# CHAPTER 218

## COASTAL LAGOON ENTRANCE DYNAMICS

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## 1. INTRODUCTION

The coastline of New South Wales (NSW), Australia features numerous lakes and lagoons. The ocean entrances of the lakes tend to be continuously open to the sea. The lagoons, however, experience only intermittent periods of ocean influence following breakouts across the beach. Although the lagoons and their catchments vary markedly in size and overall geometry their hydraulic behaviour is remarkably similar. This is particularly true of their entrance dynamics.

The lagoons, which are the subject of this paper, were formed during the Holocene sea level rise in embayments where the onshore movement of sand impounded small estuaries behind the coastal sand barriers (Roy 1984). They are generally 1 to 2m deep, have a water surface area of between 3 and 300 ha and are located in catchments ranging in size from 5 to 40 km<sup>2</sup>.

The main lagoon water body is generally located immediately landward of the ocean beach and foredune system. It can become connected to the sea if the sand barrier is breached by natural or mechanical means. Following barrier breaching the lagoon becomes tidal

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until, after a time, the entrance is resealed with a sand plug transported into the mouth by the interaction of ocean tide and wave processes.

Because there has been a history of building waterfront housing on the shorelines of these lagoons, social pressures have developed for the control of both lagoon water quality and of the low lying land around the lagoon.

These issues can be related to the lagoon water balance and entrance behaviour. The more frequently the entrance is open to the sea, the better the water quality and the lower the frequency of high flood levels. The desire for lagoon management has in turn generated a need to develop a better understanding of the processes governing entrance dynamics and lagoon water level behaviour.

## 2. FIELD STUDIES

Studies of both the lagoon water balance and the entrance behaviour were commenced in the mid 1970's on a small lagoon at Dee Why, a northern beach suburb of Sydney (Gordon 1981). This lagoon has a water surface area of 25 ha and a catchment area of 5 sq km. The catchment is undulating sandstone country, much of which has been developed for residential and commercial During the studies twenty-five lagoon purposes. breakouts and closures were observed, of which five were studied in detail. Information on the lagoon water balance was based on water level data obtained from an automatic water level recorder, a network of rainfall gauges in the catchment and a study of the phreatic line through the dune barrier and beach.

In the mid to late 1980's these studies were extended to a lagoon at Narrabeen, 3km north of Dee Why (Kulmar et al, 1989). Narrabeen Lagoon has a surface area of 250 ha and a catchment of 55 sq km. The catchment is principally sandstone country however only some 30 per cent of the catchment has been developed, the remainder is natural bushland. Between 1984 and 1988 twenty-one breakouts and closures were observed at Narrabeen. Nine of these events were studies of which three of the breakouts and four of the closures were examined in detail. Lagoon water levels were continuously recorded through the study period by an automatic water level gauge. Rainfall records were available for the catchment from a network of gauges. In addition, weekly photographs of the entrance configuration were taken from a nearby headland which overlooks the entrance.

More recently, information has become available for a larger lagoon (Aber and Downey, 1989). This lagoon is Lake Wollumboola, on the South Coast of New South Wales some 130 km south of Sydney. It has a surface area of 650 ha and its catchment consists of sandy barrier deposits backed by clay slopes. The catchment is mainly natural bushland.

### 3. MODEL STUDIES

During the late 1970's a three dimensional moving bed model of a lagoon entrance was constructed at Manly Hydraulics Laboratory using fine beach sand ( $D_{50} =$ 0.16mm) placed in a 3m x 4m x 0.3m model basin. An entrance sand plug was established and then the water level raised on the lagoon side until overtopping occurred. The "breakout" channel development observed in the model displayed similar characteristics to that observed at the prototype lagoon entrances, however, difficulty was experienced in appropriate selection of model scales to achieve simultude throughout the entire breakout sequence.

### 4. LAGOON WATER BALANCE

There are two distinct water balance regimes for the coastal lagoons. The first is the tidally dominated condition; entrance open (Figure 1(a)). The second regime is governed by the balance of inflows and outflows which occurs when the entrance is closed (Figure 1(b)).

# 4.1 Entrance Open

With the the entrance open the lagoon water level behaviour is determined by the tidal forcing at the

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ocean entrance and by the occasional flood (fresh water) event. The tidal phase lag and head loss through the entrance channel combine to superelevate the mean daily water surface of the lagoon (see Figure 2).



Figure 1 Lagoon Water Balance

The superelevation varies over 28 days from a high during the spring to a low during the neap tide cycles; this spring tide pump-up effect is a subtle but important factor in the ecology and sediment process of the lagoon. During the spring tide period the superelevation typically is of the order of 0.4m while during the neaps it is 0.2m.



Figure 2 Lagoon Tidal Superelevation

Other factors such as ocean storm events producing storm surge at the entrance and wave setup in the surf zone adjacent to the entrance, can also superelevate the mean water level for a period of days. For the NSW lagoons this can produce an increase of some 0.3m in excess of the tidally induced superelevation. In addition, there appears to be evidence of a weak seasonal periodicity in superelevation. This is thought to be caused by seasonal variations in mean air pressure due to the northward shift of the low pressure belt during winter and to seasonal changes in the ratio of onshore/offshore winds.

# 4.2 Entrance Closed

With the entrance closed the mean lagoon water level is dictated by the inflows - stream, groundwater and direct rainfall on the lagoon's water surface; and the outflows - evaporation and percolation through the sand barrier to the ocean (Figure 1(b)). During the period immediately following closure wave overtopping of the entrance sand bar can also provide a short term inflow mechanism. These factors generally produce lagoon water level between 0.8m and 1.4m above mean sea level, with the entrance closed.

Percolation losses through the barrier sand deposit, including the entrance bar is a function of the lagoon water level and the tailwater conditions on the ocean side of the sand barrier. This latter factor is determined by the ocean tide, wave run up and wave set up on the beach. The combined effect of these factors produces an effective tailwater level which is generally elevated between 0.5 and 1.6m above MSL (Figure 3).



Figure 3 Phreatic Surface

#### 5. ENTRANCE BREAKOUT

Two types of breakout have been observed: mechanical opening using earth moving equipment; and natural breakout. This paper concentrates on the latter mechanism.

Natural breakout is associated with lagoon overtopping of the entrance barrier as a result of rainfall runoff from the catchment. Ocean wave action tends to close rather than open an entrance (Gordon 1981).

For the natural breakout case, three distinct stages have been identified (Figure 4):

- \* the initiation channel stage (IC), Froude No. <1</p>
- \* the weir/hydraulic jump stage (WHJ), Froude No. >1
- \* the river flow stage (RF), Froude No. <1





# 5.1 <u>The Initiation Channel</u>

At first bar overtopping occurs as a thin sheet. This flow only extends a short distance downslope on the ocean side of the barrier before it is absorbed into the beach. Gradually as overtopping increases a preferred scour channel develops from the crest, down the slope towards the ocean. Once the channel becomes established bed slope adjustment takes place from the downstream end (Gordon 1981).

In the early part of this first stage the scour rate is low because threshold conditions are only marginally exceeded. As the stage develops however bed ripples, and then small dunes, develop and the Froude No. of the flow approaches unity. The formation of a sand delta at the channel discharge point in the swash zone of the beach, and bank collapses, can result in local slope flattening which produces choking of the channel. At this stage of the breakout flood tide and/or wave conditions may seal the initiation channel causing the breakout to fail, particularly if the runoff from the catchment reduces. If, on the other hand, runoff continues, the scour channel will develop.

For the two lagoons where this process has been repeatedly observed, Dee Why and Narrabeen, the initiation stage generally takes between 80 and 100 minutes. The factors which control time for this stage include: rate of rise of lagoon water level, the differential head between the lagoon and the ocean water level, porosity of beach, width and crosssectional shape of the barrier at the entrance and the wave conditions. Towards the end of the IC stage the channel width is generally 1 to 2m, the flow depth is 0.2 to 0.25m and the velocity 1.4 to 1.5m/sec.

# 5.2 The Weir/Hydraulic Jump

Stage two develops quite rapidly. A semi circular weir forms in the sand at the upstream end of the channel, the flow becomes supercritical on the crest and a plunge pool and a series of undulating hydraulic jumps develops downstream. The unsteady downstream flow conditions caused by the undulating jumps initiates a series of bedforms which progressively become steps in the channel (Figure 5). The flow accelerates on the downstream face of these steps and a standing roll wave Bed scour is most pronounced develops at their base. on the downstream face of the steps and hence they are translated up the channel towards the plunge pool. As each step arrives at the plunge pool there is a sudden increase in weir face erosion and hence the weir is



Figure 5 Breakout Channel Geometry

translated further inland. The channel then re-adjusts and a new step forms at the downstream end. Hence channel bed slope adjustment translates upstream from the downstream end.

An interesting feature of the weir geometry is that it is determined by the minimum specific energy condition, that is it forms an efficient dam spillway crest shape (Gordon, 1981). Discharge can be approximated using the weir formula:

$$0 = 3.97 \text{LH}^{3/2}$$

Where H is the lagoon water level height above the crest and L is the length of the crest.

The principal factors which determine the duration of the WJH stage include: lagoon water level; ocean water level; and the width and cross-sectional geometry of the barrier. Wave action has little impact during the WHJ stage. The outflow is sufficiently energetic that it dominates the normal nearshore surf zone processes.

Velocities in the channel are in the range 3 to 4 m/s with peak short term velocities of 6 m/s. The Froude

No. is generally between 1.2 and 1.8; hence the undulating jump formation. The stage usually lasts between 100 and 140 minutes. Figure 6(a) which is based on data gathered for the WHJ stage of the three lagoons studied, summarises the development in mean channel width downstream of the plunge pool while Figure 6(b) presents the cumulative volume of sand removed over time.



Figure 6 Channel Characteristics, WHJ Stage

# 5.3 <u>River Flow Stage</u>

The final stage is reached approximately 180 to 240 minutes after overtopping first commences. The weir feature completes its upstream translation through the barrier and disappears. The Froude No. reduces to below unity and a steadier flow regime is established. However, scour of the channel continues for as long as threshold conditions are exceeded. The larger the lagoon and/or the runoff event the greater the final channel width. Of the three stages, this is the only one whose duration is in part dependent on the lagoon and catchment size. As the head level difference between the lagoon and the ocean decreases, the discharge reduces. Within a matter of hours the lagoon becomes tidally dominated and the entrance starts to infill.

# 5.4 Breakout Sediment Transport

Different approaches are required for the three stages. The IC stage is mainly bedload dominated, transport capacity is rapidly achieved, however, percolation losses into the adjacent beach berm and intermittent bank slumping are important considerations.

Stream flow during the WHJ stage is highly energetic with Froude Nos. from 1.5 up to 2 and is therefore outside the domain of most existing theories. Visser (1988) has developed an interesting approach for dikeburst. Based on a modified Bagnold (1966) formulation, the Visser approach includes an expression for calculation of the progressive sediment load uptake in a channel. The approach can be summarised as:

 $S(x) = \frac{x}{l_a} S_a$  where S(x) is the sediment load transport and x is the distance down the slope

 $l_{a} = \frac{q}{w \cos \beta}$  where q is the discharge per unit width w is the fall velocity  $\beta$  is the slope angle

$$S_{s} = \frac{e C_{f} u^{4}}{(1-p)\Delta g w \cos^{2}\beta}$$
where e is the efficiency factor
$$C_{f} \text{ is the bedform drag}$$
u is the depth averaged velocity
p is the porosity
$$\Delta \text{ is } (\rho_{s}^{-}\rho)/\rho$$
g is gravity

While the Visser formulation is conceptually attractive, it is highly sensitive to the value of stream velocity. Unfortunately, this variable is the most difficult to measure during the energetic WHJ stage. Coupled with the need to determine relevant values for  $C_f$  and e, the velocity sensitivity has to date hampered evaluation of the Visser approach. Further, it is felt that the differences in channel slope (Visser case  $\beta = 14^\circ$ , Lagoon case  $\beta = 1.5^\circ$ ) and hence velocities (Visser case u = 20 m/s, Lagoon case u = 4 m/s) and bedform size (Lagoon channel bedform height  $\approx 0.5$  depth) requires some modifications of Visser's assumptions to adapt the approach to the WHJ stage.

Sediment transport during the RF stage can be satisfactorily assessed using a traditional approach such as that of Ackers and White (1973).

## 6. ENTRANCE CLOSURE

Infilling of the entrance channel commences on the first flood tide following breakout. Initially infilling is rapid (Figure 7). During flood tides the wave stirring in the surf zone adjacent to the entrance entrains sediment which is then available to be transported into the entrance by the tide and deposited in the entrance channel. In addition, wave obliquity on the beach face at the entrance combined with wave overwash into the channel across the beach, erodes material from the beach berm and deposits it along the channel edge.

On the ebb tide, however, as the impact of wave stirring on re-entrainment of the sediment in the entrance is limited to the downstream region of the mouth, the outflowing water is unable to achieve a



Figure 7 Entrance Plug Re-establishment

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matching removal of sand. Thus, there is a net imbalance favouring flood tide transport of sediment into the lagoon. Progressively an hydraulic choke which limits the tidal prism develops in the entrance.

The flood tide imbalance is exacerbated by the asymmetry of the flood and ebb tidal flows. Flood tides produce relatively high velocities near the peak flow of the tide as compared with the ebb tide which generates longer lasting but lower flow conditions (Kulmar et al, 1989). The relationship between flow velocity and sediment transport being highly nonlinear, the flood tide produces a greater transport of sediment than the ebb. Hence the channel trends towards closure under normal oceanographic and meteorological conditions.

As the entrance choke develops, the channel starts to meander across the beach berm. The wave obliquity prevailing at the time causes the channel to be deflected in a down drift direction. The slope of the channel reduces as the meander length increases. This in turn reduces tidal velocities hence entrance shoaling is accelerated.

Because of the relative sensitivity of the entrance behaviour to the prevailing wave and tidal conditions, daily changes in entrance geometry are often significant. These changes are so rapid that to date, numerical simulation of entrance behaviour has not proved a practical proposition for anything other than a short period of time. Winton and Mehta (1981) have developed a numerical model, based on the Bruun approach (1978), which can however be usefully applied to predict the rapid lagoon closure situation associated with storm wave events.

Modelling of entrance behaviour for those lagoons which experience extended periods of opening is further complicated by freshwater flood events; storm surge events; and by the spring/neap pump-up effect. Intermittent freshwater floods produce entrance scour which reverses the normal closure trend. A storm surge and/or wave setup event initially produces a net inflow of water and sediment into the lagoon. However, on the falling stage it can also result in entrance scour as the lagoon level returns to normal. The spring tide pump-up phenomenon produces a similar effect.

The time a lagoon is open is dependent on the the tidal prism of the lagoon and the gross sediment transport environment of the adjacent beach. At Dee Why the average time the lagoon was open was found to be 17.5 days (Gordon, 1981). While at the larger Narrabeen lagoon the average time was 89.2 days (Kulmar et al, 1989). The sensitivity of entrances to the variable oceanographic and meteorological conditions can be illustrated by examining the standard deviations and range of the times for which the entrances are open. For Dee Why the standard deviation was found to be 13 days and the range was 2 to 44 days. At Narrabeen the standard deviation was 122 days and the range was 5 to 365+ days.

With the channel in a choked condition, closure can occur quite suddenly; commonly over one tidal cycle. Closure is normally associated with any one, or any combination of the following: a flood tide, a storm surge event, elevated wave energy conditions, the spring tidal cycle and low rainfall in the catchment. Once the entrance is closed, the plug rapidly develops over a period of 10 days after which the crest height is at an elevation of 1.4 to 1.6m above sea level; the normal elevation of wave uprush (see Figure 7). After this initial rapid build up the rate of plug development substantially reduces. Aeolian processes take over as the dominant formation mechanism, assisted at times by wave uprush during spring tides and/or storm waves. The plug gradually assumes the geometry of the surrounding beach berm with its crest level at an elevation of between 2 and 3m above mean sea level.

## 7. DISCUSSION

Investigations to date have concentrated on developing an overall conceptual understanding of lagoon water level behaviour and entrance dynamics. Further studies are planned to examine breakout sediment transport in more detail.

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## 8. REFERENCES

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