CHAPTER 174

WAVE SETUP AT RIVER ENTRANCES

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Abstract

Detailed mean water level measurements from the Brunswick River on the NSW North Coast have, to date, suggested that the contribution of wave setup to the super-elevation of river entrance water levels is quite small. Data indicate that the over heights inside the area of wave breaking in rivers are typically smaller than at the same depth in a beach surf zone with the same waves. It is thought that difference between beach surf zones and river mouths is due to the momentum flux of the river current and the current's influence on the wave breaking process. Nevertheless, tidal anomalies of the order 0.5m are measured once or twice a year by tide gauges just inside river entrances along the east coast of New South Wales. These anomalies are thought to be mainly due to freshwater outflow and/or oceanic phenomena.

Introduction

The largest part of disaster relief in Australia is related to flooding by river systems. In New South Wales alone the cost of flooding from coastal rivers is of the order M$50 per annum. Hence, realistic modelling of flood flows and water levels in the rivers is a national concern. The State of the art of flood modelling is however unsatisfactory because the interaction between the ocean and the river systems is poorly understood.

A flood model of a river system will have two main inputs namely rainfall over the catchment and tail water level, i.e., the water level where the river meets the sea. The present paper addresses the estimation of these tail water levels.

The tail water level at a river mouth is influenced by several processes not all of which are well understood. The most predictable component is the astronomical tide. Its origin relating to the gravitational influence of the sun and the moon. In most places this component is quite predictable based on long tidal records.

Differences between the astronomical tide and the actual tide level are often referred to as tidal anomalies. In the deep ocean anomalies occur due to barometric pressure variations

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and to temperature variations in the water. In coastal areas additional anomalies can be caused by winds and waves, and in estuaries the water levels may be increased due to fresh water outflow.

The following contains a review of available theory and recent observations of tidal anomalies in the lower parts of a few rivers on the east coast of Australia, and the contribution of wave setup to these anomalies.

The main emphasis is on the Brunswick River in Northern New South Wales which is trained by almost parallel breakwaters that are approximately 40m apart at the seaward end. It has a catchment of 200 km^2 and a (spring) tidal prism of $4.8*10^6$ m^3 (Figure 1). The Brunswick River has a fairly shallow bar where even the smallest waves tend to break, and was therefore considered ideal for studying the contribution of wave setup to river tail water levels. The "ocean tide gauge" on the Brunswick River is situated at the confluence of Simpson's Creek with the River approximately 640m upstream from the ends of the breakwaters (Manly Hydraulics Laboratory, 1993).

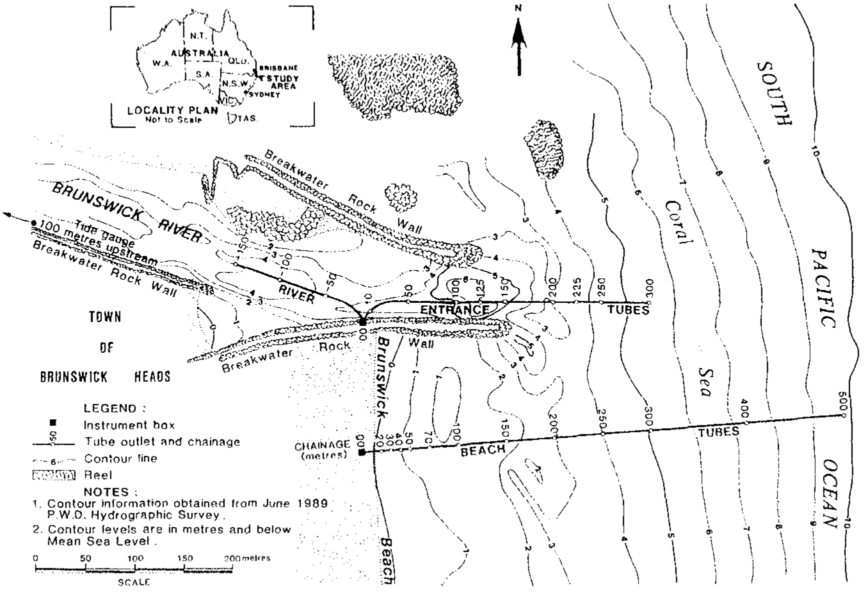

Figure 1. The Manometer tube system at the Brunswick River.

Anomaly Statistics for the Brunswick River

In the period 1986 to 1995 there were eight events during which the Brunswick Ocean tide gauge recorded water levels greater than 0.5m above the predicted astronomical tide level. The largest of these tidal anomalies was 0.87m occurring on April 11 1988. Of these major anomalies, all except for 17/3/1993 (Cyclone Roger), were associated with very large daily rainfalls on the catchment (more than 65 mm at Mullumbimby).

An example of two different anomaly events is shown in figures 2 and 3. In these figures anomalies recorded at the Brunswick tide gauge and at an offshore pressure gauge located in 26m of water offshore of Tweed Heads (30 km north of Brunswick Heads) are presented for the periods 24-29 April 1989 and 7-11 March 1990. Also presented are the offshore root mean square wave height (H_{orms}) recorded at the Byron Bay wave rider (located approximately 10km south of Brunswick Heads in 80m water depth) and the hourly rainfall recorded at Huonbrook in the Brunswick hinterland. As seen in these figures both events saw similar wave conditions with maximum RMS wave heights of around 4m in each event (5.8m significant wave height). Rainfall patterns were however very different for each event with a total of 369mm of rain being recorded over the period 24-29 April 1989, but only 35 mm recorded over the period 7-11 March 1990.

During the March 1990 event maximum anomalies recorded at both the offshore gauge and the Brunswick River entrance were of similar order (0.38m and 0.42m at the offshore gauge and the Brunswick river entrance respectively). The similarity of anomalies recorded between the two locations during this event suggests the absence of any effects of wave setup within the Brunswick River Entrance. During the April 1989 event however, maximum tidal anomalies measured at the two sites are significantly different with the Brunswick River site being elevated approximately 0.44m above the offshore water level. (0.33 and 0.77m were measured at the offshore site and the Brunswick River gauge respectively). Given the similar wave conditions during each of these events the difference between the offshore anomalies and that recorded in the river entrance between these two events appears to be related to the effects of rainfall and the resulting flood gradient.

The correlation of tidal anomalies with daily rainfall is indicated in figure 4A. For a few major events 24 hourly anomaly values have been plotted against the same daily rainfall total. This leads to the “vertical clusters” where the lower anomalies would have occurred before the bulk of the rainfall is felt at the tide gauge.

The incorporation of more detailed (spatially and temporally) rainfall information combined with the cumulative effect of rain on previous days would enable closer correlation to be obtained.

In contrast to this obvious correlation between tidal anomalies and rainfall, there is virtually no correlation between tidal anomalies and offshore wave height. This is shown by figure 4B where the tidal anomalies at the Brunswick “ocean tide gauge” are plotted against the root mean square wave height H_{orms} off Cape Byron. Both gauges are operated by the Manly Hydraulics Laboratory. The plot shows no significant correlation between tidal anomaly and wave height. An explanation for this lack of correlation may be found in the following discussion of wave set up in surf zones.

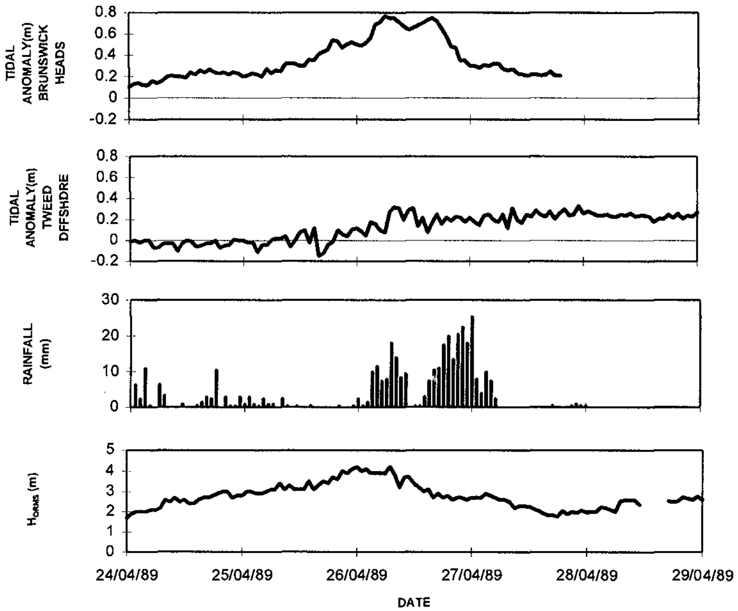

Figure 2. The tidal anomalies measured at the Brunswick River gauge and the Tweed offshore aanderaa, hourly rainfall at Huonbrook, and RMS wave height at the Byron Wave rider for the period 24-29 April 1989. Data courtesy of Manly Hydraulics Laboratory.

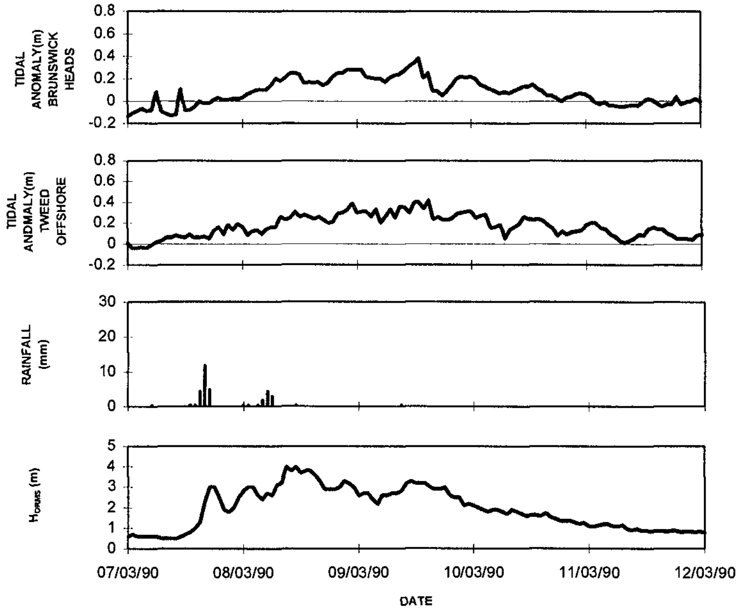

Figure 3. The tidal anomalies measured at the Brunswick River gauge and the Tweed offshore aanderaa, hourly rainfall at Huonbrook, and RMS wave height at the Byron Wave rider for the period 7-11 March 1990. Data courtesy of Manly Hydraulics Laboratory.

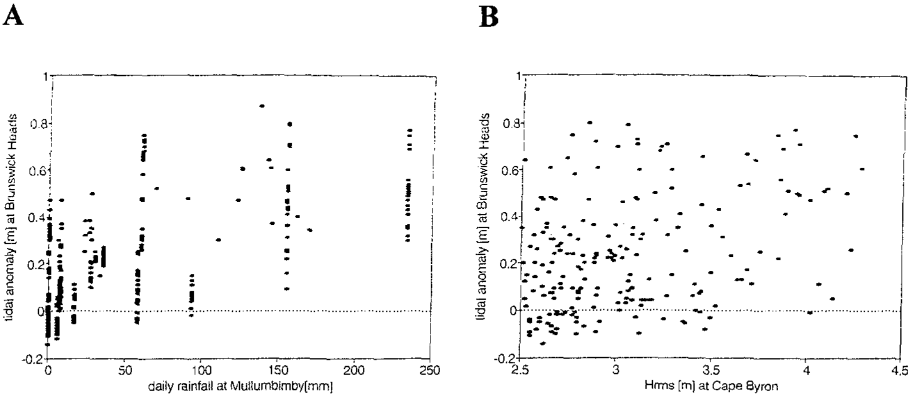

Figure 4. The tidal anomalies observed at the "ocean tide gauge" in the Brunswick River plotted versus (A) Daily Rainfalls at Mullumbimby; and (B) offshore wave height H_{orms} off Cape Byron for wave heights $H_{orms} > 2.5$m. Vertical clusters in the rainfall data occur where several anomalies are plotted against the same daily rainfall value. Data courtesy of Manly Hydraulics Laboratory.

Wave Setup

Surf Zone Wave Setup

The phenomenon of wave setup in surf zones has been known from observations (eg. Savage 1957) since the nineteen fifties and quantitatively understood since the development of the concept of wave radiation stress by Longuet-Higgins and Stewart (1964).

It occurs because the radiation stress or thrust S_{xx} of the waves is gradually translated into a mean water surface overheight, the setup B, as the waves decay towards the shore. Based on the force balance on a surf zone control volume, the governing equation is found to be

$$\rho g h \frac{dB}{dx} = -\frac{dS_{xx}}{dx} + \tau_w + \tau_b \qquad (1)$$

where the wind τ_w and the bed shear stress τ_b are often neglected.

The earliest setup models by Longuet-Higgins and Steward (1964) and Bowen et al (1968) which assume a constant ratio between wave height and depth ($H \sim \gamma h$) through the surf zone and use linear wave theory to express the radiation stress.

$$S_{xx} = \frac{3}{16} \rho g H^2 \qquad (2)$$

lead to a linearly increasing setup towards the shore. However, experiments, eg. van Dorn (1976), have shown that such a distribution is only realistic for short waves on flat slopes or more precisely for small values of the surf similarity parameter $\xi = \tan\beta \; L_o/H \leq 0.2$, *where* L_o is the deep water wave length and $\tan\beta$ is the beach slope.

For larger values of the surf similarity parameter, the *H/h* ratio is not constant through the surf zone and Equation (2) is not a good approximation. The result is an upward concave mean water surface (MWS), see eg. Nielsen (1989) and Gourlay (1992).

The variability of the height of natural (irregular) waves also tends to make the MWS upward concave even at small values of ξ see eg. the field data of Nielsen (1988). The reason is that the onset of breaking occurs at different depths for waves of different heights.

While setup profiles due to regular laboratory waves show great shape variability depending on the surf similarity parameter, it turns out that the shape of setup profiles on natural beaches varies very little. An empirical description of these profiles will be given in the following.

An Empirical Model for Setup on Natural Beaches

The shoreline setup level (that is the setup at zero water depth) varies very little between natural beaches and between naturally occurring wave conditions as documented by Hanslow & Nielsen (1994). They found that data from the full spectrum of New South Wales beaches showed no systematic deviations from either of the shoreline setup (B_s) formulae

$$B_s = 0.38\, H_{orms} \qquad \text{(correlation coefficient 0.65)} \tag{3}$$

or

$$B_s = 0.048\, H_{orms} L_o \qquad \text{(correlation coefficient 0.77)} \tag{4}$$

where H_{orms} is the deep water root mean square wave height and L_o is the deep water wave length. Correspondingly, the whole setup distributions measured on different beaches under not too unusual wave conditions are very similar. (Note that laboratory conditions with very flat waves on steep slopes corresponding to $\xi = \tan\beta_F \, L_o/H_o > 3.0$ may lead to very large relative shoreline setup, eg., $B_s/H > 2.0$ and that very long swell waves might generate similar results in the field. Such conditions would however be very rare).

A typical set of setup profile data from a single storm event (Brunswick Heads 22/8 1989) is shown in Figure 5.

The curve fitted to this setup profile is given by

$$B(h) = \frac{B_s}{1 + \alpha h / H_{orms}} \quad \text{with} \; \alpha = 10 \tag{5}$$

For other beach topographies the shape is similar, but the value of α may vary by a factor 2 either way, i.e. $5 < \alpha < 20$.

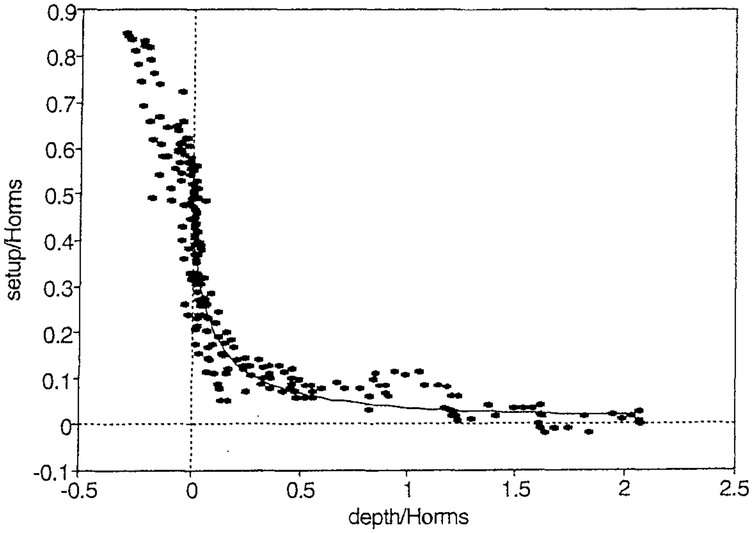

Figure 5. Measured setup profile data from Brunswick Beach August 22 1989.

S_{xx} according to measured setup profiles

The simplified setup equation $\rho g h \frac{dB}{dx} = -\frac{dS_{xx}}{dx}$ which for a monotonically sloping bottom can rewritten $\frac{dS_{xx}}{dh} = -\rho g h \frac{dB}{dh}$ gives through integration by parts

$$Sxx = -\rho g\left[Bh - \int Bdh\right] \tag{5}$$

which with (5) inserted gives

$$S_{xx}(h) = \rho g H^2{}_{orms} \frac{B_s}{H_{orms}}\left[\frac{1}{\alpha}\ln\left(1+\alpha\frac{h}{H_{orms}}\right) - \frac{h/H_{orms}}{1+\alpha h/H_{orms}}\right] + \text{constant} \tag{6}$$

The constant of integration is found by matching with S_{xx} for non breaking waves at a suitable depth outside the surf zone. The alternative: $S_{xx}(0) = 0$ does not apply for natural beaches where runup occurs beyond $h = 0$.

Estimation of River Mouth Setup from Surf Zone Profiles

If one boldly assumes that a similar relation exists between depth and setup in a river entrance as in a surf zone (Equations 2 and 9) one might use the following estimate for the wave setup contribution to the river tailwater level

$$B_{\max} = \frac{B_s}{1 + \frac{\alpha h_{\min}}{H_{orms}}} \tag{7}$$

where h_{min} is the minimum depth in the river mouth. The shoreline setup B_s determined from either (3) or (4).

As an example with reference to the Brunswick River one might choose $H_{min} = 2.0, \alpha = 10$ and H_{orms} = 2.5m, which gives $B_{max} \approx$ 0.2m. We shall see in the following that this estimate is quite excessive which indicates that the assumptions required (see Section 8 for details) for this approach are not satisfied.

Detailed Mean Water Surface Measurements from the Brunswick River

In order to obtain detailed experimental data on river mouth water levels a manometer tube system, similar to the surf zone system described by Nielsen (1988), was installed in the Brunswick river in 1988 and extended in 1990, see Figure 1

From this system a large data base has been accumulated including river water levels during the flood event of April 26-27 1989 shown in Figure 6.

These measurements show that during this event the water level at the tide gauge was considerably above the ocean level due to the hydraulic gradient in the entrance.

In contrast, events with moderately large waves but little rainfall show very little water level difference between the inner and outer tubes, see Figure 7.

The fact that a water level difference of about 1m exists between the swash zone on the beach and the river on the other side of the breakwater some times results in large scour holes.

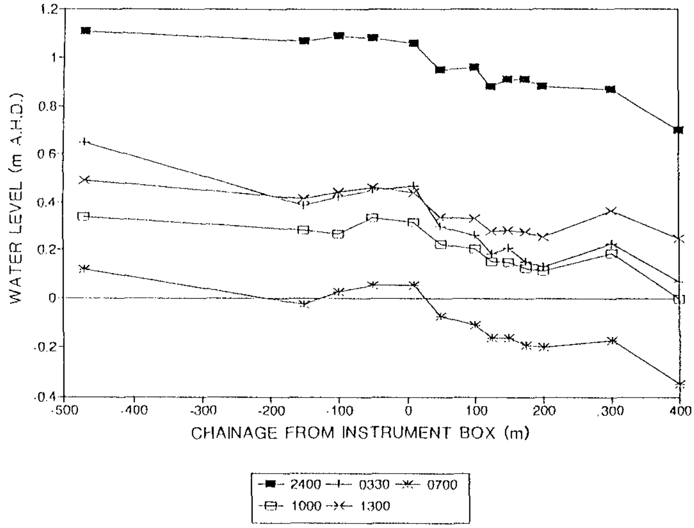

Figure 6. River water levels during a flood event (26/4/89), even at high tide the hydraulic gradient in the river generates water level differences of over 30 cm between the tide gauge (chainage -460m) and the ocean (chainage +150m).

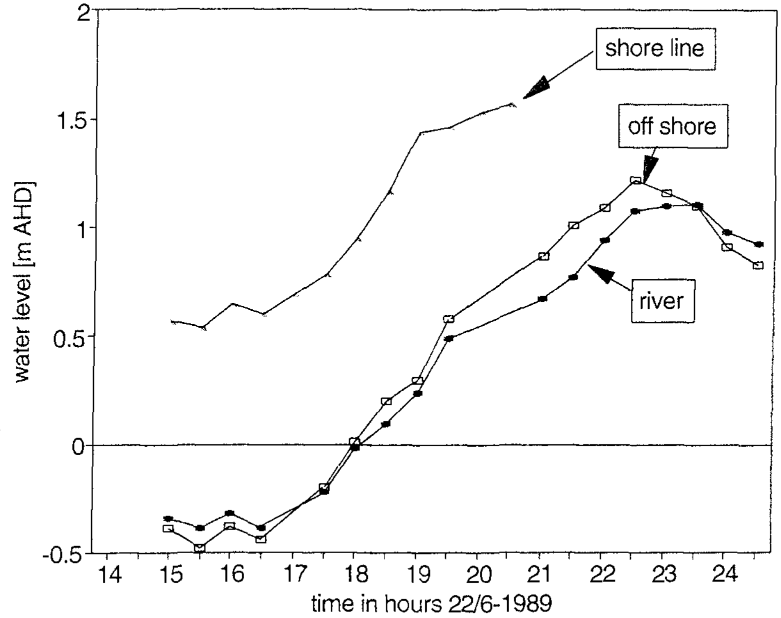

Figure 7. Time series of water levels offshore, inside of the wave breaking in the river and at the shoreline of the southern adjacent beach 22/6/89. A shoreline setup of the order of 1.0m is observed while the river levels only reflect the small tidal gradient ie. no setup was observed during Cyclone Nancy (2-4 March 1990).

The occurrence of the scour holes is of course conditional upon the water finding a path through the breakwater, which is not supposed to occur as most breakwaters are designed to be impermeable. Nevertheless, they are not uncommon. Professor M. Losada of the University of Cantabria has observed them at river entrances on the North Coast of Spain (personal communication 1992) and Mr J Bodycott (personal communication 1990) has reported on "mystery sand banks" occurring inside some of the New South Wales rivers with no other plausible explanation that the sand being washed through the breakwater by the mechanism shown above.

Anomalies due to Long Period Waves in the Ocean

Storm events which seem quite similar in intensity and shape may cause very different amounts of tidal anomaly. For example, Cyclone Roger (March 1993) produced an anomaly of about 0.5 m while Cyclone Violet (March 1995) produced an anomaly of only half this amount. This is despite the fact that several of the contributing mechanisms would have been stronger at Brunswick Heads during Cyclone Violet. See the time series of rainfall, wave height and measured anomaly in Figures 8a,b.

These figures show that the tidal anomaly caused by Cyclone Roger was two times greater than that caused by Cyclone Violet even though the wave height at the nearby Cape Byron wave rider was greater during Violet and the rainfall was greater as well. Furthermore, the atmospheric pressure in the Brunswick area would have been considerably lower during Cyclone Violet, which came very close to Brunswick Heads, than during Roger which came no further south than Maryborough.

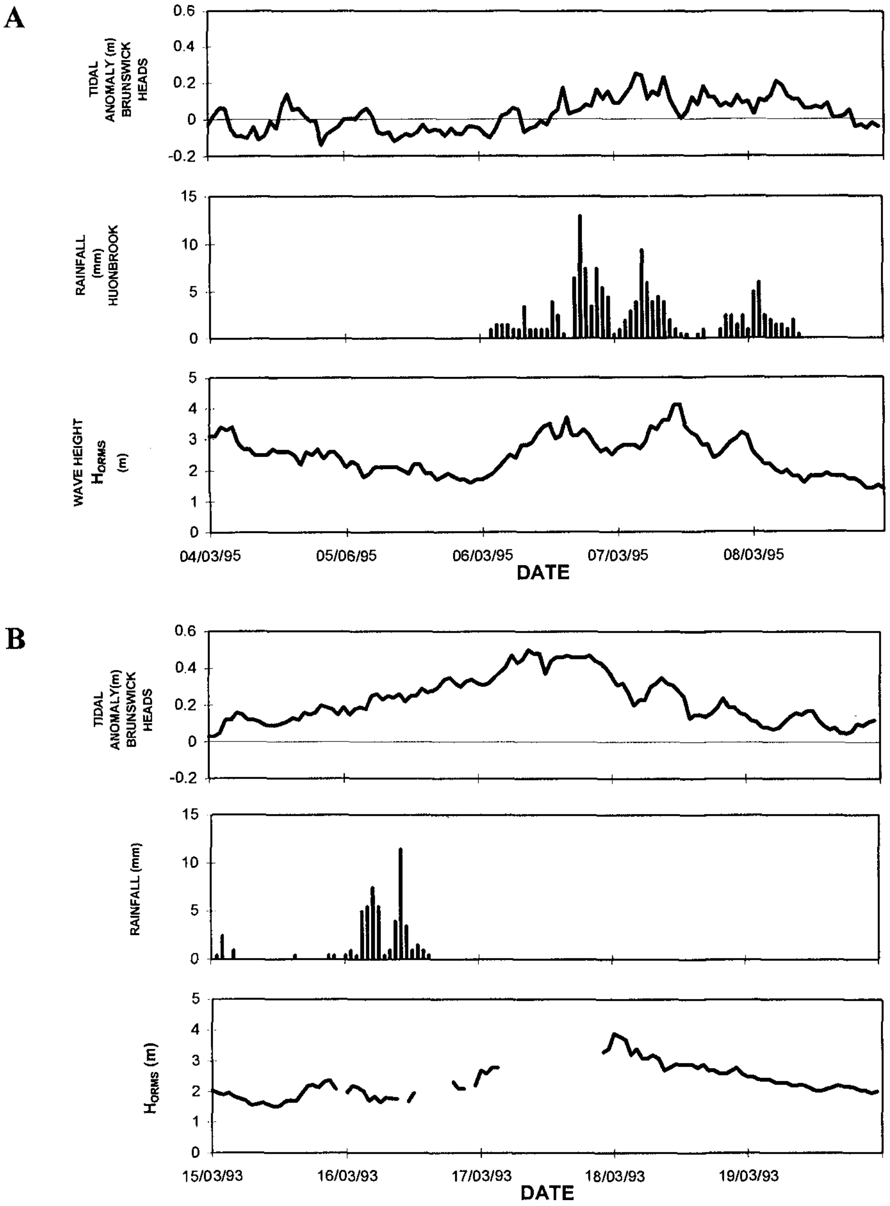

Figure 8. Time series of rainfall, wave height and measured tidal anomaly in the Brunswick River during (A) Cyclone Roger and (B) Cyclone Violet.

These observations point towards long periodic ocean waves as the main contributors to tidal anomalies in the absence of rainfall effects. These long waves would also contribute to tidal anomalies measured at Coffs Harbour and in Sydney Harbour where the effect of waves and fresh water flow would be negligible. For a discussion of tidal anomalies in Sydney Harbour, see Wyllie et al (1993).

The fact that anomalies of the "Cyclone Roger type" do not occur in connection with all cyclones underlines the complication nature of the long periodic ocean waves that might cause them (eg Tang & Grimshaw, 1995).

Modelling River Entrance Water Levels

The approximate role of waves, winds and currents in generating river entrance water levels can be understood using a fairly simple numerical model as indicated in the following.

Governing equations

The model is based on the momentum principle applied to the control volume in Figure 9.

The x- momentum equation for this volume can be written:

$$\rho h dx W \frac{\partial U}{\partial t} = -\delta\left(\rho[D+\eta]WU^2\right) - \delta\left(\rho g\eta[D+\eta]W\right) - \delta\left(S_{xx}W\right) + \tau_w \delta_x W - \tau_b \delta_x W \qquad (8)$$

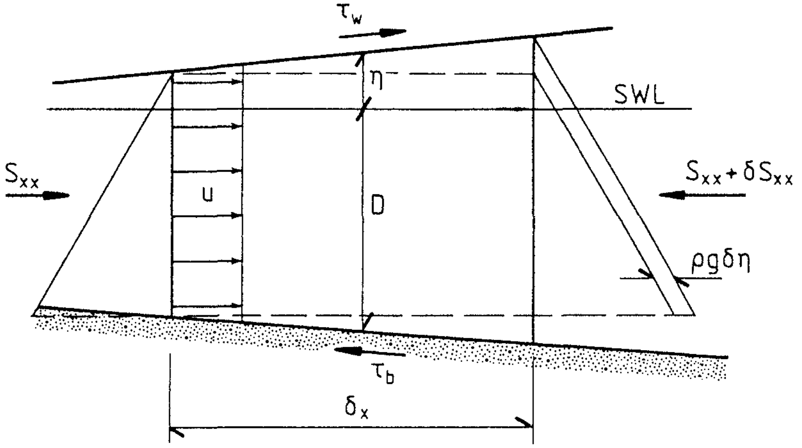

Figure 9. Control volume at a river mouth. The width of the channel is *W=W(x)*, *h* is the total depth $h=D+\eta$, and x is positive landwards.

Where U is the velocity averaged over a wave period so that the left hand side represents acceleration of the mean flow for example due to tidal changes. On the right hand side, the first term represents the change in current momentum flux over the length δ_x. The second term is the change in the hydrostatic pressure force, the third is the wave radiation stress force, the fourth is the wind stress force and the fifth is the bed shear stress force. Friction along the sides of the channel is also included in the last term. As usual, ρ is the density of water and g is the acceleration of gravity.

If the length of the model area is short compared to $T_{tidal}\sqrt{gD}$ quasi steadiness can be assumed and the left hand side becomes zero. Then division by $\rho g W\,[D+\eta]$ leads to

$$\delta\eta = -\delta\left(\frac{U^2}{2g}\right) - \frac{1}{\rho g[D+\eta]}\delta S_{xx} + \frac{\tau_w \delta x}{\rho g[D+\eta]} - \frac{\tau_b \delta x}{\rho g[D+\eta]} \qquad (9)$$

This equation can, with a given discharge $Q = UW\,(D+\eta)$ be used alternatively to find the setup $\eta\,(x)$ starting from the seaward boundary (x_s, D_S, η_s) with $D+\eta \approx D$ in the first iteration.

Preliminary Results

To gain a general impression of the behaviour of the system an example is shown in Figure 10 a, b.

These results show that the spreading current generates a set down effect of the order U^2_{max}/gh at the end of the breakwaters ($x=0$) which works opposite to the setup caused by wave breaking in the same area. This is probably why the detailed water level measurements from the Brunswick River show no measurable setup even in conditions with a metre or more of shoreline setup at the neighbouring beach. For the case above, the shoreline setup would be of the order $0.4\,H_o = 0.8$m.

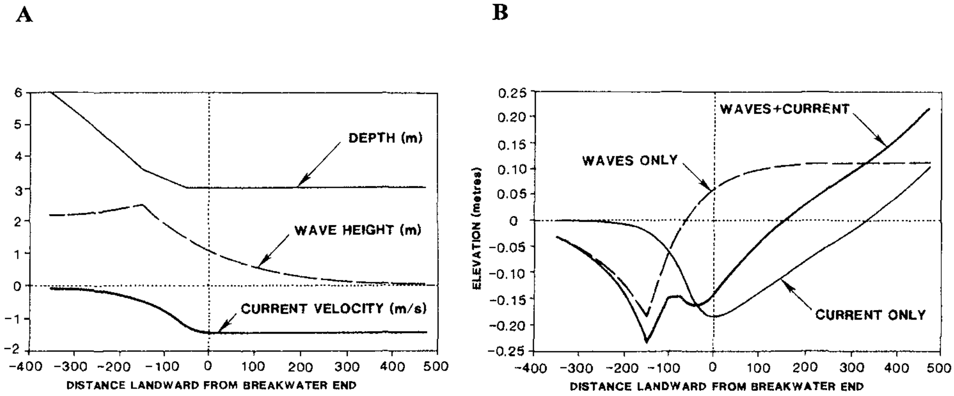

Figure 10(A) Assumed distributions of wave height, depth and current velocity.

(B) Resulting surface elevations with current alone, waves alone and with both waves and current. The bed (+side) friction was calculated as: $\tau_b = 0.5\rho f_c |U|\, U$ with f_c - 0.001, and the wind stress as: $\tau_w = C_{10}\,\rho_{air}\,U^2_{10}\cos\alpha_w$ with U_{10} = 10m/s, C_{10} = 0.003 and α_w = 20°.

Conclusions

Detailed mean water level measurements from the Brunswick River suggest that waves generate very little setup at river entrances of this type. Measurements indicate that over heights inside the area of wave breaking in the Brunswick River are typically smaller than at the same depth in the neighbouring surf zone with the same waves. This difference between surf zones and river mouths is thought to be due to the momentum flux of the river current and the current's influence on the wave breaking process. Nevertheless, tidal anomalies of the order 0.5m are measured once or twice a year by tide gauges just inside river entrances along the east coast of New South Wales. These anomalies are thought to be mainly due to freshwater outflow and/or oceanic phenomena which have yet to be fully explained.

Acknowledgments

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