TIDAL INLET BEHAVIOURAL ANALYSIS

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ABSTRACT

For many years stability theories have been used both to design inlets and to appraise the performance of them. There are a variety of approaches to the formulation of stability criteria ranging from the purely empirical (Stevenson, 1884 - cited by Bruun & Gerritsen, 1958; O'Brien, 1931; Bruun, 1977) to the generalised analytical (Escoffier, 1940; Bruun & Gerritsen, 1958; Keulegan, 1967; O'Brien and Dean, 1972).

In 1966 a seemingly small perturbation made to the inlet of Wallis Lake resulted in significant changes to the estuary. The direct application of existing stability theories was of marginal value in explaining these changes and predicting the stable regime that the estuary may ultimately reach. This paper highlights some of the limitations of existing stability theories, presents a new method of

Plate 1 Wallis Lake inlet in 1952 and 1974 (northern breakwater constructed in 1966).

dynamic behavioural analysis, outlines the case study of an estuary to which existing stability theories could not be effectively applied but to which the behavioural analysis produced interesting results, and recommends the direction in which further research could yield beneficial results.

1. INTRODUCTION

The twin towns of Forster and Tuncurry are sited on the banks of the entrance channel to Wallis Lake (Figure 1); an estuary located 220 km north of Sydney on the New South Wales coastline. The economic viability of the towns is based on the fishing, oyster and tourist

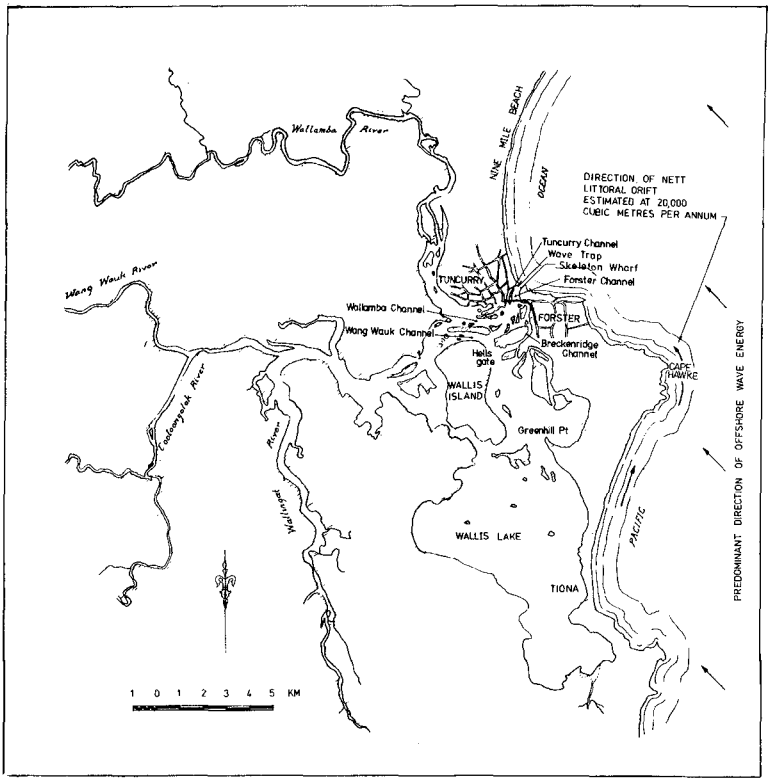


Figure 1 Locality Sketch

industries which focus on the amenity of the estuary and nearby coastal waters. Hence, the entrance conditions and hydraulic characteristics of the estuary are vital factors regarding the existence and development of the region.

Wallis Lake has a plan area of 100 square kilometres and an average depth of 3 m. Three rivers - the Coolongolok, the Wang Wauk and the Wallingat - enter the north-western sector of the estuary. The Wallamba River enters the northern part of the estuary amongst a confusion of small islands and channels. Whilst the four rivers and the lake all share the same ocean entrance, three major and several minor channels connect the river/lake system to the coast. In the vicinity of the ocean inlet the channel system simplifies to the Tuncurry (northern) and Forster (southern) channels.

The average daily fresh water flow in these rivers is small compared with the tidal flows and only extreme flood events have any influence on the estuarine channels. The tidal prism at the higher spring tides is some 18 x 10^6 cubic metres (ocean tidal range 1.93 m). The average annual flood has a total discharge of about 30 x 10^6cubic metres, but the stilling basin effect of the lake greatly damps the potential of floods to scour the entrance channels. This century there has only been one very large flood through the system. This flood occurred in 1929 and had an estimated total discharge of 250 x 10^6cubic metres. It caused considerable scouring of the entrance channels.

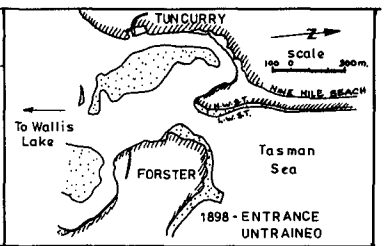
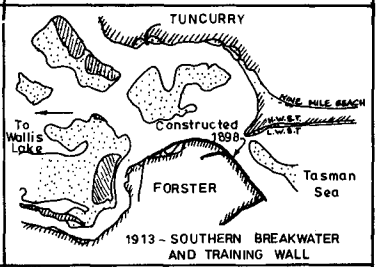
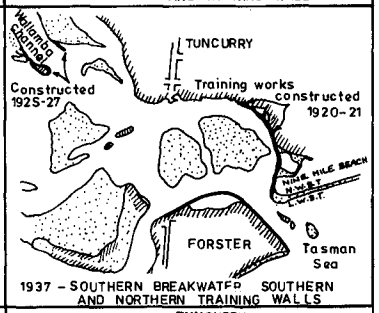
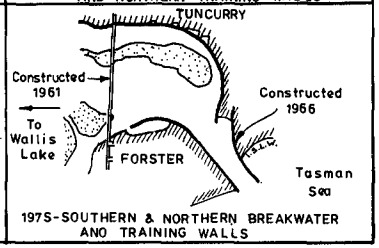
The inlet is located on a moderate to high energy coastline. However, the entrance is somewhat protected from the predominant southeasterly swells by Cape Hawke (Figure 1). The nett littoral drift is northerly and is estimated to be in the order of 20,000 cubic metres per annum. Studies are presently underway to further assess this littoral drift estimate and to develop a more detailed description of the coastal processes in this region.

2. HISTORICAL DEVELOPMENT AND EFFECTS OF ENTRANCE WORKS

In its natural state prior to the construction of any training works the inlet comprised a series of sandy, shoal filled channels that meandered across a wide, beach ridge plain. Both the location and cross-section of the ocean entrance varied with time. Over the past 82 years various entrance training works have been constructed to improve the navigability of both the entrance and estuarine channels and to cater for the historical trend towards larger ocean going trawlers. These works are summarised in Table 1.

It was not possible to fully assess the impact of works carried out before 1966 on the estuary/inlet system due to the paucity of data. However, indications are that from 1898 to 1966 the estuary mouth exhibited many of the typical features of single breakwater inlets. These features include an assymetrical entrance bar with a channel that meandered across it, large shifting swash shoals, a marginal flood tide channel on the unprotected (northern) side and shifting shoals in the lower entrance channel region. Immediately inside the inlet a twin flood/ebb channel system had developed.

Table 1 History of Entrance Works taken from Hydrographic Plans

YEAR OF SURVEY	DESCRIPTION	
1898	Untrained entrance	
1913	Southern breakwater and training wall In 1898 a contract was let for the construction of a breakwater (500m) and training wall (560m) along the southern (Forster) embankment	
1937	Northern training works and bay shoal stabilisation attempt. In 1919 further works at the entrance were carried out by constructing a 380m long training wall on the northern (Tuncurry) side of the inlet. The work was completed in 1922 and was followed in 1925 and 1928 by the construction of training walls within the estuary in an attempt to stabilise the internal sand bars.	
1975	Northern breakwater and extension of southern breakwater. By 1966 a 460m long breakwater had been constructed on the Tuncurry side of the inlet and the Forster breakwater had been extended by 90m. The width between the breakwaters is 120m.	

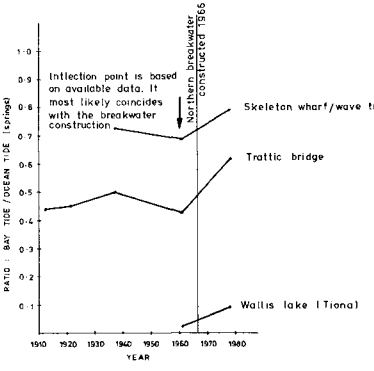


Figure 2 History of Estuary Tidal Ranges

The Forster (southern) channel predominantly conveyed the flood tide whereas the Tuncurry (northern) channel predominantly conveyed the ebb. Tidal gradients presented on hydrographic charts indicate that prior to 1966, entrance works had no significant impact on tidal ranges or phasings throughout the estuary.

Following the construction of the northern breakwater in 1966 there was a dramatic increase in tidal ranges throughout the estuary (Figure 2). Associated with this change was an accentuation of the distortion between flood and ebb tidal hydrographs, a marked change in the predominance of tidal channels and the scouring of the entire 3 km estuary channel system; a scouring mode which is showing no sign of reversal to the present day.

3. STABILITY THEORIES

Approaches to the formulation of the most commonly used stability criteria fall into two basic categories:

(i) The empirical approach - the identification of parameters relating cause and effect followed by the development of simple relationships between these parameters using coefficients which have been derived from many field observations.

(ii) The generalised analytical approach - the development of generalised formulae from mechanism understanding and description.

3.1 Empirical Approach

Bruun and Gerritsen (1958) outlined the history of stability theories from Stevenson (1884) through the work of O'Brien (1931) up to that proposed by Bruun and Gerritsen in their 1958 paper.

One of the most popular empirical approaches is based on the work of O'Brien (1931). O'Brien proposed that the stable inlet cross-sectional area could be determined from the tidal prism using the relationship:

$$A = 1000\left(\frac{\Omega}{640}\right)^{0.85} \qquad (1)$$

where

A = inlet cross-sectional area
Ω = tidal prism

Considerable embellishment of this model has been carried out by O'Brien (1969) and others, the most notable being Jarret (1976) who has presented prism/area relationships for estuaries with various inlet configurations and tidal conditions.

These predictive prism/area relationships are of marginal value to analytical work. The reasons for this are that firstly, the scatter of field data points around the predictive curve implies that the relationship is at best approximate and secondly, for estuaries with long and complex entrance channels connecting the water body to the ocean it is virtually impossible to relate an equivalent theoretically determined stable channel cross-sectional area to channels in the field.

Bruun (1977, 1978) has advanced the empirical approach by proposing a method which considers the relationship between littoral drift and the tidal prism of the estuary. This approach represents a shift in emphasis of pertinent parameters from the morphological (cross-sectional area) to those describing forces (sediment transport). In essence, this approach is concerned with entrance bar conditions. Bruun contends that the stability of an inlet must be analysed in terms of the ability of the tidal flow to flush out the sediments that are carried by wave and current action to the inlet gorge. On this basis he proposes that inlets be classified in terms of Ω/M ratios, where

Ω = tidal prism
M = sediment feed to the gorge

Low ratios (less than 50) are indicative of poor entrance conditions whereas high ratios (greater than 150) are indicative of good entrance conditions. This approach is simply one of classification by parameter ratios and has severe limitations if it is to be used as a predictive tool.

However, it is important to be aware of the development, limitations and strengths of the emperical approaches as they represent significant steps down the path of understanding inlet dynamics.

3.2 Analytical Approach

Of the generalised analytical approaches, that presented by O'Brien and Dean (1972) is a significant contribution to inlet mechanism understanding. It is based on the earlier well documented work of Escoffier (1940) and Keulegan (1967). This method relates the bay tide phasing and amplitude to that of the ocean tide through the hydraulic characteristics of the entrance channel. The approach is applicable to small inlets and large tidal estuaries on shorelines where littoral drift is small. It favours estuaries with relatively short and regular entrance channels connecting the water body to the ocean. With this method of analysis, through the construction of an Escoffier diagram,

the status of an inlet at any point in time can be examined and the ultimate stable cross-sectional area of the entrance channel can be predicted. The O'Brien and Dean method is outlined below as it forms a basis from which the analytical approach adopted for the Forster/Tuncurry study was developed.

Keulgen developed the relationships between the repletion coefficient K and the tidal phase lag, and the ratio of the bay-to-ocean tidal amplitudes, A_b/a_o. These relationships are shown in Figure 3. The repletion coefficient may also be expressed as a function of the hydraulic and geometric properties of the estuary in the following way:

$$K = \frac{T}{2\pi a_o} \cdot \frac{Ac}{Ab} \cdot \sqrt{\frac{2ga_o}{Ken + Kex + \frac{fl}{4R}}} \qquad (2)$$

where

T = tidal period
a_o = amplitude of the ocean tide
Ac = inlet cross-sectional flow area
Ab = surface area of the basin
g = gravitational constant
Ken, Kex = entrance and exit head losses of the entrance channel
f = friction factor
l = friction length
R = hydraulic radius of entrance channel

Keulegan also presented the relationship between the repletion coefficient and the dimensionless maximum velocity in the inlet V'max, as shown in Figure 4. The maximum velocity through a specific inlet is given by equation (3):

$$Vmax = V'max. \frac{2\pi}{T} . a_o . \frac{Ab}{Ac} \qquad (3)$$

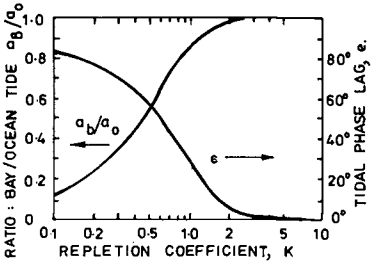


Figure 3

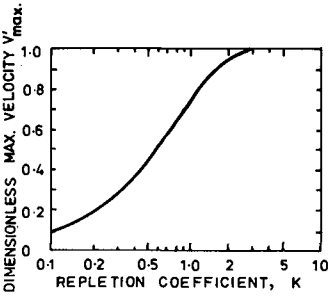


Figure 4

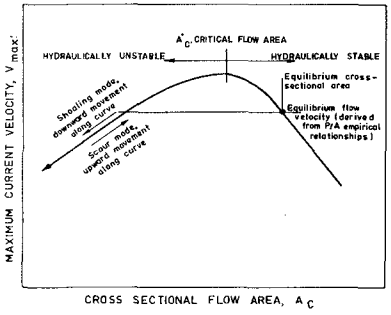


Figure 5 Generalised inlet hydraulic stability curve, or "Escoffier Diagram".

Where equations (2) and (3) and Figure 4 are used together a range of inlet hydraulic conditions can be calculated in terms of the maximum velocity versus cross-sectional flow area. The inlet mechanics are portrayed by the inlet stability curve (Escoffier diagram - Figure 5).

It can be seen from this diagram that an induced change in the cross-sectional flow area of an hitherto hydraulically stable inlet will result in either a change in inlet current velocity which will work to return the inlet towards its equilibrium size by appropriate deposition or scour, or, if the induced area change is so large as to reduce the cross-sectional area below the critical flow area, making the inlet hydraulically unstable. An hydraulically unstable inlet is characterised by increasing friction with decreasing cross-sectional area. The result is that if any natural or man-induced change in flow area occurs this is accompanied by a change in the flow velocity which will, by inducing scour or deposition, perpetuate the induced area change. Since area changes are perpetuated, an hydraulically unstable inlet will either continuously scour until a stable flow area is achieved (unstable scour mode) or its will continuously shoal until inlet closure (unstable shoaling mode).

Many limitations of this model have been documented by Bruun (1977, 1978). In particular, major difficulties are encountered in determining the equivalent length and cross-sectional area of a long and complex entrance channel system. However, the major failing of the model is that it can not be used as a predictive tool in situations where significant perturbations such as those associated with the construction of breakwaters are or will be made to the entrance bar of the inlet. Moreover, if it is desired to predict the effect of such perturbations the O'Brien and Dean model cannot be used for the reason that an Escoffier diagram representing the range of future likely hydraulic characteristics cannot be constructed if more than one parameter (A_c and consequently R) is varied.

Following on from the O'Brien and Dean approach, Bruun (1978) shifted the emphasis to sediment transport considerations on the basis that stability must reflect the ability of sediment to move through the inlet in such a way that nett deposition does not occur. Bruun suggests that inlet analysis be undertaken by calculating sediment transport:

(i) in the gorge (entrance channel),

(ii) in the region between the inlet and the ocean bar,

(iii) in the ocean channel including its passage over the bar, and

(iv) in the bay channels.

It is then possible to construct a quantitative sediment budget from which erosion and depositional areas may be identified, hence a model of estuary/inlet behaviour can be constructed.

The limitations of the Bruun approach are less obvious than those of O'Brien and Dean. There are difficulties in accurately carrying out many of the required calculations. The sediment budget determination may in many cases be very sensitive to these inaccuracies. Further, there is no well documented method to determine sediment transport in the region of the ocean bars for differing inlet configurations. Finally the method is not readily adapted to situations where relatively long channels connect the bay to the ocean.

4. INLET BEHAVIOURAL APPROACH

The concepts of O'Brien and Dean and Bruun may be modified and used in a complimentary manner when studying the changes induced by major inlet forcing works such as breakwater construction. Extension of these approaches has led to the development of an inlet behavioural approach which allowed studies to be undertaken on typical New South Wales inlets. This behavioural approach included the recognition and inclusion of the following:

There are two major sources of head loss between the forcing function (ocean tide) and the bay response. These are the head loss over the entrance bar and the losses associated with the hydraulic characteristics of the inlet and entrance channel (Figure 6). When constructing the Escoffier diagram for a particular estuary the following approach is used (Czerniak, 1977 - see Section 3.2):

(i) A_b/a_o is calculated from existing data and K is determined from Figure 3.

(ii) Equation (2) is solved for l using K and known values of R, Ac, T, a_o, Ab, f, Ken and Kex. The latter six parameters are assumed not to vary.

(iii) The hydraulic stability curve is computed using equations (2) and (3) and Figure 4 with only Ac (and consequently R) varying over the entire range.

In equation (2), four head loss parameters (Ken, Kex, f, l) are used to describe the total impedance of the tidal inlet and entrance channels to the flow. This implies that the forcing function a_o (the amplitude of the ocean tide) is applied immediately outside the inlet. Hence, a_o is not a true ocean tidal amplitude unless entrance bar losses are negligible.

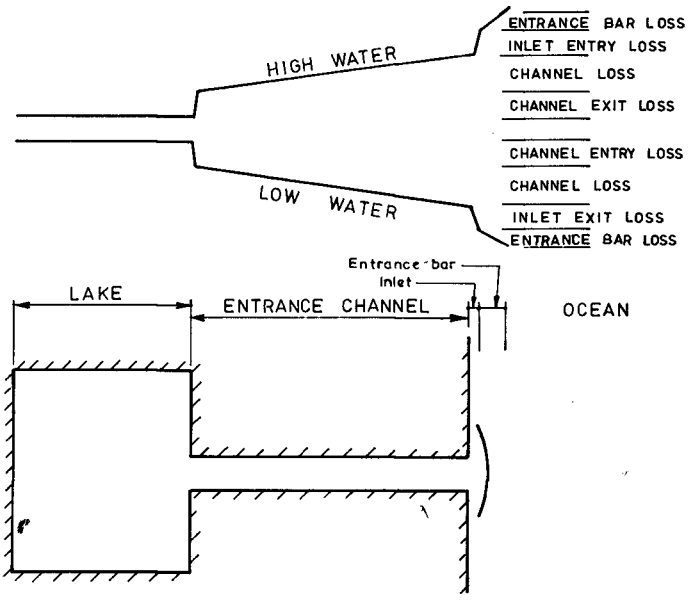


Figure 6 Generalised head loss diagram for inlet/estuary system

Accordingly, a_o should be defined as the amplitude of the tide immediately outside the inlet. This is not in accord with Bruun's recommendation that a_o be determined from outer coast ranges.

Sediment budgeting as proposed by Bruun can be modified by the application of regime theory to the inlet hydraulics both

before and after the perturbation to provide a predictive numero-descriptive model.

5. APPLICATION OF BEHAVIOURAL ANALYSIS

It has been identified that changes to head loss over the ocean bar are important when considering the impact of inlet modification on estuary behaviour because such modifications can significantly affect the forcing function of the system. Moreover, changes to tractive stresses and the regions over which they act can be expected to radically alter sediment transport paths and the quantities of sediment involved in the budget.

An essential part of inlet behavioural analysis includes an examination of changes to the hydraulic and sediment transporting characteristics of the ocean bar following inlet modification works. The changes to the hydraulic characteristics can be analysed in terms of alterations to the head loss over the bar and in the inlet due to modifications to the inlet cross-sectional shape, velocities and frictional properties. The modification of sediment supply to the inlet gorge must include examination of:

(i) Changes to tractive stress patterns resulting from modifications to tidal flow patterns across the bar.

(ii) Changes to velocity profiles resulting from increased/decreased inlet efficiency.

(iii) Changes to the sediment entrainment and depositional rates resulting from morphological modifications to the ocean bar and hence areas over which increased bed shear due to wave effects occur.

(iv) Changes to wave setup effects, hence their relationship to flood/ebb hydraulic gradients.

Having determined the changes in head loss characteristics, the regime equations of Engelund and Hansen (1967 - cited by Bruun, 1978) can be considered with the Manning formula to predict changes to the friction slope in the estuary channels. The Engelund-Hansen equations can be expressed in the following way:

$$B \propto Q^{0.525} \tag{4}$$

$$D \propto Q^{0.317} \tag{5}$$

$$A \propto Q^{0.842} \tag{6}$$

$$V \propto Q^{0.158} \tag{7}$$

Using equations (5) and (7) with Manning's formula in the form:

$$S = \left(\frac{v.n}{R^{2/3}}\right)^2 \qquad (8)$$

and with D approximating R for wide shallow channels, the behavioural change slope ratio is:

$$\frac{S_{ultimate}}{S_{prior}} = \left(\frac{Q_{ultimate}}{Q_{prior}}\right)^{-0.107} \qquad (9)$$

Finally, with the above information and certain assumptions the response rate of the estuary from the pre-perturbated condition to the "ultimate" condition can be mapped. From this history, using an appropriate sediment transport formula, it is possible to predict sediment movements and future scour/depositional patterns.

The analysis of the Wallis Lake estuary will be used to illustrate the method.

6. APPLICATION OF INLET BEHAVIOURAL ANALYSIS TO WALLIS LAKE ESTUARY

The construction of the northern breakwater at Forster/Tuncurry in 1966 resulted in profound changes to the Wallis Lake estuary. The inlet behavioural analysis was used to predict the ultimate configuration and size of the inlet channels, to predict the response time of the estuary to the perturbation and to assess the impact of proposed further perturbations in the lower estuary regions.

6.1 Ocean Bar/Inlet Morphology and Flow Patterns (also see Druery and Nielsen, 1980)

Figure 7 shows typical current flow paths, velocity distributions and sediment transport paths pertaining to the inlet before the northern breakwater was constructed. During ebb flow sediments were entrained on the channel shoals and carried to sea through the inlet. As the ebb jet expanded the flow velocity reduced. The assymetrical nature of the jet expansion resulted in a skewed velocity distribution and sediments were deposited in the low energy region along the edge of the swash shoals. A large separation eddy developed on the northern side of the jet resulting in an inlet directed current through the northern marginal flood tide channel (see Figure 7). This feature resulted in the formation of an opposing current on the northern side of the entrance and produced a head loss to the ebb tide flow. Wave action from the predominant southeasterly swells carried sediment northward along the swash bars. During flood tide sediments were entrained on the swash bars and carried into the inlet.

The construction of the northern breakwater in 1966 resulted in significant alterations to the bar morphology, tidal flow paths and sediment movement patterns (Figure 8). On ebb tide the jet expansion became more symmetrical. The interception of the marginal flood tide channel and large swash shoals by the breakwater resulted in the elimination of the large flow separation eddy and the inlet directed

current during ebb flow. The breakwater has also caused a redirection of the flood tide flow which became orientated along the centreline of the breakwaters. Figure 9 summarises the pertinant changes caused by the northern breakwater construction, the salient points being the reduction to the sediment entrainment area of tidal currents over the entrance bar during flood tide, the reduction in area on the bar affected by increased bed shear due to wave effects and the increase in ruling depths on the bar.

6.2 Head Loss at the Entrance

A significant reduction in the total head loss over the entrance bar has occurred. An estimate of this reduction was obtained by comparing the tidal envelopes measured before (1961) and after (1978) the breakwater construction (Figure 10). On the assumption that the tidal envelope in the region of the bar approximates the peak instantaneous head loss over the bar, the head losses for the higher spring tide ranges have been reduced from 0.19 m to 0.11 m (0.08 m reduction) for high waters and from 0.24 m to 0.18 m (0.06 m reduction) for low waters.

It is estimated that the inlet losses have reduced from about 0.1 m to about 0.05 m which is a measure of the increased hydraulic

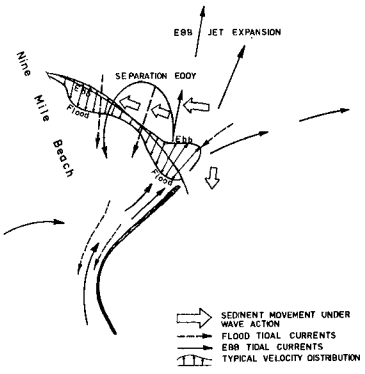


Figure 7 Littoral processes at a single breakwater entrance

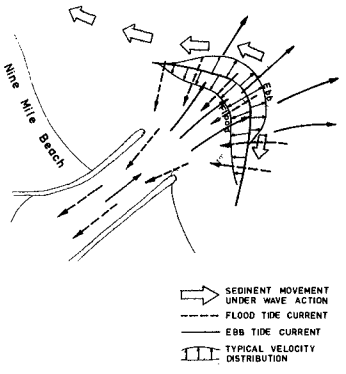


Figure 8 Littoral processes at a double breakwater entrance

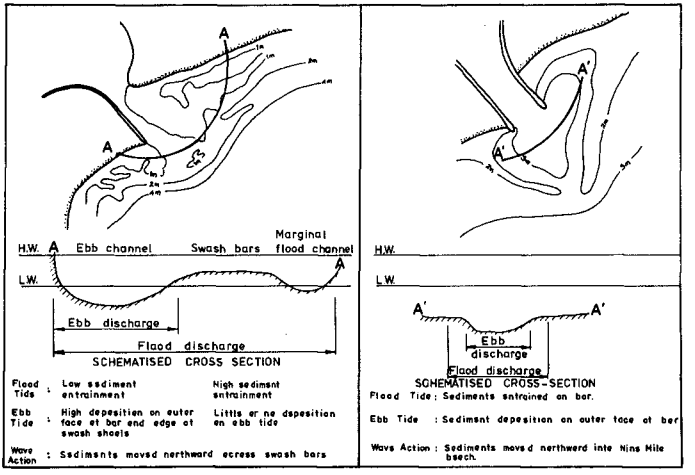


Figure 9 Differences between single and double breakwater entrances

efficiency of the new trapezoidal section between the breakwaters, as outlined by Bruun (1978).

In the O'Brien and Dean approach the inlet entry losses are accounted for by Ken, the entry head loss coefficient. The entry head loss is:

$$\text{Ken.} \frac{u^2}{2g}$$

Dean (1971, cited by Bruun, 1978) recommends a value of Ken = 0.25 for inlets with exposed breakwaters. O'Brien and Dean (1972) recommend a value of Ken + Kex = 1.3. As a value of Kex = 1 is usually adopted (Bruun, 1978) then this sets Ken = 0.3. These values were also adopted by Czerniak (1977).

In this application, given peak velocities of about 2 m/s during the highest spring tides and for a measured inlet head loss of about 0.05m, a value of Ken = 0.25 was calculated. This value is in accordance with the recommended values cited above. It is clear that the generalised analytical model of O'Brien and Dean does not take into account head losses that occur over the ocean bar.

6.3 Regime/Gradient Analysis

An estimate of the ultimate stable channel regime and the total response time of the estuary was made by a generalised analytical appraisal of the channel hydraulics. The assumptions made include:

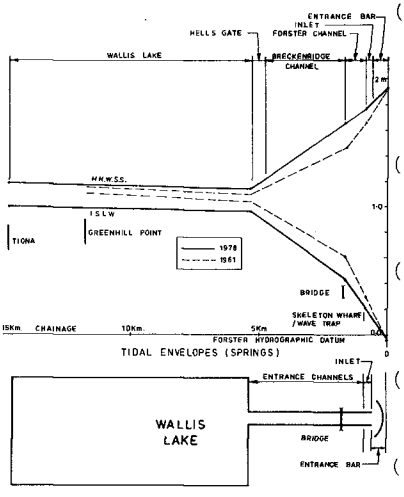


Figure 10 1961 and 1978 tidal envelopes for Wallis Lake inlet/estuary system

(i) The ultimate head loss values between the traffic bridge and the ocean were reached within a short period of time after the northern breakwater was constructed.

(ii) The channels are erodable between the traffic bridge and the lake, hence regime equation apply.

(iii) The hydraulic gradients at peak flows are proportional to the gradients of the tidal envelope at spring tides.

(iv) The tidal range in the lake is proportional to the tidal prism and discharge.

(v) Manning's "n" in the various channels remains constant throughout the response period, that is, there will be no significant change in the composition of the sediments or in bed forms in the channels.

(vi) The tidal prism in 1966 is equal to the tidal prism in 1961 - necessary because of lack of data.

Based on assumptions (i), (iv) and (v) a relationship between discharges and hydraulic gradients was developed:

$$\frac{Q_{ult.}}{Q_{1966}} = \frac{\left(1.65 - 0.37\ \frac{S_{ult}}{S_{1966}}\right)_{HHWSS} - \left(0.43 + 0.43\ \frac{S_{ult}}{S_{1966}}\right)_{ISLW}}{0.06\ (\text{lake tidal range, } 1966)} \qquad (10)$$

Equations (9) - Section 5 - and (10) were solved graphically (Figure 11) resulting in the following regime parameters:

(i) Tidal prism (HHWSS) = 67,000 cubic metres, a tenfold increase.

(ii) Lake range = 0.60 m (increase from 0.06 m).

(iii) Channel velocities increase by 44%.

(iv) Channel depths double.

(v) Channel widths treble.

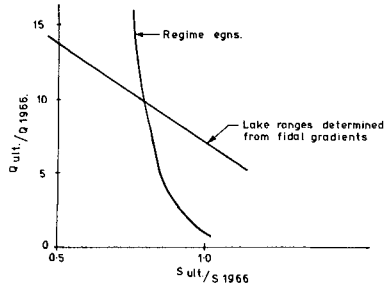


Figure 11 Solution of regime/gradient equations

Given that there was a threefold increase in tidal prism between 1967 and 1978 (see Figure 10), and assuming that the rate of increase was and will remain constant, it will take 50 years from 1967 for the estuary to fully respond to the northern breakwater construction.

The assumptions and the basis for these predictions are at this point of time felt to be suboptimal. However, the methodology employed is considered to be reasonable. In the case of Forster/Tuncurry a number of factors will further influence the ultimate result:

- The presence of indurated sands at some locations in the estuary will act to control and modify channel erosion patterns, hence the predicted tidal range in the lake may never be realised.

- The extent of the oyster leases throughout the estuary will have an effect on erosion patterns and may invalidate the Mannings "n" assumption.

6.4 Sediment Budget Analysis

The increase in the efficiency of the inlet has resulted in an increase in bar depths with a resulting reduction in wave setup effects. There has also been a reduction to the area on the entrance bar over which threshold shear stresses are exceeded during flood tide. The nett result of these effects has been to enhance the ebb tide sand transporting capabilities and to reduce the sediment feed to the inlet during flood tides.

Sediment transport rates under tidal current action were calculated at various locations in the lower entrance region using the Ackers and White (1973) approach. This approach was used for reasons of convenience as the computational steps have been automated on our office computers. The results at each gauging station were plotted in terms of transport rate vs velocity and a curve in the form:

$$Q = kv^n \qquad (11)$$

where

Q = sediment transport rate
k = constant
v = average channel velocity

was fitted to each set of results. It was found that n varied from about 4 to about 6 over the monitoring stations. The mean grain size of the sand is about 0.3 mm and depths of flow were in the order of a few metres. This result is therefore in close agreement with the A.S.C.E. recommendation which sets n = 5, and it is also in accord with the analysis carried out by Costa and Isaacs (1977).

For each tidal gauging sediment transport rates were calculated at hourly and, in some instances, half hourly intervals. The transport rate/time curve was integrated to give the sediment load for the tidal gauging. Annual sediment transport rates were calculated based on statistics of annual tidal ranges and derived relationships between tidal ranges and tidal discharges.

To check the validity of this approach it was assumed that the sediment transport rates remained constant over the period since the northern breakwater was constructed and the sediment budget was calculated (Figure 12) and compared with that obtained from the analysis of hydrographic surveys. The analysis was carried out for two sections of the estuary (see Figure 12). Limitation to the extent of the hydrographic surveys dictated that different time periods for the two sections were analysed. However, it was felt that this in itself provided further proof of consistancy of the results.

The values are given in Table 2 from which it can be seen that a remarkably good agreement was obtained.

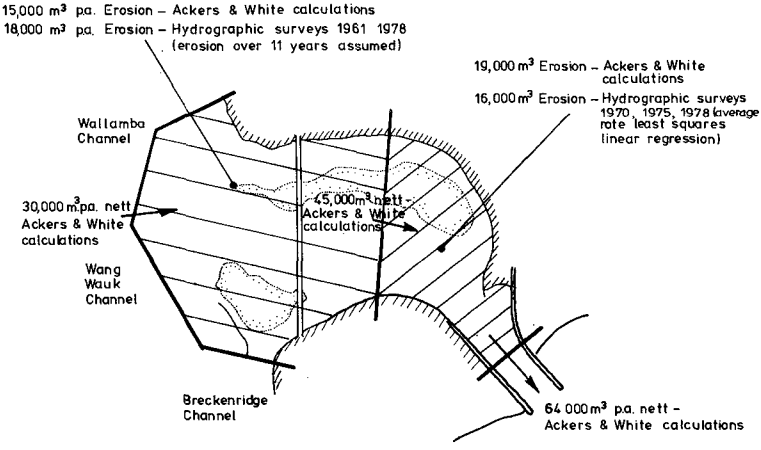


Figure 12 Sediment budget for lower entrance channel region at Forster/Tuncurry

TABLE 2

Comparison of Theoretically Determined and Measured Erosion Rates

Section (See Figure 12)	Period of Analysis	Erosion of entrance shoals (cubic metres per annum)	
		As predicted by Transport Calcs.	As given by Hydro-survey
From breakwater to section D/S of bridge	1970 - 1978	19,000	16,000
From section D/S of bridge to section U/S of bridge	1967 - 1978	15,000	18,000

The calculated sediment budget for the estuary was therefore adopted. From this it can be seen that the nett sediment movement has been directed out of the estuary, considerable scour has occurred in the lower entrance channel region and, as sediments are not carried into the entrance channels from the lake during ebb tide, the upper region of the entrance channel system is scouring. These effects have been dramatically borne out in the field where scouring has resulted in severe subsidence of the traffic bridge with piers settling 400 mm, erosion of the untrained channel banks throughout the estuary with some channels doubling in waterway cross-sectional area, increased upstream penetration of marine sand flood tide deltas. Further, a significant accretion on nine mile beach has occurred since 1966 as a result of the sediment being supplied to the coastal littoral system from the "point source" generated within the estuary by the breakwater construction.

7. CONCLUSIONS

The construction of a northern breakwater at Forster/Tuncurry converted the previous single breakwater entrance into a double breakwater entrance. This perturbation, unlike the previous one occasioned by the construction of the first breakwater, caused significant changes to the tidal prism, the inlet entry and exit head loss characteristics and the entrance bar morphology. Existing stability theories were unable to describe the changes or predict the future consequences of the perturbation. The long and complex estuary channel system connecting the ocean inlet to the "bay" region, Wallis Lake, provided additional complications.

It was necessary to adopt a new approach of "Inlet Behavioural Analysis" which was based on a combination and extension of past methods.

The major features of this approach included:

Examination and description of changes to ocean bar morphology, current patterns and entrainment condition in order to identify

the relevant parameters and their importance with respect to the changes.

- Determination of the impact of the perturbation on ocean bar/inlet efficiency. That is, determination of head loss variation caused by changes to bar morphology, flood/ebb current patters and cross-sectional optimality at the entrance -particularly between the breakwaters.

- Use of a regime type approach to predict the propagation and distribution of the changed hydraulic conditions at the entrance throughout the inlet-estuary system.

- The development of a predictive sediment budget model based on sediment transport formula and the calculated hydraulic conditions from the regime analysis.

- The use of this sediment budget model and conceptual hydraulic model to chart the future of the estuary and determine the time span over which impacts from the perturbation will occur.

Application of this approach to Forster/Tuncurry produced interesting results which at this point of time - 14 years after the perturbation - are in good agreement with field observations.

The magnitude of the "ultimate" changes, that is, a tenfold increase in tidal prism (a threefold change has already occured), a doubling of channel depths, a trebling of channel widths and a 50 year adjustment period is difficult to contemplate. This end result may however never be realised due to the simplistic assumptions which were made in the analysis and the development of controls such as the exposure of indurated sand rock bars, which were not considered in the study.

The increasing need to be able to adequately predict long term impacts of entrance training works has shifted the emphasis away from the static "stability analysis" approach towards the more dynamic one of "behavioural analysis". The methodology outlined in this paper is seen as an attempt by the authors to respond to this need.

The authors keenly look forward to discussion and guidance on this matter. An exciting field of future research must be undertaken to overcome many of the crude assumptions and simplifications which have been made to date.

8. REFERENCES

1. Ackers, P. and White, W.R. (1973). "Sediment Transport : New Approach and Analysis". A.S.C.E. Journal of the Hydraulics Division, Vol. 99, No. HY11, November, 1973.

2. Bruun, P.M. and Gerritsen, F. (1958). "Stability of Coastal Inlets". A.S.C.E., Journal of the Waterways, Harbours and Coastal Engineering Division, Vol. 84, No. WW 3.

3. Bruun, P.M. (1977). "Design of Tidal Inlets on Littoral Drift Shores". Coastal Sediments '77. Proc. Fifth Symposium of the Waterway Port, Coastal and Ocean Division of A.S.C.E. Charleston, pp 754-773.

4. Bruun, P.M. (1978). "Stability of Tidal Inlets." Elsevier Scientific Publishing Company. Amsterdam.

5. Costa, S.L. and Isaacs, J.D. (1977). "The Modification of Sand Transport in Tidal Inlets." Coastal Sediments '77. Proc. Fifth Symposium of the Waterway Port, Coastal and Ocean Divison of A.S.C.E. Charleston, pp 946-965.

6. Czerniak, M.T. (1977). "Inlet Interaction and Stability Theory Verification". Coastal Sediments '77. Proc. fifth Symposium of the Waterway Port, Coastal and Ocean Division of A.S.C.E. Charleston, pp 754-773.

7. Druery, B.M. and Nielsen, A.F. (1980). "Mechanisms Operating at a Jettied River Entrance". Proc. 17th International Conference on Coastal Engineering. Sydney.

8. Escoffier, F.F. (1940). "The Stability of Tidal Inlets." Shore and Beach, Vol. 8, No.4, pp 114-115.

9. Jarret, J.T. (1976). "Tidal Prism - In let Area Relationships", GITI Report 3, U.S. Army, Corps of Engineers, Coastal Engineering Research Centre, Fort Belvoir, Va., and U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Feb. 1976.

10. Keulegan, G.H. (1967). "Tidal Flow in Entrances Water Level Fluctuations of Basins in Communication with Seas". Committee on Tidal Hydraulics U.S. Army, Corps. of Engineers. Tech. Bulletin No. 14.

11. O'Brien, M.P. (1931). "Estuary Tidal Prism Related to Entrance Areas." Civil Engr., Vol. 1, No. 8.

12. O'Brien, M.P. (1969). "Equilibrium Flow Areas of Inlets on Sandy Coasts". A.S.C.E., Journal of the Waterways and Harbours Division, Vol. 95, No. WW1.

13. O'Brien, M.P., and Dean, R.G. (1972). "Hydraulics and Sedimentary Stability of Coastal Inlets." Proc. 13th Coastal Engineering conference. Vancouver, pp 761-780.