium criteria developed from inlets with unrestricted bed mobility. Two empirical criteria are considered here. The first concerns the relationship between an inlet's cross section area and its tidal prism. The data plot of figure 6, together with the regression analysis indicate that the Barwon Heads data fall well within the expected range as determined from inlets with unlimited bed mobility. The second criterion refers to the inlet's mean maximum tidal velocity for a mean spring tide. Bruun and Gerritsen (1960) demonstrated that

$$Q_{max} \doteqdot A \qquad (2)$$

This implies that the maximum tidal velocity for a stable inlet is approximately 1.0 m/s. At Barwon Heads the ratio of the maximum discharge (mean spring tide) to the mean cross section area below mean sea level is 1.06 m/s. However, if the phasing between the discharge and water level variations with time are taken into account the actual maximum velocity is nearer 0.9 m/s. The data again agree closely with those determined from inlets with unlimited bed mobility.

6. SUMMARY AND CONCLUSIONS:

a. While the depth of the inlet remained fixed by the bed rock, the variation in cross section area and width were such that their maximum observed values were approximately double their minimum values. Major adjustments in cross section area were achieved by the retreat or advance of the inlet's sandy eastern boundary across the underlying rock platform.

b. Freshwater flood flows had by far the most significant influence on inlet area change (enlargement) but recovery was both rapid and sustained. High meteorological tides combined with severe and prolonged south westerly sea and swell states also created area enlargements, contrary to expected behaviour. Area reduction always occurred following floods and during periods when more moderate seas and swell prevailed together with more moderate mean sea levels.

c. Bed rock was always exposed in the bottom of the inlet restricting the depth that could be attained. Despite this, the inlet's tidal prism and average cross section area below mean sea level, conformed closely to equilibrium criteria developed from inlets with unlimited bed mobility. The same finding applied to the inlet's mean maximum tidal velocity.

d. The statistical uncertainites associated with predicting an inlet's equilibrium cross section area from existing equilibrium equations, are approximately the same as those associated with the natural variability of any one inlet, if the Barwon Heads observations are typical. Therefore, attempts to refine equilibrium equations will not be profitable unless coupled with studies, over a period of time, of the response of individual inlets to varying hydraulic and meteorological conditions.

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