MORPHOLOGY OF COASTAL LAGOON ENTRANCES: WAVES VERSUS TIDES

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Lagoon inlets and river entrances on sandy coasts are shaped by waves, tides and freshwater outflows interacting subject to geological constraints. In dimensionless terms the relative importance of fresh water discharge Q_f versus peak tidal discharge $\hat{Q}$ is quantified simply by $Q_f/\hat{Q}$, where the tidal peak discharge may be taken either as the actual $\hat{Q}_{actual} = \omega_{tide} a_B A_B$ corresponding to the actual bay tidal amplitude a_B or the potential $\hat{Q}_{pot} = \omega_{tide} a_O A_B$, which is based on the ocean tide amplitude a_O. ω_{tide} is the tidal angular frequency and A_B is the bay surface area at mid tide. The quantification of the relative strength of waves versus tides is less obvious and has not previously been clearly resolved. The case is made here for it being quantified by $\hat{Q}/\sqrt{g\overline{H_s}^5}$, where tidal dominance resulting in the canonical funnel shaped estuary occurs for $\hat{Q}/\sqrt{g\overline{H_s}^5} \gtrsim 75$ and, at the other end of the spectrum, intermittently open/closed systems (ICOLLS) occur for $\hat{Q}/\sqrt{g\overline{H_s}^5} \lesssim 20$. $\overline{H_s}$ denotes the average offshore significant wave height and g is acceleration due to gravity. More comprehensive data may lead to the inclusion of the wave period as well as the wave height in future formulations.

Keywords: Tidal inlets, funnel shaped estuaries, inlet closure, morphological time-scales, ICOLLS

INTRODUCTION

Tidal inlets are important parts of coastal ecosystems and have been the topic of active coastal geomorphology and engineering research for more than a century. The earliest researchers probably realised that the equilibrium cross-section shape, around which a given inlet oscillates due to changing tides and waves and due to occasional storm surges and/or freshwater floods, can be described in terms of the potential bay or lagoon area and the typical wave and tide parameters for the location. See the nice qualitative introduction to inlets by Dean & Dalrymple (2002) p 413. However, till now, the competing effects of waves and tides have not been combined into effective parameters for inlet classification or formulae for inlet cross section area, delta volumes, typical duration of open or closed conditions etc. The following gives the rationalisation of such a parameter, which necessarily accounts for tidal period as well as tidal prism and wave height. The effectiveness of this new parameter for quantitative classification of inlets is subsequently demonstrated.

TIDES AS MORPHODYNAMICS DRIVERS

Early works, e g, Obrien (1931, 1969) considered the tidal prism volume P as the measure of the tide's strength as a morphology driver. However, most researchers now agree that the peak tidal discharge $\hat{Q}$ is a better measure, because a given tidal prism gives twice the velocities and hence much larger erosion power with semi-diurnal tides compared with diurnal tides. For semi-diurnal tides O'Brien gave a simple relation between the tidal prism and the inlet gorge cross section, which, as Bruun (1966) p 121, pointed out, corresponds to the rule of thumb that natural inlets on sandy coasts take a shape such that the peak tidal velocity through the throat of the inlet is close to 1m/s.

For an equilibrium situation one might then work with the actual $\hat{Q}$ evaluated in terms of the bay tidal amplitude a_B, the tidal angular frequency ω_{tide} and the bay surface area A_B :

$$\hat{Q}_{actual} = \omega_{tide} A_B a_B \quad (1)$$

However, a_B may not be available from measurements or it may indeed be variable due to morphological changes, which are being investigated, in which case the potential peak discharge

$$\hat{Q}_{pot} = \omega_{tide} A_B a_O \quad (2)$$

based on the ocean tidal amplitude a_O is more useful, because it is an 'external parameter' to the inlet morphodynamics.

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Both of these measures of tidal ‘morphodynamic strength’ have straightforward meanings for simple harmonic ocean tides but require some specification, when the ocean tides are mixed diurnal/semi-diurnal.

In this study, irregular tides are quantified in terms of half of the mean spring tidal range, i e:

$$\hat{Q}_{\mathrm{pot}} = \omega_{\mathrm{tide}} A_{\mathrm{B}} \frac{MHWS - MLWS}{2} \tag{3}$$

with the angular frequency ω_{tide} corresponding to the dominant tidal period, i e, 12.25hours for a semidiurnal tide and 24.5hours for diurnal tides.

WAVES AS MORPHODYNAMICS DRIVERS

Bruun (1978) discusses inlet stability in terms of the ratio between the tidal prism and the annual volume of sand carried along the coast as littoral drift and this line of investigation has since been pursued by Kraus and co-workers, e g, Kraus (1998, 2010). However, waves are able to close inlets inside embayments and along coasts, which are perfectly aligned with the waves so that the averaged littoral drift rate is zero. For example, the entrance to Lake Wonboyn (37°15’S 149°58’E), Figure 4, which experiences very minimal littoral drift, was closed in October 2009. It was eventually reopened by a major freshwater flood on February 15 2010, cf Manly Hydraulics Laboratory (2010) Figure 263. Ranasinghe & Pattiaratchi (2003) also argued that the closure event for Wilson Inlet in Western Australia, 35°01’S 117°20’E, which they studied, was more likely due to shore-normal than to longshore sediment transport.

Hence, for an initial quantification of the ability of waves to close inlets we use simply the wave height, or more specifically, the average offshore significant wave height $\overline{H}_s$. For more detailed investigations, the effective wave height reaching the inlet must be evaluated considering refraction and diffraction through the shoaling zone. Future availability of more detailed wave data may also enable analysis of the effect of the typical breaker angle and the wave period, which is known to affect the waves’ berm building capacity and hence possibly their ability to close inlets. Bruun’s (and others’) suggestion of using the littoral drift rate instead of the wave height, calls for the cautioning w.r.t. the present approach, that there must of course be sand present, for the waves to be able to close an inlet.

THE BALANCE BETWEEN TIDES AND WAVES

Based on the arguments above it seems natural to consider the balance, between tides and waves in shaping tidal inlets, in terms of the dimensionless relative tidal strength:

$$R_{\mathrm{T/W}} = \frac{\hat{Q}}{\sqrt{g\overline{H}_s^5}} \tag{4}$$

where we note that the longshore sediment transport rate is also proportional to $\sqrt{g\overline{H}_s^5}$ according to the commonly used ‘CERC’ Formula, see e g, Nielsen (2009) p 271.

An alternative parameter based on the observation by Takeda & Sunamura (1982) that the waves ability to build berms, which may close inlets, depends quite strongly on the wave period T suggests

$$R'_{\mathrm{T/W}} = \frac{\hat{Q}}{gT\overline{H}_s^2} \tag{5}$$

However, the choice between (4) and (5) on the base of prediction skill requires a large amount of wave refraction and shoaling calculations based on inshore topography and detailed setting of individual inlets relative to headlands etc, which is left for further study.

THE IMPORTANCE OF A_B THROUGH $\hat{Q}_{\mathrm{pot}}$ FOR MEASURING TIDAL DOMINANCE

As mentioned above the use of the tidal prism P as a measure of the tide’s ability to shape inlets is not optimal because the influence of the tidal period or the angular frequency ω_{tide} is important. Likewise, the use of simply the tidal range as recommended by Hayes (1979), is unlikely to succeed. This approach neglects the bay area A_{B} as well as ω_{tide}. Figure 1 shows three neighbouring inlets of which the smaller ones show wave influence while the larger one is of the canonical funnel shaped tide-dominated type.

Figure 1: Three inlets on the NW coast of Western Australia near 20°49'S, 116°26'E. The spring tidal amplitude in this area is a_O= 2.2m, while the average significant wave height is around $\overline{H}_s \approx$ 0.70m. Starting from the left, the small river-like system has $A_B \approx$ 0.04km^2 leading to $\hat{Q}_{pot}/\sqrt{g\overline{H}_s^5}$ =10. The system in the middle has $A_B \approx$ 0.06km^2 leading to $\hat{Q}_{pot}/\sqrt{g\overline{H}_s^5}$ =15, while the funnel shaped system on the right has $A_B \approx$ 0.60km^2 leading to $\hat{Q}_{pot}/\sqrt{g\overline{H}_s^5}$ =147.

The two smaller inlets show clear wave influence while the larger system on the right has the canonical funnel shape of tide-dominated systems. Thus, for these macro-tidal inlets, the threshold for total tide dominance is in the range

$$15 < \frac{\hat{Q}_{pot}}{\sqrt{g\overline{H}_s^5}} < 150 \qquad (6)$$

A similar message is given by the 178 estuaries from the micro-tidal SE Coast of Australia considered by Roper et al (2011). These indicate a limiting value for tidal dominance of 75 along the micro-tidal coast of New South Wales, cf. Figure 2 (Thuy, 2013).

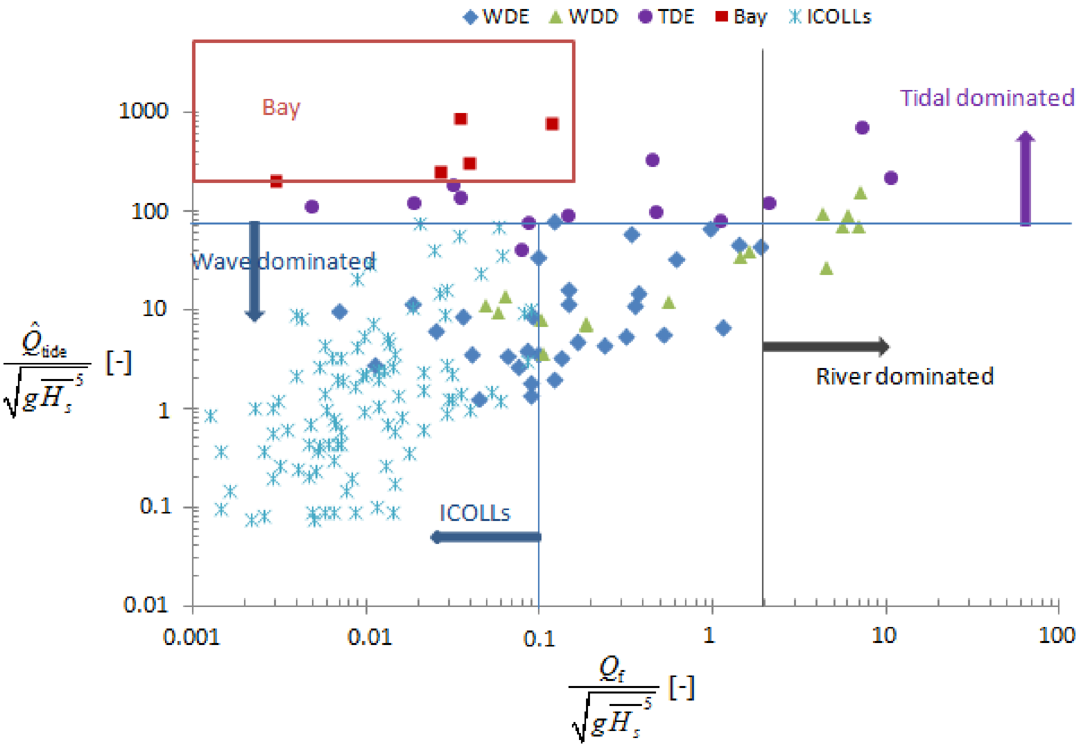

Figure 2: Classification by Roy et al (2001) and Heap et al (2001) for 178 estuaries in NSW, Australia, quantified in terms of $\frac{\hat{Q}_{actual}}{\sqrt{g\overline{H}_s^5}}$ for 80 estuaries for which *P* is available, $\frac{\hat{Q}_{pot}}{\sqrt{g\overline{H}_s^5}}$ for the remaining 98 ICOLLs, $\hat{Q}_{actual}$ is highly variable. $\frac{Q_f}{\sqrt{g\overline{H}_s^5}}$ -values are from the data summary of Roper et al (2011). The typical NSW deep water wave height around *H*=1.6m, Kulmar et al (2013), is applied irrespective of the setting of individual inlets. WDE: wave dominated estuaries, WDD: Wave dominated deltas, TDE: Tidal dominated estuaries, ICOLLs: Intermittently Closed and Open Lakes and Lagoons.

The inlets in Figures 1 and 2 are from coasts with predominantly semidiurnal tides, while the Pensacola Pass, Florida, US (30º19.5'N 87º18.5'W), is exposed to diurnal tides. Based on the average conditions from CIRP ($a_b \approx a_o$, T_{tide}, A_B, $\overline{H}_s$) = (0.21m, 24.5h, 477km^2, 1.0 m) this inlet is clearly tide dominated with

$$\frac{\overline{Q}_{pot}}{\sqrt{g\overline{H}_s^5}} \approx \frac{\overline{Q}_{actual}}{\sqrt{g\overline{H}_s^5}} = 2278 >> 150 \tag{7}$$

And even larger with $\frac{\hat{Q}_{actual}}{\sqrt{g\overline{H}_s^5}} = 3029$ calculated with spring tidal prism P=2.7x10^{8}m^3. Visual morphological feature confirms this classification with well-developed ebb deltas as shown in Figure 3. However, the inlet falls in wave dominated estuary according to Hayes (1979).

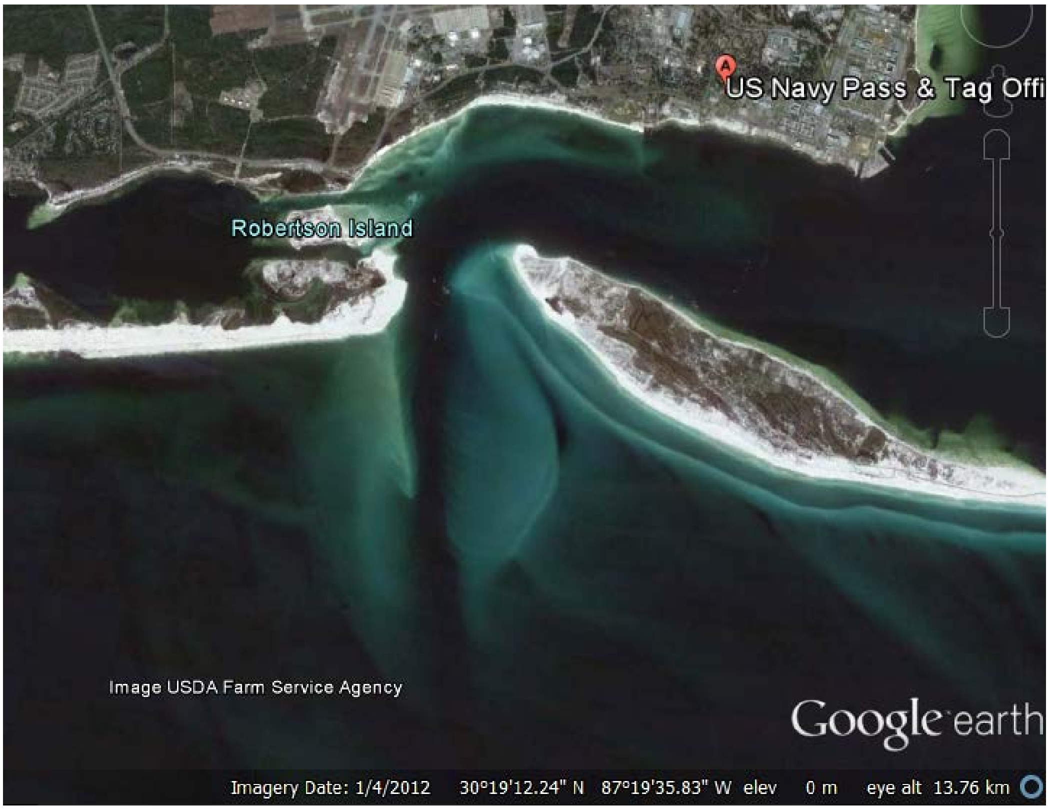

Figure 3: Pensacola Pass on Florida, US near 30°19.5'N 87°18.5'W. The inlet spring tidal prism of P=2.7x10^{8}m^3, corresponding to large bay surface area of A_B≈ 477 km^2 (FL32399 report, 2012) and mean spring tidal amplitude approximately a_B =0.27m while average ocean amplitude in this area is a_O= 0.21m. The Bay tide has perfect response to the ocean tide due to large entrance area of the order of 10000m^2. The average significant wave height is around $\overline{H}_s$ ≈ 1m. Two well-developed ebb deltas and large value of $\frac{\hat{Q}_{\text{actual}}}{\sqrt{g\overline{H}_s^5}} = 3029$ indicate that the system is tidal dominated estuary while it is wave dominated according to Hayes (1979).

WAVE DOMINATED SYSTEMS

For small values of $\hat{Q}_{\text{pot}} / \sqrt{g\overline{H}_s^5}$ the waves will close the inlet and it will remain closed until a major freshwater event or human intervention reopens it. Lake Brou on the South coast of NSW Australia, Figure 3, is a small estuary which gets closed by the waves in a few tens of days after being opened by freshwater floods. It is a rare system, perfect in that its setting is unaffected by headlands and that it breaks out naturally because it is not surrounded by flood sensitive developments. – Unfortunately, the latter also means that water level data are scarce.

Figure 3: Lake Brou, on the South coast of New South Wales Australia (36º07'S 150º06'E) has A_B= 2.4km^2 and faces the Tasman Sea where the mean spring tidal amplitude is around 0.5m and the mean, offshore significant wave height is approximately 1.6m corresponding to $\hat{Q}_{pot} / \sqrt{g\overline{H_s}^5}$ = 17.

After a recent freshwater flood it took the waves 42days to close the inlet to Lake Brou. (Manly Hydraulics Laboratory unpublished water level data).

Thuy et al (2013) have documented 4 similar closure events of Lake Avoca (33º27'S 151º26'E), which is smaller than Lake Brou, having $\hat{Q}_{pot} / \sqrt{g\overline{H_s}^5}$ = 4.7 (compared to 17 for Brou). The inlet to Avoca is not quite as simply exposed to waves as Lake Brou. Nevertheless, it was observed to be closed by waves 10 times between July 2007 and June 2012 (Manly Hydraulics Laboratory annual data summaries). It remained open on the average 12.1±8.4 days. It seems fair to suggest that the morphological time scale, T_{morph}, defined by the average time an inlet stays open after opening by floods, storm surges or human intervention, be proportional to $\hat{Q}_{\text{pot}} / \sqrt{g\overline{H_s}^5}$. However, the setting of the inlet and the corresponding details of the wave refraction/shoaling process has a strong effect:

$$T_{\text{morph}} = \frac{\hat{Q}_{\text{pot}}}{\sqrt{g\overline{H_s}^5}} \times \text{function of inlet setting} \tag{9}$$

Thus, Werri Lagoon (34º43'S, 150º50'E) with $\hat{Q}_{pot} / \sqrt{g\overline{H_s}^5}$ = 1.0 is even smaller than Avoca (4.7) but takes longer to close: 16.2±17.1days because of its inlet being somewhat protected by a headland. For a comprehensive discussion of inlet morphological time scales, see Thuy (2013) Section 6.5.

DISCUSSION

The accurate values for the parameters used in Equation (9) are not always easy to estimate. In particular, the effective wave height for inlets, which are sheltered by headlands are not easily decided.

Lake Brou (Figure 3) is unusual in being free of rocky constraints. Such rocky constraints, like manmade training walls, have two opposite effects, which may thus be difficult to evaluate individually.

Lake Wonboyn, Figure 4, has similar ocean tides and offshore wave heights to Lake Brou, corresponding to $\hat{Q}_{\mathbf{pot}} / \sqrt{g\overline{H_s}^5}$ = 26 based on offshore wave height compared with 17 for Lake Brou. Lake Wonboyn is however nearly always open because of sheltering from rocks. This corresponds to the effective wave height to apply in (7) being considerably smaller than the open coast value of 1.6m. Taking half the open coast value, i e, $\overline{H_s} \approx$ 0.8m, leads to $\hat{Q}_{\mathbf{pot}} / \sqrt{g\overline{H_s}^5}$ = 147 for Lake Wonboyn.

A more complete classification of inlet morphologies will require consideration of the strength and frequency of freshwater flows Q_{fresh} compared with the tidal peak discharge as well as the supply of terrigenous sediment $Q_{\text{s,ter}}$. For example, the Fly River estuary, which is shown by Masselink & Hughes (2003) p 158 as a tide dominated estuary, has a very different appearance from the funnel shaped estuaries around Broad Sound Queensland Australia (22° 22'S, 149°44'E). That is because the Fly River has large and persistant Q_{fresh}, $Q_{\text{s,ter}}$ compared with the rivers and creeks of northern Australia.

Figure 4: The inlet to Lake Wonboyn Australia (37°15'S 149°58'E) is sheltered by steep rocks, which help the inlet to stay open most of the time but also restrain growth of the inlet on one side.

Bringing the wave height into the classification of estuaries/inlets in terms of $\dfrac{\hat{Q}}{\sqrt{g\overline{H_s}^5}}$ may also resolve the question raised by Byrne et al (1980) about the relationship between inlet throat cross section *A* and tidal prism *P*. Byrne's small inlets around Chesapeake Bay have relatively much larger A than the oceanic inlets studied by Jarrett (1976). A visual inspection of Byrnes Figure 1 and/or Google Earth shows that the Chesapeake Bay inlets are all more or less funnel shaped indicating tide dominance as for the larger system in Figure 1 above. In other words, one should not expect the same *A-P* relation to hold for Byrne's and Jarret's inlets, the former being tide-dominated while the latter have significant wave influence. Unfortunately Byrne did not supply wave data.

CONCLUSIONS

It has been shown that the strength of the tide as an inlet morphology driver is most appropriately quantified by the peak discharge $\hat{Q}$, which accounts for the estuary surface area as well as the tidal range and period. Depending on the purpose, $\hat{Q}$may be calculated on the basis of the actual bay tidal amplitude a_B giving $\hat{Q}_{\mathbf{actual}} = \boldsymbol{\omega}_{\mathbf{tide}} \boldsymbol{a}_{\mathrm{B}} \boldsymbol{A}_{\mathrm{B}}$, which is time dependent during morphological changes. Alternatively one may use $\hat{Q}_{\mathbf{pot}} = \boldsymbol{\omega}_{\mathbf{tide}} \boldsymbol{a}_{\mathrm{O}} \boldsymbol{A}_{\mathrm{B}}$ which is invariant for a given bay, and hence more appropriate for classification and morphology prediction.

The difference in A-P relationship between Jarret (1976)'s oceanic inlets and Byrne et al (1980)'s Chesapeake Bay inlets is not a matter of the latter being smaller but rather of them being protected from waves and hence more or less funnel shaped.

Examples from micro- through macro-tidal estuaries in Australia show that total tidal dominance indicated by the canonical funnel shape occurs for $\frac{\hat{Q}}{\sqrt{g\overline{H}_s^5}} \tilde{>} 75$. At the other end of the spectrum, intermittently open/closed systems (ICOLLS) occur for $\frac{\hat{Q}}{\sqrt{g\overline{H}_s^5}} \tilde{<} 20$.

ACKNOWLEDGEMENTS

The writers thank Manly Hydraulics Laboratory for prompt and comprehensive assistance with tide and wave data and Michael Hughes, Tom Baldock for stimulating discussions.

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