CHAPTER 100

MORPHODYNAMICS OF A WAVE-DOMINATED RIVER MOUTH

L.D. Wright
Coastal Studies Unit, Dept. of Geography
University of Sydney
Sydney, N.S.W. 2006 Australia

Abstract

The mouth of the Shoalhaven River on the southeast coast of Australia is subject to direct attack by high energy waves and offers a general model of wave-dominated river-mouth deposition. During river floods seawater is completely flushed from the lower reaches of the channel and significant quantities of sandy bed load and suspended silts are debouched into the Tasman Sea. However, breaking waves cause intense mixing between the effluent and ambient waters while wave-induced mass transport and setup oppose and partially impound outflow. Unusually rapid deceleration and lateral effluent expansion result. Sediments accumulate in the form of a broad crescentic river-mouth bar with its crest situated about 2 channel widths seaward of the outlet and as broad shallow subaqueous levees capped by swash bars. Post-depositional shoreward return of sands by shoaling waves produces a constricted outlet. During low river stage wave setup enhances flood tidal currents and partially inhibits ebb tide outflow. This leads to a gradual shoreward migration of the river-mouth bar, a narrowing of the constricted outlet and to upstream migration of river-mouth sands into the lower reaches of the channel.

Introduction

Recent studies show that river mouth depositional patterns depend on the relative contribution from three primary processes which derive their energy directly from the river outflow and on modifications by marine processes. The three primary processes are: (1) turbulent diffusion, (2) turbulent bed friction; and (3) buoyant expansion. Major modifying processes include those induced by tides and waves. Depositional patterns at many river mouths may be explained largely in terms of one or more of the primary processes. The well-studied mouths of the Mississippi, for example, are dominated by buoyant expaniion and experience minimal influence from tides and waves (Wright and Coleman, 1974). In contrast, many river mouths are attacked directly by high wave energy. Wave-current interactions cause pronounced modifications to effluent behavior while waves directly redistribute the river mouth sediments contemporaneously with their initial discharge. Some notable examples of wave-dominated river mouths include the mouths of the Senegal (West Africa); Sao Francisco and Jequitinhonha (Brazil); Magdalena (Columbia); Orange (South Africa); Burdekin (Queensland, Australia); and Shoalhaven (New South Wales, Australia). The process signatures and depositional morphologies of these river mouths show common attributes among themselves but differ markedly from those of river-dominated or tide-dominated river mouths. The high-energy southeast coast of Australia offers excellent examples of wave-dominated river mouths. This paper summarizes 18 months of observations at the mouth of the Shoalhaven River about 150 km south of Sydney, Australia.

Environment of the Study Area

The Shoalhaven River Delta and estuary (Fig.1) are situated near the township of Nowra, New South Wales on the east coast of Australia. By world standards the Shoalhaven is a small river although it is the largest on the south coast of New South Wales. The river's catchment has a total area of 7250 km^2 and receives an average rainfall of 760 mm. The mean discharge rate at the Nowra Bridge near the head of the delta is only 57.3 m^3 sec^{-1}; however, flows of over 5,000 m^3 sec^{-1} occur at a return interval of 10 years. Flows in excess of this magnitude occurred in both 1974 and 1975. The bed load of the river consists of fine to medium sands of angular to rounded quartz, feldspar and rock fragments. During flood the river also transports high concentrations of suspended silts and clays.

The Shoalhaven has built a Recent deltaic plain 85 km^2 in area, extending from Nowra to the coast. At the present time the discharge of the Shoalhaven enters the sea via 2 outlets; the Crookhaven entrance which is situated in a relatively protected environment in the lee of Crookhaven Heads and the Shoalhaven entrance which is exposed to the full spectrum of wave conditions. The protected Crookhaven entrance provides a low energy "control" example for comparing the behavior of the wave-dominated Shoalhaven entrance. The river debouches into Shoalhaven Bight, a broad, arcuate embayment bordering the Tasman Sea. The nearshore bed, though flatter than that fronting neighboring coastal sectors, is relatively steep, with an average gradient of 0° 45' and a concave-upwards profile. Water depths of 20 metres occur within 1.5 km from the present shoreline.

The tides of the region are semidiurnal with a mean range of 1.2 metres and a spring range of 1.8 metres. The combined tidal prism of the Shoalhaven and Crookhaven estuaries is estimated to be about 23 x 10^6 m^3 during spring tides. This exceeds the base flow by 18 times but is only 1/5 the volume of extreme flood discharge. The river mouth and adjacent coastline are dominated by high energy waves. The region experiences a highly variable wind wave climate superimposed on persistent refracted long period southerly and southeasterly swell. Deepwater wave power averages 178 Watts per cm of crest width and exceeds 1250 Watts cm^{-1} for 1% of the time. Significant deepwater wave height exceeds 1.5 metres 50% of the time, is greater than 3 metres for 5% of the time and has appraoched 10 metres several times over the past 2 years.

Field Techniques

This paper is based largely on direct field observations made over the period August 1974 to January 1976. Observations of outflow behavior, estuarine circulation, wave characteristics and resultant morphologic patterns were made over a wide range of hydrologic and marine energy conditions. Bathymetric surveys in the Shoalhaven estuary and offshore were conducted using a Ratheon model DE 731 echo sounder; positions were determined by theodolite and horizontal sextant angles. Autolab salinity-temperature meters were used for S-T profiling and Toho-Dentan direct-reading current meters were used for current profiling. Drogues and dye were employed to determine larger scale flow patterns. Continuous tidal and river stage height data were recorded by means of 5 Bristol recording tide gages maintained by the Shoalhaven Shire Coucil and by a Stephens water level recorder. Incident deepwater wave characteristics were measured by the Maritime Services Board of New South Wales' offshore wave rider located 5 km seaward of the entrance to Botany Bay (100 km north of the study region).

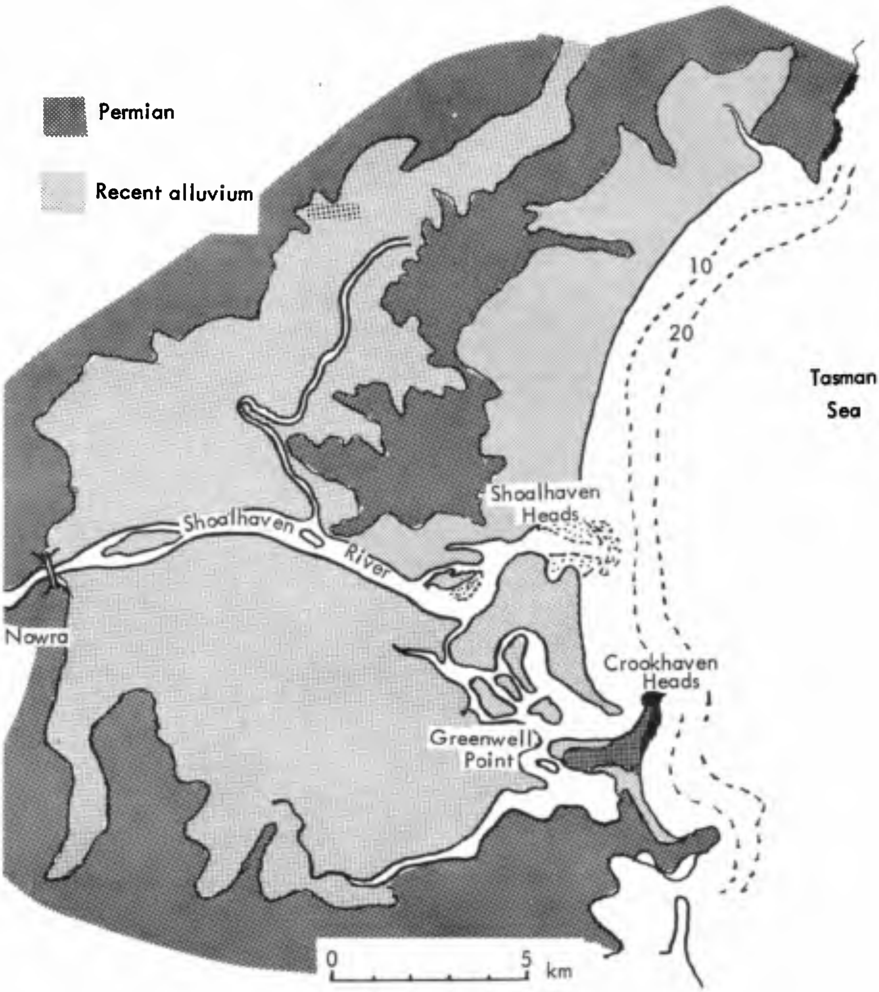

Figure 1: The Shoalhaven Delta

Flood-Stage Outflow

Significant transport and deposition of river-derived sediments at and immediately upstream from the mouth of the Shoalhaven takes place primarily during river flood when seawater is flushed from the estuary. During floods the beach which often seals the Shoalhaven Heads entrance is breached (or widened if the entrance has not been previously sealed) and sands are debouched through the outlet into Shoalhaven Bight. The Shoalhaven experienced extreme flood conditions in August 1974 and again in June 1975. The discharge rates associated with both floods substantially exceeded the 10 year discharge rates: peak discharge associated with the August 1974 and June 1975 floods were 7400 m^3 sec^{-1} and 6900 m^3 sec^{-1} respectively at the Nowra Bridge 13 km upstream from the entrance (Dept. Public Works, N.S.W., 1975). During the August 1974 flood observations were restricted logistically to field reconnaissance; however, field data were obtained during the June 1975 flood.

Figure 2 shows water surface elevation curves from Nowra Bridge and Shoalhaven Heads encompassing the period preceding, during and immediately following the flood (June 19-25, 1976). The portion of the curves for the period June 19-20 indicates the normal low-stage surface behavior and demonstrates the tidal dominance of the lower channel. It is apparent from this low-stage curve that tidal amplitude undergoes only slight attenuation and deformation over the distance from the entrance to Nowra. A tidal lag of about 1 hour 45 minutes is also evident. With the onset of the flood water levels rose abruptly at both the upstream and river mouth stations. A flood peak of 5.09 metres at Nowra (2130 hrs. on June 21) was accompanied by a peak of 2.15 at the Shoalhaven Heads entrance, thus resulting in a maximum water surface gradient of 23 cm km^{-1} in the lower estuary. Flood flow completely obliterated the effects of tidal rise and fall at the Nowra Bridge over the period June 21-26. However, at the mouth tidal influence persisted throughout the flood even though marine waters were completely flushed from both entrances.

Unfortunately it was logistically impossible to obtain direct current observations in the entrance during the flood peak; however, current, salinity-temperature and bathymetric data were obtained immediately following the peak during the period of subsiding stage. Figure 3 shows typical velocity profiles and water density structures in the Shoalhaven Heads entrance during ebbing and flooding tides on June 26-27. The flood-stage river-mouth bar profile is also shown. (In this figure and figures which follow, water density is expressed in units of σ_t which is related to density, ρ, by $\sigma_t = (\rho - 1) \cdot 1{,}000$ and is calculated from salinity and temperature data.) As the diagram indicates salt water was completely flushed from the entrance and flow was seaward at all depths during both phases of the tide. The influence of tides is strongly evident from a comparison of the ebbing versus flooding currents: outflow was accelerated during ebbing tide and inhibited during flooding tide. The ebb-tide outflow attained surface speeds of over 2 metres sec^{-1} whereas surface outflow averaged only about 40-50 cm sec^{-1} during flooding tide. Strong bed shear accompanied the flood stage outflow on both tidal phases and pronounced seaward transport of bed load was evidenced from the presence of seaward-migrating mega-ripples with amplitudes on the order of 50 to 100 cm.

Vertical density stratification in the entrance throat and over the river-mouth bar was negligible (Fig.3). It has been shown elsewhere that the effectiveness of buoyancy in suppressing effluent turbulence depends

To a large extent on F', the densimetric Froude number at the outlet (Hazashi and Shuto, 1967,1968; Wright and Coleman, 1971) where

$$F'_o = U / \sqrt{\gamma g h'}$$

where U is the mean outflow velocity, g is the acceleration of gravity, h' is the depth of the maximum density gradient and γ is the density ratio

$\gamma = 1 - (\rho_f / \rho_s)$ where ρ_f and ρ_s are respectively the densities of fresh water and sea water. Throughout the high stage and falling stage period F' exceeded substantially the value of 16.1 regarded by Hayashi and Shuto (1967,1968) as necessary for fully turbulent effluent diffusion.

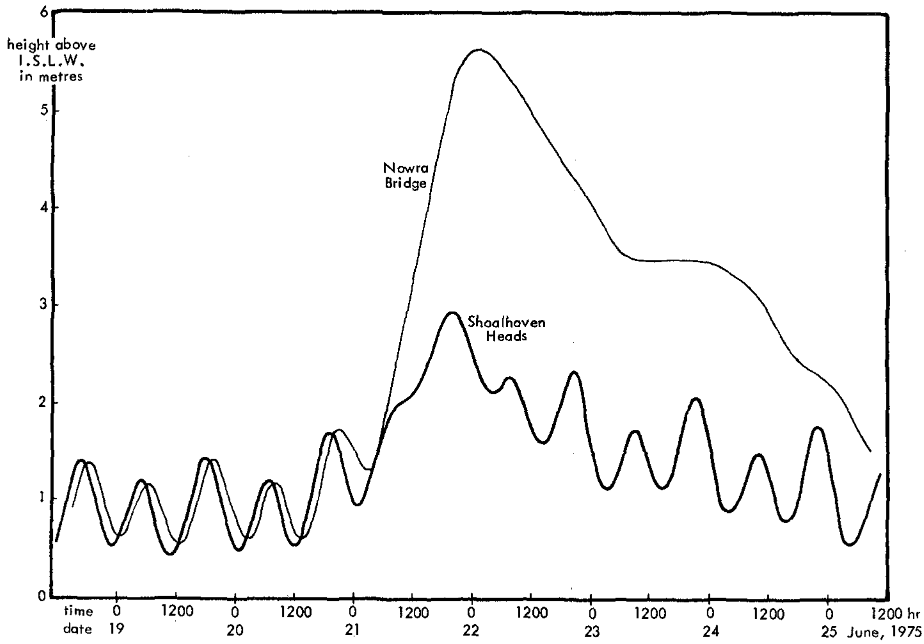

Figure 2: Water Surface Elevation Curves for Shoalhaven Heads and Nowra Bridge, June 19-25, 1975

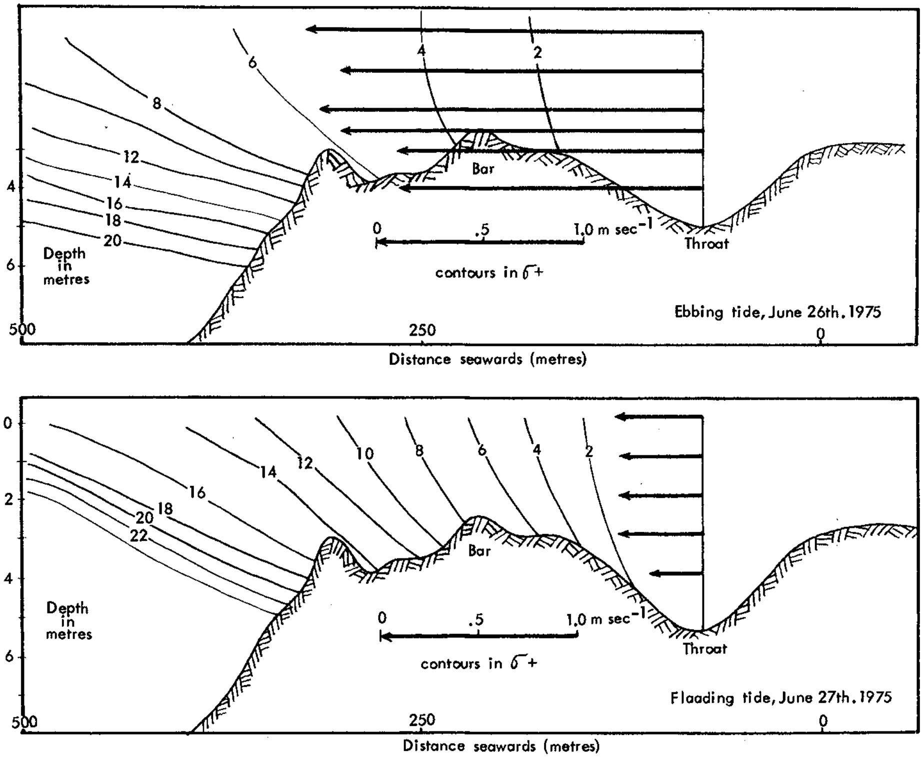

Figure 3: Current and Density Profiles at the Mouth of the Shoalhaven River on Ebbing and Flooding Tides, June 26-27, 1976

It is common on the southeast coast of Australia for increased streamflow to coincide with the occurrence of powerful southeasterly waves. The floods of August 1974 and June 1975 were associated with lows situated over the coast which also generated high energy waves: the June 1975 flood was accompanied by a significant wave height of 7 metres. The dominant waves associated with the storm arrived from the southeast and had a peak period of 13 seconds. Owing to the direction of incidence of these waves the Crookhaven entrance was comparatively sheltered from extreme energy conditions; however, the Shoalhaven Heads entrance was fully exposed to direct wave attack.

The most conspicuous influences of high wave energy on flood-stage outflow were wave-induced setup and increased effluent diffusion and deceleration. The importance of wave setup on the Shoalhaven Heads entrance is apparent from Figure 4 which shows simultaneous flood-stage water level curves from Shoalhaven Heads and Greenwell Point (situated just upstream from the Crookhaven Heads entrance) together with the significant wave heights for the same period. From the graphs it can be seen that flood-stage water levels were substantially higher at the exposed Shoalhaven Heads entrance than at the more sheltered Crookhaven outlet. At the time of the peak wave height, which preceded the flood crest by about 15 hours, water level at Shoalhaven Heads exceeded that at Greenwell Point by 60 centimetres.

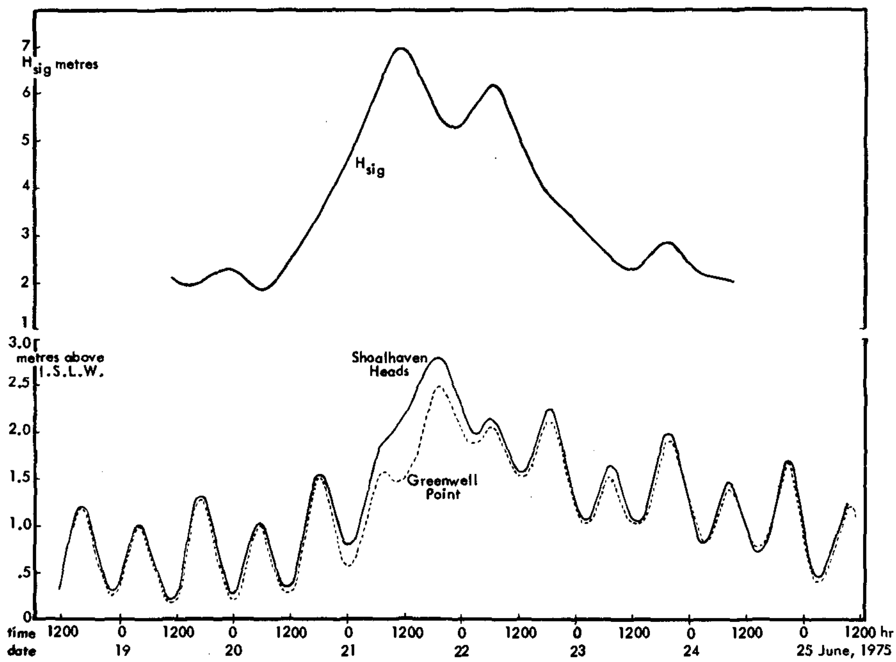

Figure 4: Simultaneous Curves of Significant Wave Height as Recorded by the Botany Bay Offshore Wave Rider and Water Surface Elevations at Shoalhaven Heads and Greenwell Point, June 19-25, 1975

The important role of waves in enhancing effluent mixing and deceleration was evident from a comparison of observations at the two outlets made on June 27 and 28 during falling stage as sea water reentered the extreme lower reaches of the distributaries. At the time of these observations river discharge had decreased to levels insufficient to flush completely the seawater from the channels but still significantly exceeded the tidal prism of the estuary. Conditions such as these have been observed elsewhere to favour strong vertical stratification and salt-wedge intrusion under normal conditions (e.g., Wright, 1971). At highly stratified river mouths such as the mouths of the Mississippi River the outlet densimetric Froude number tends to maintain values near unity and outflow expands largely as a buoyant plume which experiences only gradual deceleration (Wright and Coleman, 1971,1974). Figure 5 shows the typical density (σ_t) structure and current profile observed at the Crookhaven outlet during falling stage. A close analogy to the Mississippi model is apparent: there was a steep pycnocline, the densimetric Froude number was slightly less than 1 and there was a flow reversal just beneatb the pycnocline. Seaward of the outlet the Crookhaven effluent expanded in the shelter of Crookhaven Heads as a buoyant surface layer with minimal lateral and vertical mixing.

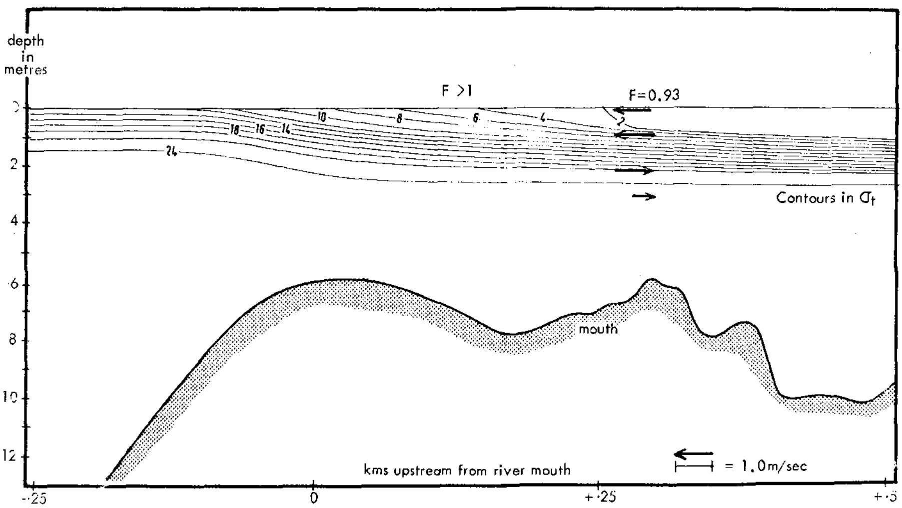

Figure 5: Density and Flow Structure in and Seaward of the Crookhaven Mouth During Falling Stage, June 27, 1975

Outflow patterns at the exposed Shoalhaven Heads entrance during the same period contrasted sharply with those of the Crookhaven. From Figure 6 it can be seen that denser brackish water had intruded a short distance into the Shoalhaven entrance by June 28, 1975. However, unlike the Crookhaven, flow through the Shoalhaven Heads outlet was seaward at all depths and the density structure indicated a vertically well-mixed condition owing to the action of breaking waves. Immediately seaward of the entrance throat breaking waves caused rapid mixing and momentum exchange between effluent and ambient water. In addition to intensified mixing, outflow was opposed by wave-induced shoreward transport of seawater which abruptly converged with the effluent immediately seaward of the seawardmost break point. The combined effect was to cause extremely rapid seaward deceleration of the outflow: maximum velocities decreased from 1.5 m sec^{-1} at the entrance throat to 20 cm sec^{-1} within a distance of 2 channel widths (250 m) seaward. This rate of deceleration was several times greater than that predictable from the theories or observations of fully turbulent or buoyant jets (e.g., Wright and Coleman, 1974) and must be attributable to wave effects.

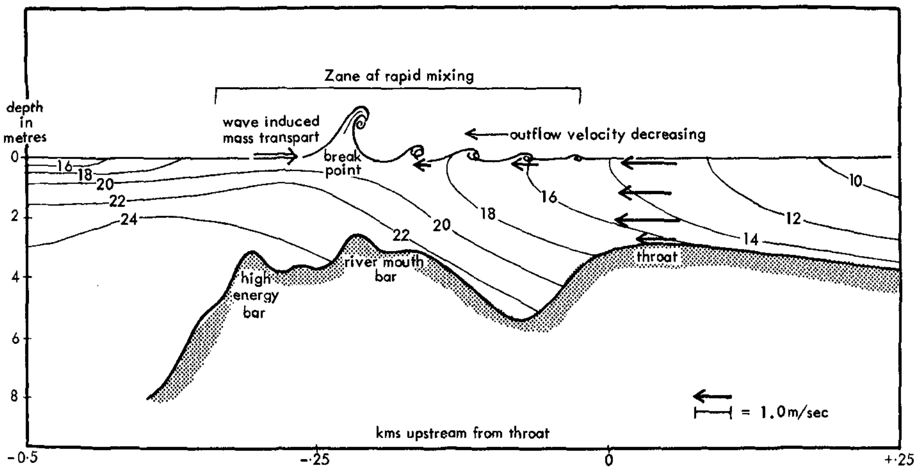

Figure 6: Density and Flow Structure and Two-Dimensional River-Mouth Morphology at the Shoalhaven Heads Mouth During Falling Stage, June 28, 1975.

The plan-view surface outflow patterns associated with flood discharge are illustrated in Figure 7 together with the resultant depositional morphology. Flow patterns shown in this diagram were determined by drogue and dye tracking and from aerial observations. Waves which broke over the crescentic river-mouth bar impeding seaward flow caused the effluent to spread abruptly alongshore. Flow divergence landward of the bar crest was accompanied by shoreward transport and emergence of seawater over the seaward front of the bar. Lateral to the effluent centreline, velocity gradients were extremely steep causing abrupt deposition and shoaling in the form of subaqueous levees.

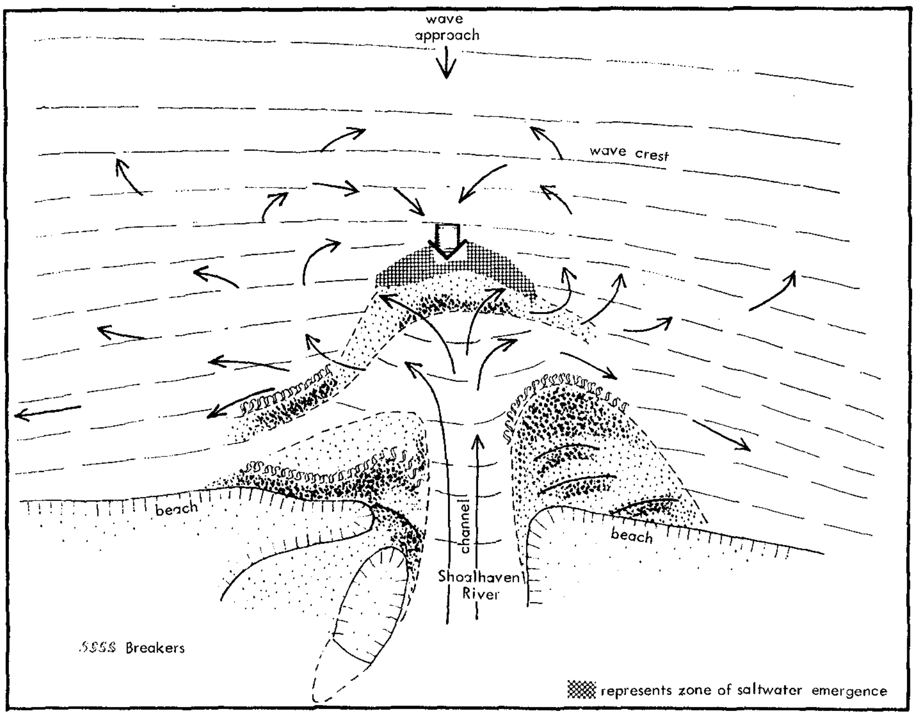

Figure 7: Horizontal Surface Outflow Patterns and Plan-View Morphology at the Shoalhaven Heads Mouth, June 28, 1975 (lengths of arrows not proportional to current speed)

Flood-Stage River-Mouth Morphology

The depoaitional morphology produced by the flood stage outflow is ahown in profile and plan in Figures 6 and 7. Rapid wave-induced deceleration caused abrupt depoaition of bed load reaulting in a conspicuous river-mout bar at a short distance from the inlet throat. The bar waa wide and crescentic in plan-view and was situated at 2 channel widtha seaward of the outlet (as compared with 4 to 6 channel widtha at the mouth of the Misaissippi: Wright and Coleman, 1974). Surveys immediately after the flood in June, 1975, in August, 1975, and in December, 1975 indicated that the bar conaistently had 2 cresta. The seawardmost bar crest was aaaymetrical with a steeper landward face and appeared to be migrating shoreward under the influence of ahoaling waves.

In plan, the distinguishing featurea of the river mouth were: (1) a crescentic and highly regular river-mouth bar; (2) a constricted outlet; and (3) broad aubaqueoua levees which widen to shoreward and are surmounted by swash bars. The wide subaqueous levees are apparently associated with the combination of steep lateral velocity gradients and post-depositional reworking of river-mouth sands by shoaling waves. These levees were the most extensive depositional unit at the river mouth in terms of both surface area and aand volume. Sediments returned shoreward by wave-induced swash bar migration over the levee/shoals accumulate adjacent to the entrance throat and constrict the mouth until a balance is achieved between the reconcentrated outflow and the waves. The crescentic bar and wide subaqueous levees of the flood-stage Shoalhaven mouth appeared to be analogoua in form and function to the terminal lobea and ramp-margin shoals of ebb-tidal deltaa (e.g., Hayea et al., 1970; Oertel, 1972).

Low-Stage Outflow

As the river returns to normal or low flowa, saltwater quickly intrudes into the lower reaches of the channel. Figure 8 showa the low stage density structure in the lower 15 km of the Shoalhaven estuary. Throughout most of its length the estuary ia well mixed by tides. At and immediately upstream from the Shoalhaven Heads entrance marine aalinities prevail; salinities decrease progressively upstream becoming fresh a short distance aobve the Nowra Bridge. Under low atage conditions flow ia bi-directional through the two entrances which function eaaentially aa tidal inleta. Tidal influence extends to well above the Nowra Bridge and there is minimal tidal attenuation in the lower 15 km of the channel.

Figure 9 shows a comparison of the low atage tide curvea from the Shoalhaven Heada and Crookhaven entrancea, and illustrates the continual effects of wave-induced setup on the Shoalhaven Heada outlet. This setup impedea ebb outflow and augments flood tide inflow through the Shoalhaven entrance. Under these low stage conditiona wavea breaking over the crest of the river-mouth bar impound ebb outflow, cauaing it to spread laterally along the inahore zone (Fig.10). Sediment-laden efflux trapped in this way ultimately eacapes by way of ripa which prevail on either side of the large transverse bar, created by the river-mouth bar.

A recent set of 25 hourly observations by C. Brown (Posford, Pavry, Sinclair and Knight Consulting Engineers, 1976) testified to the importance of wave setup in creating tidal transport assymetry through the Shoalhaven entrance.

The results of these observations are summarized in Table I. The table demonstrates that at the tima of the observations (March, 1976) low stage inflow through Shoalhaven Heads exceeded the outflow by more than 2 times. The excess inflow through Shoalhaven Heads exits together with the base flow of the river by way of the more protected Crookhaven entrance.

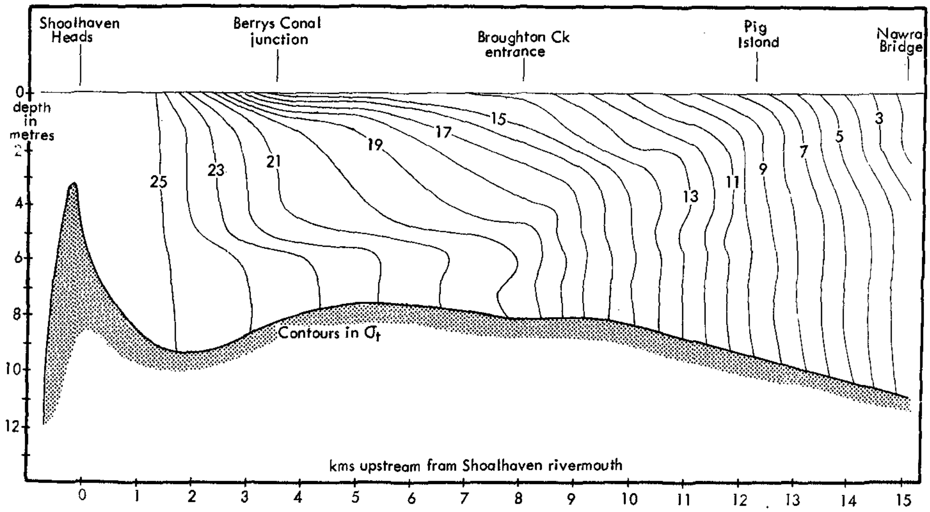

Figure 8: Longitudinal Density Profile of the Lower Shoalhaven Estuary at Low Stage, August 11, 1975

	Main Channel Upstream from Canal	Shoalhaven Heads	Crookhaven Heads
Flood (inflow)	9.6×10^6 m^3	11×10^6 m^3	12×10^6 m^3
Ebb (outflow)	13.6×10^6 m^3	5×10^6 m^3	22×10^6 m^3

Table 1: Mean Flood and Ebb Tidal Discharges Through Shoalhaven Heads and Crookhaven Heads, March 13-14, 1976
(Source: Posford, Pavry, Sinclair and Knight Consulting Engineers)

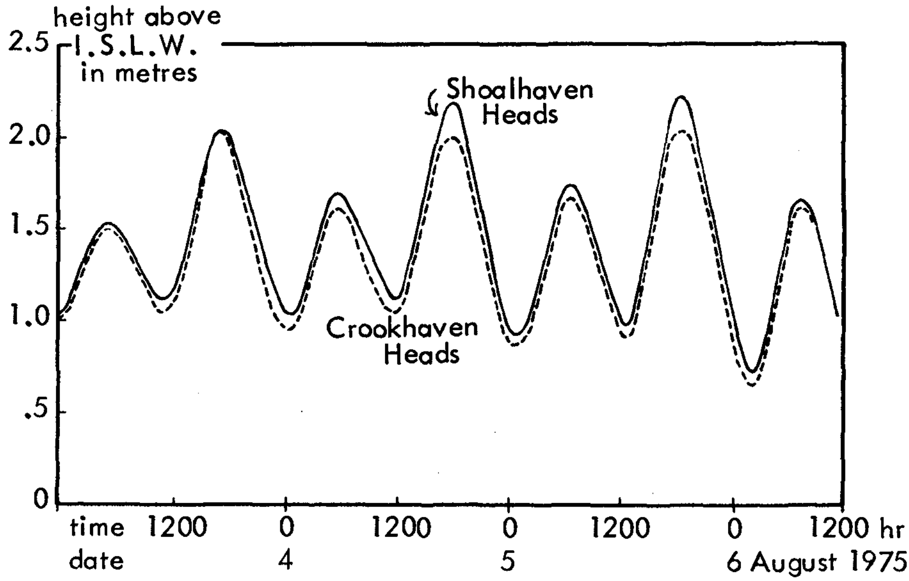

Figure 9: Simultaneous Tidal Curves for Shoalhaven Heads and Crookhaven Heads during Low Stage, August 3-6, 1975

Low-Stage Sediment Transport and Morphology

During prolonged low-discharge periods the combination of shoaling waves, flooding tides and setup results in a net shoreward return of sediment which ultimately reenters the lower reaches of the lower Shoalhaven estuary. Much of this sediment accumulates as a flood-tidal delta just upstream from the entrance throat along the flanks of the channel; however, a significant proportion of the sediment migrates over 5 kilometres upstream and accumulates on tidal point bars and mid-channel islands. Analyses of sediments from the river mouth and lower Shoalhaven channel indicate a mixture of well-rounded quartz typical of offshore and open coast environments and riverine sands consisting of angular rock fragments, feldspars and quartz. The percentage of riverine sand increases upstream from 30% to 50% at the river mouth to 100% at 13 km upstream.

Figure 11 shows the depositional morphology of the Shoalhaven Heads outlet as it appeared in January 1976 following a low-stage period of 5.5 months. By this stage large swash bars had migrated shoreward over the subaqueous levees and entered the mouth as a complex succession of recurved ridges which substantially reduced the width of the outlet. The crescentic river-mouth bar had migrated shoreward while the southern subaqueous levee had become extended across the outlet by dominant southeasterly waves, causing outflow to be deflected to the north. In profile the double-crested bar form previously described was still apparent. However, both crests had migrated approximately 100 metres shoreward and the outer crest had become more pronounced and 1.5 metres shallower. In addition, the outer bar had increased in longshore width and had assumed a more regular form. Except for an outflow channel across the northeast quadrant the bar extended continuously shoreward to the beach on either side of the outlet. Where the river-mouth bar welded to the beach wide transverse bars surmounted by large emergent swash bars resulted. The transverse bars were flanked on either side by large rips by way of which the wave-impounded river effluent escaped seaward (Fig. 11).

Figure 10: The Mouth of the Shoalhaven During Low Stage, January, 1976
Note Turbid Effluent Water Trapped Inshore of Surf Zone

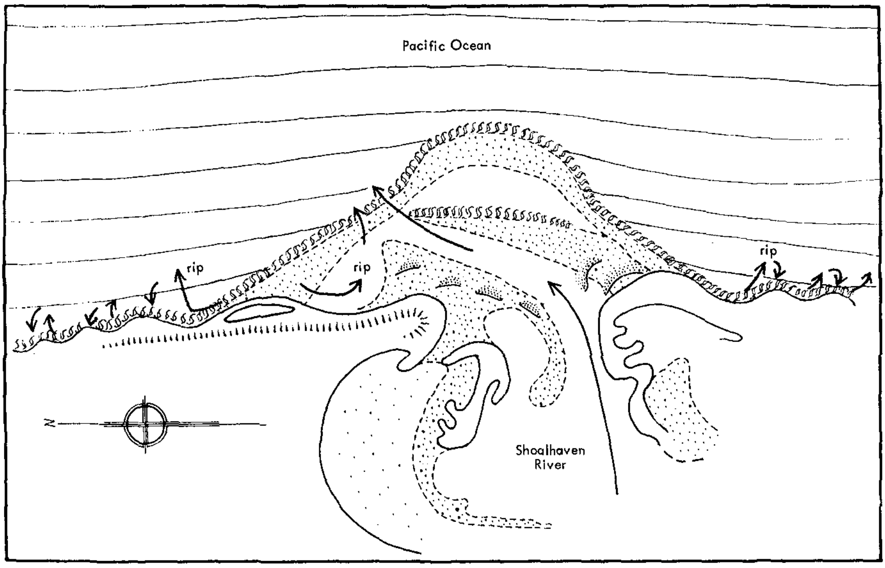

Figure 11: Low Stage Morphology and Outflow Patterns of the Mouth of the Shoalhaven, January, 1976

Inspection of aerial photographs reveals that when conditions of low river flow and wave dominance persist for a prolonged period, bar sands will continue to enter the mouth, narrowing the throat and choking the outlet. This causes discharge to be increasingly diverted through the Crookhaven entrance. Eventually shoreward migration of the bar completely seals off the Shoalhaven outlet. Once sealed, the mouth remains closed until it is breached by the next flood (Fig.12).

Figure 12:

The Mouth of the Shoalhaven as it Appears when Fully Closed Following Prolonged Low Discharge Periods

Summary and Conclusions

The depositional morphologic patterns observed at the mouth of the Shoalhaven contrast drastically with patterns observed at river mouths in low-wave energy environments but are analogous in major respects to those of other wave-dominated river mouths. It is inferred from this study that the distinguishing aspects of the morphology of the mouth of the Shoalhaven River are largely attributable to interactions between the river outflow and high-energy shoaling waves. Waves influence effluent behavior in at least two fundamental ways: (1) wave breaking and associated turbulence enhances mixing, obliterates vertical density gradients and causes more rapid deceleration; and (2) wave-induced mass transport and setup oppose the outflow, causing a local reduction in longitudinal hydrostatic gradient, "trapping" the issuing river water inshore and promoting abrupt lateral spreading of the outflow.

The major morphologic features produced by these wave-effluent interactions include: (1) a broad crescentic and highly regular river-mouth bar located at a short distance seaward of the outlet; (2) broad shallow subaqueous levees; and (3) a conspicuously constricted outlet.

Acknowledgments

This study was supported by the Australian Research Grants Committee (ARGC) and by a University of Sydney Research Grant (URG). Able assistance both in the field and the data analysis stage was provided by Mr. P. Cowell and Ms. D. Waddy. Valuable information and cooperation were provided by Mr. C. Brown of Posford, Pavry, Sinclair and Knight Consulting Engineers, and Mr. J. Downey, Shire Engineer, Shoalhaven Shire Council. Wave rider data were provided by Neil Lawson of the Maritime Services Board of N.S.W.

References

Department of Public Works, N.S.W., 1975, "Shoalhaven Floods: August 1974, June 1975", Hydraulics and Soils Laboratory Report No. 194, 20 pp. + 20 figs.

Hayashi, J. and N. Shuto, 1967, "Diffusion of Warm-Water Jets Discharged Horizontally at the Water Surface", Internat. Assoc. Hydrsulic Res., 12th Congress Proc. 4, pp.47-59.

_______ and _______, 1968, "Diffision of Warm Cooling Water Discharged from a Power Plant", Proc. 11th Conf. Coastal Engineering.

Hayes, M.O., V. Goldsmith and C.H, Hobbs, 1970, "Offset Coastal Inlets", Proc. 12th Conf. Coastal Engineering, pp.1187-1200.

Oertel, G.F., 1972, "Sediment Transport of Estuary Entrance Shoals and the Formation of Swash Platforms", J. Sed. Petrol., vol.42, pp. 858-863.

Posford, Pavry, Sinclair and Knight, Consulting Engineers, 1976, Shoalhaven Entrance Study, report submitted to Dept. of Public Works, N.S.W.

Wright, L.D., 1971, "Hydrography of South Pass, Mississippi River Delta", Am. Soc. Civ. Eng., Proc. Waterways, Harbors and Coastal Engr. Div. No.97, pp.491-504.

_______ and J.M. Coleman, 1971, "Effluent Expansion and Interfacial Mixing in the Presence of a Salt Wedge, Mississippi River Delta", Jour. Geophys. Res., Vol.76, pp.8649-8661.

_______ and _______, 1974, "Mississippi River Mouth Processes: Effluent Dynamics and Morphologic Development", Jour. Geol., Vol.82, pp.751-778.