ESTUARINE RESPONSE TO DREDGING IN THE TWEED RIVER, AUSTRALIA

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ABSTRACT

Between mid 1974 and mid 1975,760,000 m^3 of sand was dredged from the bed of the Tweed River for the purpose of nourishing cyclone damaged beaches of the Gold Coast (Queensland). A comprehensive field data programme was established in 1976 to record the changes in the hydraulic processes of the Tweed River brought about by the dredging. The field measurements demonstrated that the dredged area was being infilled with sediments of both marine and estuarine origin. The dredging increased tidal ranges throughout the lower estuary, the effect being more pronounced at low water.

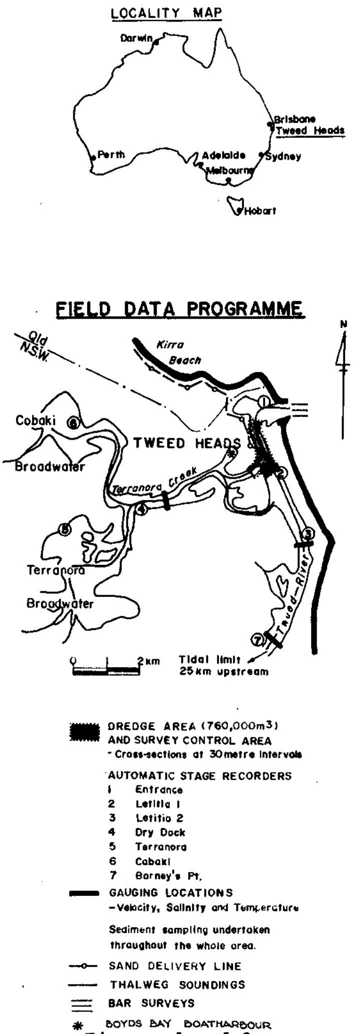
Sediment bedload rates were estimated from detailed measurements of bedforms and used to calibrate a sediment transport formula. The formula was used in conjunction with a 1 Dim. numerical model of tidal hydraulics to simulate estuarine shoal dynamics by means of a simple sediment routing technique. The results showed that the dredging had altered the tidal hydrodynamics so as to enhance the ebb transport of sediment towards the dredged hole. In the long term it was found that the sediment transport switched to a weak net upstream movement of sediment. The detailed hydraulic mechanisms involved are discussed. The study demonstrates that the impact of dredging can be minimised by location upstream of the entrance plug of marine sand.

1. INTRODUCTION

The coastal margins of a large number of estuaries in New South Wales (N.S.W.) have developed near regime channels in marine sands which were pushed against the coastline during the sea level transgressions of the late Pleistocene and Holocene epochs (Thom 1978). Typically the beds of these estuaries are composed of moderate to well sorted sands (D50 approx. 0.3 mm) and small scale sand extraction has been common place.

Areas of large scale sand extraction are associated generally with the building industry and are located well upstream of the estuary mouths. These upriver operations tend to have very little effect on the tidal hydrodynamics (N.B. fluvial hydrodynamics can be certainly affected though). Past dredging activities in the entrance reaches have been generally small scale, involving maintenance of navigation channels only.

There is strong evidence to indicate that substantial portions of the N.S.W. coastline are receeding (Gordon et al 1978, Roy 1980). Increased public acceptance of the realities of a receeding coastline



Figures 1 and 2

creates more demand for coastal management techniques, such as beach nourishment, by which the amenity of the coast can be maintained. The lower reaches of estuaries are convenient sources of sand for beach nourishment but the quantities of sand required are no longer small and significant alteration of tidal hydrodynamics is possible. Consequently large scale sand extraction in estuaries should be examined closely so that all the environmental contraindications are identified.

2. SAND EXTRACTION FROM THE TWEED RIVER

The Tweed River is the most northern river of N.S.W., located in part along the boundary between N.S.W. and Queensland - see fig. 1. Mean Spring Range at the estuary mouth is 1.3 m and is associated with a peak tidal discharge of 600 cumecs. The river catchment is relatively short and steep producing floods which are characteristically fast flowing but short lived. Fluvial flow is flashy with floods punctuating lengthy periods of low freshwater runoff.

Early in 1974 cyclones caused extensive damage to the Queensland resort of Kirra Beach - see fig. 2. The beach was restored by nourishment with 760,000 cubic metres of sand extracted from the Tweed River and pumped overland between July 1974 and October 1975. Once the dredging had been completed, however, there were reports of a number of marked changes in tidal levels, flows and phasing within the estuary, for instance:

Navigational difficulties were encountered by some of the larger craft operating from Boyd's Bay fishing harbour as a result of a reduction in low water levels.
Oyster farmers in Terranora Broadwater reported an increase in the range of the tide about their oyster racks.
Oyster farmers also reported a significant reduction in the tidal lag between Terranora Broadwater and the river entrance.

Whilst these reports would have involved some element of exaggeration and most of the reported consequences were of minor concern only, there was an overall concern that the effects could be "the tip of the iceberg" if further sand removal was carried out before the estuary had fully recovered. This concern was underlined by the Queensland authorities' desire to dredge similar quantities of sand from the river in the future.

3. FIELD MONITORING PROGRAMME

A comprehensive field monitoring programme was set up progressively from the end of 1976 - see fig. 2. The objective of the programme was to record the gradual recovery of the estuary and in so doing identify and quantify the real effects of the dredging. It incorporated the following:

* A network of 7 automatic recorders.
* Repetitive hydrosurveys of dredging area (in detail) and upper reaches (broad control).
* Stream gauging of tides and floods.
* Underwater photography of bedforms.
* Measurement of bedform movement.
* Sidescan and conventional sonar profiles.

3.1 Hydrographic Surveys

Seven hydrographic surveys were completed between December 1976 and March 1979, providing coverage of the dredged area at 30 metre intervals. Contour plans of each survey and isopach plots between successive surveys were prepared to illustrate the mode of shoaling. The surveys showed that the dredged area was undergoing both marine and estuarine infilling. The overall trend is summarised in fig. 3 which shows the total erosion and accretion over the period of the surveys (i.e. 2 1/4 years). Marine sand appears as a broad continuous shoal up to 3 m thick extending from the entrance. The estuarine sand appears as a 2-5 metre thick localised accumulation on the upstream edges of the dredged area. In the vicinity of chainage 1895 the two sands mix.

Fig 4. demonstrates the bathymetric impact of the April 1978 flood which had a probability of occurrence of 20%. The flood scoured the bed of the main arm upstream of the dredged area and the sharp reduction in sediment transport capacity, as the flood flow entered the deeper dredged area, caused deposition up to 1.5 metres in the confluence area. Deposition up to 2.5 metres occurred at the entrance to Terranora Inlet probably due to redistribution of flood deposits from the main arm. The entrance shoal of marine sand had restricted flood flow and considerable scouring of the surface had taken place.

The results of volumetric analyses of survey cross sections are presented in Table 1. Generally the estuarine infilling has been 10-20% of the total. The increasing trend of the estuarine infilling rate is probably indicative of the effect of mixing at the leading edge of the marine sand.

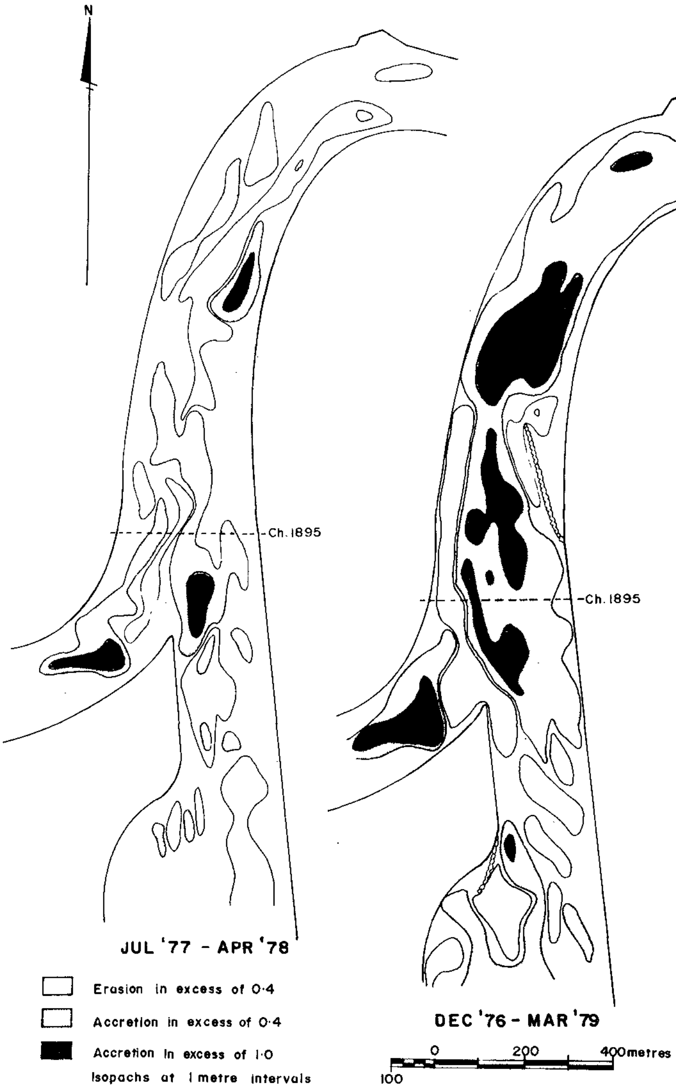


Figure 4 Figure 3

Hydrographic Surveys - Isopach Plots

TABLE 1 SEDIMENT INFILL RATES OF DREDGED AREA

SURVEY PERIOD DATES /DURATION (months)	TOTAL INFILL (m^3)	MARINE INFILL (m^3)	ESTUARINE INFILL (m^3)	MARINE INFILLING RATE (m^3/yr)	ESTUARINE INFILLING RATE (m^3/yr)
DEC '76 - JUL '77 (8·0)	68,300	62,200	6,100	93,300	9,100
JUL '77 - APR '78 (8·6)	28,000	66,900*	6,500*	93,300*	9,100*
APR '78 - OCT '78 (6·3)	48,700	38,000	10,700	72,300	20,400
OCT '78 - MAR '79 (5·4)	44,500	37,100	7,500	82,400	16,600

* Estimated from Dec.'76 - Jul.'77 survey period implying a flood scour of $45,400 m^3$.

3.2 Tidal Gradients

Fig. 5 demonstrates the modification of the tidal wave which can take place due to shallow water effects.

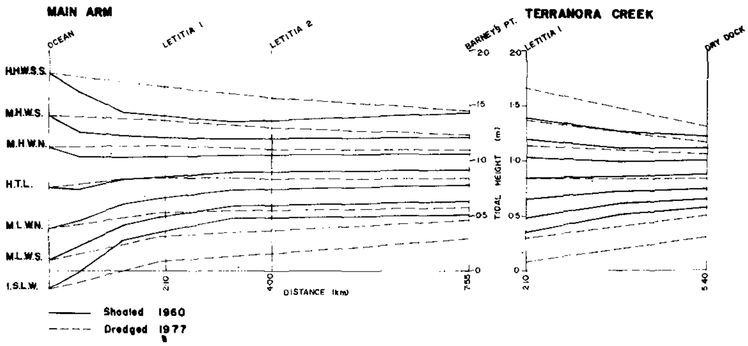


Figure 5 Comparison of Tidal Reference Planes

In 1977 the lower estuary was free of shoals because of the nourishment dredging and this contrasted with the heavily shoaled conditions of 1960. The constricted tidal ranges and the raising of half tide level are characteristics of the 1960 gradients (fig. 5) which signify the presence of pronounced shoaling. Considerable damping of the tidal wave, loading to high head losses, occurred within the first one to two kilometers from the entrance.

The determination of the tidal planes was based on the Range Ratio Method as developed by the Royal Navy Hydrographer (1969), using observations of high and low water over a period of one month in 1960 and 4 months in 1977. Druery and Curedale (1979) examined the inherent variability of local half tide levels and tidal amplitudes and concluded that for these short period observations the values of M.H.W.S. and M.L.W.S. could only be defined to $\pm$ 0.059 m and $\pm$ 0.032 m respectively at Letitia 1 (95% Confidence Interval). Whilst this means that considerable caution must be exercised when making quantitative comparisons between different sets of tidal gradients, nonetheless, the behavioural trends described previously are well in excess of these confidence limits.

3.3 Bedform Dynamics

Suspended sediment sampling and underwater observation, during peak flows, indicated that away from the immediate entrance area the movement of the bed sediment (D_{50} = 0.3 to 0.35 mm) was restricted primarily to bedload. Individual sand grains either scudded across the surface or moved in discrete jumps which rarely extended more than 150 mm into the water column. During peak velocities (viz: 0.64 m/sec, 0.4 m above the bed) the majority of the dune surface was moving as either sheet flow, a few grains thick, or as short crested ripples of height 1-2 cm. Occasional boils of sediment occurred when one of the ripples disintegrated but the momentarily suspended sediment rapidly settled back to the bed and the ripple reformed a short distance downsteam.

Detailed measurements of dune profiles were carried out at Letitia 1 (see fig. 2 for location) using an underwater frame to provide a fixed reference - see fig. 6. Bedform profiles were measured at slack water for a range of Spring and Neap conditions. Vertical and horizontal accuracy was ± 1-2 cm.

Figure 6 Underwater Bedframe

Typical profiles taken during Spring tide conditions are shown in fig. 7. Gross transport took place in the form of migrating dunes of typical amplitude 30-40 cm and 6 m wavelength in water depths varying from 2 m to 5 m across the estuary. During ebb tide the surface ripples migrated along the flat slope of the much larger dunes, passed over the crest and sand was deposited on the steep forward advancing face of the dune. In this manner the overall dune progressed downstream.

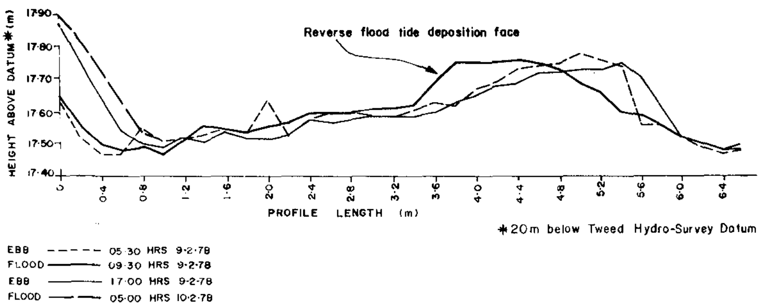


Figure 7 Dune Profiles at Letitia 1, Spring Tides

During the succeeding flood tide the ripples reversed and erosion of the downsteam face of the dune occurred. The eroded sediment then proceeded to move upstream on the back face of the dune as a much smaller depositional face - see fig. 7. The dunes always preserved their downstream orientation due to the dominance of the ebb tide at Letitia 1 but the small reverse flood tide dune face was always eliminated by the following ebb tide. Nasner (1976) observed similar behaviour with large ebb oriented dunes on the bed of the Weser River, Germany, (D50 0.3 to 0.7 mm). He attributed a decrease in dune height during flood tide to a flattening of the steep lee slope and deposition of the eroded material on the luff slope. Allen (1974) also refers to a re-activation face during tidal flows counter to the orientation of the bedforms.

3.4 Determination of Estuarine Sediment Transport Rates

The gross sediment bedload per ebb or flood half tide was calculated as the volume of accretion or erosion, respectively, which occurred on the front face of the dune between successive slackwater profiles. This transport rate represents the gross bedload flux across the dune crest, expressed in m^3/m crest width.

Initially the gross bedload (Qs) was calculated from profile measurements of a single dune using the bed frame (viz. 1.5 m x 6 m with 200 mm grid) and the results are shown in fig. 8A. However it was found that the bed frame could be replaced with a single line profile without significant loss of accuracy. The single line profile enabled accurate bed measurements over 20 m of river bed thereby allowing 3-4 consecutive dune profiles to be obtained. The gross bedload averaged over the multiple number of dunes is shown in fig. 8B. In addition the profiling was carried out simultaneously at three locations across the river width (viz. A, B. & C in fig. 8B).

The tendency for lower values of Qs in fig. 8A stems from the single dune measurement. It was recognised on each occasion that the dune was not the largest in the dune field and hence the calculated transport rates were less than the later and more representative rates of fig. 9B. It was concluded that fig. 8B was a more realistic measure of the bedload rate, however the general trends of fig. 8A would still be applicable.

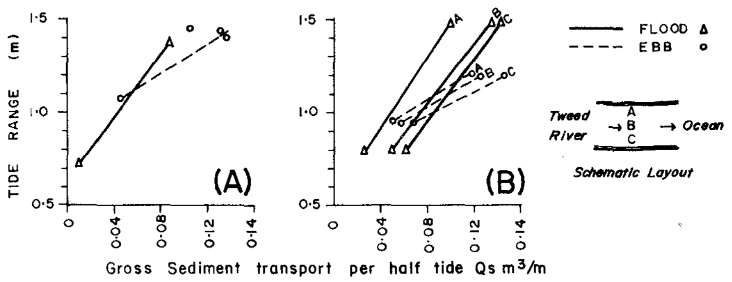


Figure 8 Results of Bedform Measurements at Letitia 1

4. DISCUSSION OF MEASURED BEDLOAD RATES

The peak gross bedload during Spring tides was measured to be 0.15 cubic metres/m/half tide which was approximately five times that for Neaps. Peak net transport was measured at approx. 0.1 cubic metres/m/day at Letitia 1 which is comparable to the bedload estimates obtained by Heathershaw and Carr (1974) from sand tracer studies in Swansea Bay, U.K., where sand transport took place primarily in response to strong tidal streams. Their studies indicated transport rates of 0.11 and 0.21 cubic metres/m/day in the deep and shallow areas of the bay respectively involving fine sands (D50 = 0.21 mm).

During Spring tides the difference between ebb and flood sediment transport was at its greatest loading to dune migration of up to 0.4 m per tide cycle. However during Neaps, conditions were near threshold and there was no substantial net transport of sediment and negligible dune migration.

Allen and Friend (1976) carried out continuous monitoring of dunes at Lifeboat Station Bank, Norfolk, U.K., over two consecutive Spring/Neap cycles and concluded that the largest "mature" dunes in a tidal dune field are tuned to the peak flow conditions at higher Spring Tides. Lesser tides had insufficient energy to significantly alter the dimensions of the mature dunes. If it is assumed that a fully developed tidal dune is functionally related to peak Spring Tide flow conditions, the work of Fredsoe (1979) can be applied. Fredsoe (1979) relates the ratio of dune height to wave length in alluvial conditions by the following expression:

$$h/L = 0.12\,(1 - 0.06/\theta - 0.4\theta)^2$$

where θ is Shields shear stress parameter viz:

$$\theta = \tau_b/(\gamma_s - \gamma)d = RSf/(S-1)d$$

where R is the hydraulic radius, Sf is the friction slope, s is the relative density of sediment and d is the mean grain diameter.

Using typical Spring values at Letitia 1 of R = 2.8 m at the dune crest during ebb flow, $Sf = 38 \times 10^{-6}$, S = 1.65, d = 0.0003 m implies:

$$\theta = 0.21 \text{ and } h/L = 0.048$$

The actual values of h/L for all dunes ranged from 0.037 to 0.05 with an average of 0.044. Furthermore it can be shown from Fredsoe's transport formula viz:

$$q = \left[(S-1) g\, d^3\right]^{0.5}\ 5\left\{1 + \left(\frac{0.267}{\theta - \theta_c}\right)^4\right\}^{0.25} \left(\theta^{0.5} - 0.7\theta_c^{0.5}\right)$$

where $\theta_c = 0{\cdot}05$

that the theoretical unit transport rate of a dune with θ = .21 is 0.19 cubic metres/m/hour i.e. approx. 0.38 cubic metres/m/half tide which compares with the peak values, inferred from field measurements, of 0.2 - 0.25. It appears that the work of Fredsoe shows promise for possible quantified interpretation of tidal bedforms.

5. MODELLING OF TIDAL HYDRAULICS

5.1 Model Development

Tidal stage and discharge were modelled using a one-dimensional numerical model based on the specified time version of the method of characteristics as developed by Fischer (1970). The model was calibrated using stage and discharge data from a full Spring tide cycle and verified against two sets of neap data. Even though the estuary possessed some complex branching it was found that the one-dimensional schematisation adequately represented the bulk flow characterictics. The Spring tide calibration and a neap tide verification are shown in fig. 9.

5.2 Impact of Dredging on Tidal Hydraulics

The calibrated model was used to hindcast the changes in tidal levels caused by the sand extraction. The propagation of a Summer Solstice Tide using 1977 bed geometry is shown in fig. 10. The progagation of the same tide based on the bed geometry of the most recent comprehensive survey prior to the dredging (i.e. 1971) is also shown.

Fig. 11 portrays the same behavioural trends as fig. 5 however it is valid to draw quantititive conclusions from fig. 10. The numerical hindcasting demonstrated that the dredging produced a pronounced increase in the tidal range throughout the lower estuary, the effect being more pronounced at low water. The increase in range of 7 cm on Terranora Broadwater and the lowering of low water by 25 cm inside Terranora Inlet are substantial changes and are consistent with the observations reported in Section 2. Harten (1980) describes similar effects arising from channel deepening associated with port development in a number of German estuaries. The dredging produced an increase in tidal range roughly apportioned as one third due to an increase in high water and two thirds due to lowering of low water.

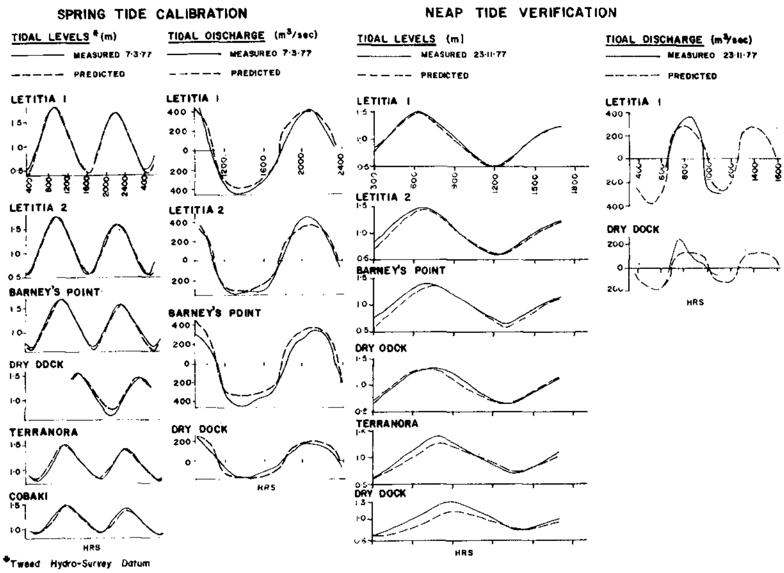


Figure 9 Numerical Model Calibration and Verification

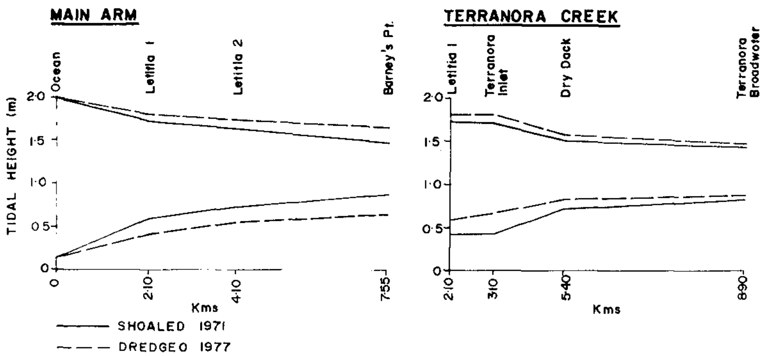


Figure 10 Predicted Tidal Propagation

6. MODELLING OF ESTUARINE SEDIMENT TRANSPORT

The foregoing numerical model of tidal hydraulics was incapable of assessing the recovery rates of the estuarine shoals or the long term impact of dredging on the estuarine sediment regime. Hence a sediment routing procedure was developed.

6.1 Selection of Transport Formula

Yalin (1976) undertook a fundamental examination of the transport of coarse bed material under conditions of oscillatory tidal flow and indicated that ebb and flood sediment transports can be viewed as separate unidirectional events. The result is a pattern of alternating, but intermittent, sediment motion. It was proposed that unidirectional theories could apply except near slack water where inertial effects become significant. Hence conventional formulae may be applicable during the bulk of the tidal cycle.

Based on a review of eight major transport equations by White, Milli and Crabbe (1975) the method of Ackers and White (1973) was adopted.

6.2 Sediment Transport Parameters

Friction Gradient (Sf)

The Ackers and White formula was developed from laboratory and field data under steady, uniform flow conditions in which the surface slope (Sw) and the friction slope (Sf) were identical. In order to facilitate the general application of the formula to tidal flows it was desirable to adopt Sw as the friction slope. Mehta et. al. (1976) concluded inertial effects were negligible except at slack water on the basis of field studies carried out on two tidal inlets of Florida. It was therefore considered that Sw was a reliable estimate of Sf for the majority of the tide during which sediment transport took place. When calculating the instantaneous sediment transport rate at any particular cross section the convention adopted was to set Sw equal to the water surface slope of the model element immediately upflow of the cross section.

Section Averaged Velocity

Initial predictions of sediment transport using the predicted cross section average velocity indicated no transport during low flow conditions such as Neaps. Even though net sediment transport approached zero during a full Neap tidal cycle, significant gross sediment transport occurred during each ebb and flood half tide - see fig. 8. This discrepancy occurred because the cross section average velocity in a 1 Dim. model will always be substantially less than the depth averaged velocity at any particular point. Hence an empirical correlation was established between the field values of depth averaged velocities and the predicted cross section average velocity. It was found that a single linear regression was sufficient to satisfy both Spring and Neap flow conditions at each gauging station.

6.3 Calibration of Gross Sediment Transport Rates

The individual bedload measurements at each Station A, B and C (see fig. 8B) were integrated across the river width and divided by the total cross section width to yield an average section transport rate per unit width. The result is shown in fig. 11. The general trend of fig. 8A was used to extrapolate fig. 11 at the higher tide ranges.

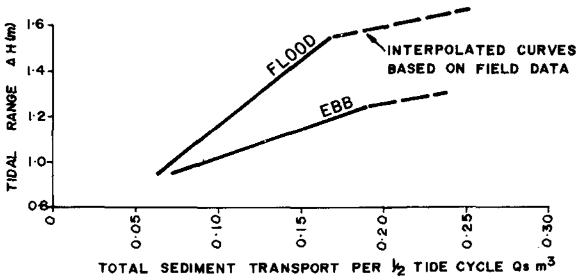


Figure 11 Integrated Bedload Transport Rates (Letitia 1)

A variety of tides of varying range were run through the numerical model to predict values of water surface slope and scaled velocities (at Letitia 1) at twenty minute intervals during each tide. Instantaneous sediment transport rates were calculated and a sediment flux curve was produced which was integrated with respect to time to determine the theoretical gross sediment transport for each half tide.

The theoretical gross transport rate per half tide was compared to the rate interpolated from the curves of field results for the same tidal range (i.e. fig. 11) - see fig. 12. It was found that the Ackers and White formula, using Sw and scaled velocities, gave reasonable results ($\pm$ factor of 50%) for Spring conditions. However the greatest deviation occurred as the threshold condition was approached and hence sediment transport was still significantly underestimated under conditions of marginal velocity or gradient.

The general trend of fig. 12 was used to adjust the procedure for calculating sediment transport rates viz.:

(a) If $.011 \leqslant P^1 \leqslant .15$

$$P = 0.36\, P^1 + 0.096$$

(b) If $P^1 > 0.15$ then

$$P = P^1$$

where:

P^1 = initial prediction of gross transport rate using Ackers and White with scaled model velocity, average depth and water surface gradient: cubic metres/m/half tide

P = Corrected prediction of gross transport rate: cubic metres/m/half tide

For values of $P^1 < .011$ a simple correlation with the peak velocity was developed. This corrected procedure for the calculation of sediment transport was used for all locations throughout the estuary.

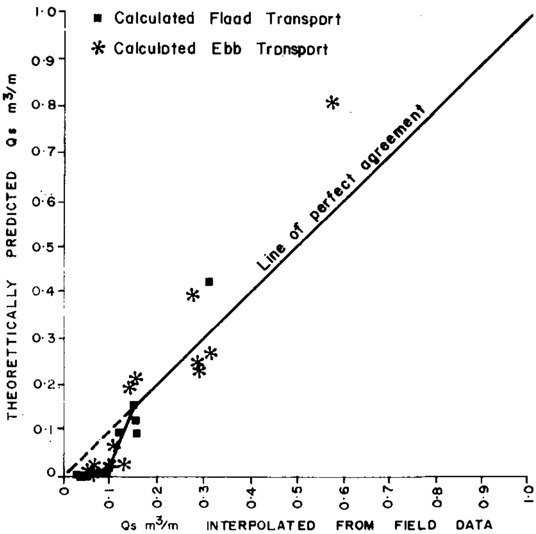


Figure 12 Comparison of Calculated and Measured Transport

6.4 Verification of Calibrated Transport Formula

Infilling of the dredged area during 1977, by the downstream transport of sediment, was predicted by the following procedure:

(i) The Spring-Neap cycle at the River mouth was divided into six representative, symmetrical tide cycles of varying tidal ranges R_i - see fig. 13.

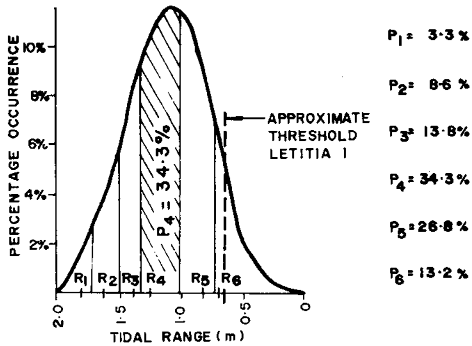


Figure 13 Annual Occurrence of Tides at Tweed Entrance

(ii) The net sediment transport of each tide, q_i, was calculated at a number of locations throughout the estuary.

(iii) Each representative tide cycle was assigned a size band within the 1977 tidal frequency curve. The relative percentage occurrence of each band, P_i, was determined as the proportional area under the curve.

(iv) The annual transport of sediment at each particular location was calculated as:

$$700 \sum_{i=1}^{i=6} q_i \, P_i$$

where 700 is the number of tide cycles in one year.

The predicted total estuarine transport of sediment moving downstream in the Tweed main arm and Terranora Creek was 8,300 m^3 which is in reasonable agreement with the quantities of estuarine infill determined from hydrographic surveys (see Section 3.1). In addition the directions of net transport throughout the estuary agreed with all direct and indirect lines of evidence. This will be discussed further in the next section.

7. PREDICTED ESTUARINE SHOALING RATES

The impact of the nourishment dredging on the broad pattern of shoaling in the estuary by tides alone (i.e. ignoring the short term effects of floods and cyclones) was investigated with a sediment routing technique. The sediment routing incorporated interaction of bed levels with flow.

Except at the estuary mouth the predicted annual sediment transport values were increased by a factor of five to produce a coarse five year routing step. Because of the complexity of wave and current interaction at the entrance and the presence of strong secondary currents on the entrance bend, the predicted peak velocity and gradient were used to calculate an index of net sediment transport potential at the estuary mouth. When applying the first sediment routing step this index was assumed to represent the measured entrance sediment infeed rate of 93,000 m^3 p.a. (see Table 1). The entrance sediment infeed for all subsequent routing steps was reduced proportionately according to the predicted reduction in this index.

At the end of each five year routing step the channel geometry was reschematised according to the volumes of net accretion or erosion in each sediment routing compartment. Throughout the sediment routing it was necessary to assume that the empirical velocity scaling factors did not vary in time. The results are shown in fig. 14. While the results are not good for strict accuracy they do provide insight into the broad behavioural patterns of sediment movement and shoaling under pure tidal influence.

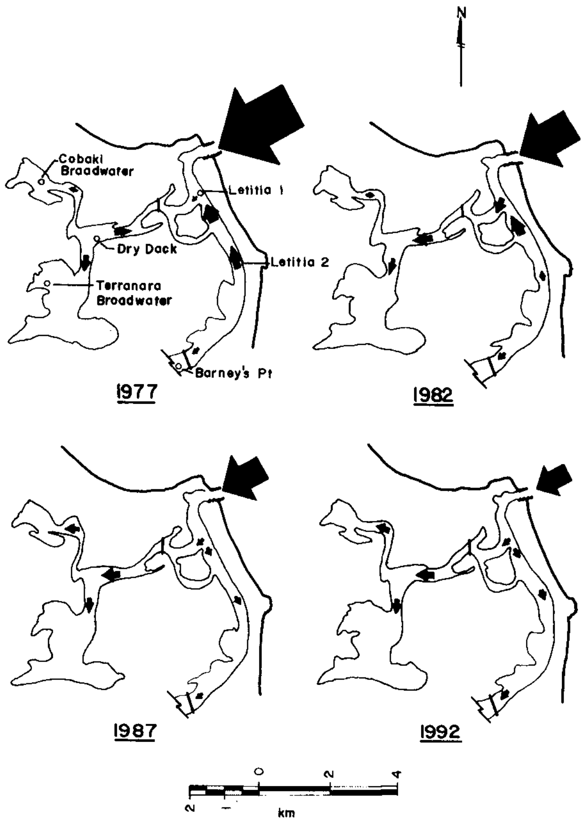


Figure 14 Results of Sediment Routing

7.1 Discussion of Predictions

Immediately after dredging (1977) there is a strong infeed of sand through the entrance. Immediately upstream of the dredged area the net sediment transport is downstream in both arms of the River.

By 1982 the dredged area is approx. 60% infilled and the impact on estuary flows is substantially reduced. Sediment reversal in Terranora Creek has occurred because the dredged area no longer has a significant influence on tidal flow patterns. Similarly in the main arm, at Letitia 2, the effect of the dredging on the sediment transport has diminished.

By 1987 the dredged area is completely restored and complete sediment transport reversal has taken place in the main area.

By 1992 the estuary is very shoaled due to continued sand feed (at a greatly reduced rate) from the entrance. The shoaling is causing considerable head losses in the lower estuary leading to a damping of velocities and gradients in the upper estuary where the net sediment transport is weakly directed upstream. The presence of the broadwaters in Terranora Creek helps to maintain relatively steeper gradients and higher sediment transport rates.

An interesting feature of these behavioural predictions is that the dredging produced a temporary reversal in the direction of net sediment transport immediately upstream of the dredged area. In the main arm this effect was predicted to extend upstream to some region between Letitia 2 and Barneys Point. Although no bedfrom survey was carried out prior to the dredging, partial verification of the predicted reversal point is shown in fig. 15. Further verification came from a careful study of all available aerial photography by Druery and Curedale (1979) which demonstrated that shoaling in Terranora Creek, near the Boyd's Bay fishing harbour, was due to the downstream movement of a shoal which had been stable for twenty years prior to any dredging of the lower estuary.

8. ESTUARINE SHOALING MECHANISMS

A detailed breakdown of the quantitative results of the numerical simulation of estuarine sediment dynamics is given in fig. 16 for a Summer Solstice tide. These will be discussed in order to obtain a better understanding of the hydraulic mechanisms involved.

8.1 Detailed Discussion Letitia 2

In Section 5.2 it was demonstrated that the immediate impact of the dredging was manifest as a drop in low water level and an increase in high water, the effect being more pronounced at low water. So, as the dredged area infills with time a progressive decrease in high water and a progressive increase in the level low water would take place. This is indicated by the decrease in the depth at peak flood tide velocity and the increase in depth at peak ebb tide velocity.

In terms of peak velocity at Letitia 2 there would be a tendency for the peak ebb velocity to decrease due to the increased depths and the opposite for the flood tide where velocities would tend to increase because of the decreasing depth. However there must also be an overall trend for reduction in velocities due to the decreasing peak discharge. Hence the depth effect results in the flood velocity decreasing to a much lesser extent that the ebb velocities.

Peak surface gradients show a decline with shoaling due to damping of the tidal wave but the peak flood gradient always remains higher than the peak ebb gradient.

The gross sediment transport per half tide is greatest on the ebb, initially, due to the depth effect providing greater enhancement of the ebb velocities. Hence there is net ebb oriented sediment transport. As the dredge area shoals, ebb velocities decrease due to the depth effect, both gradients diminish and the flood tide transport begins to dominate. So as shoaling takes place the net sediment transport reverts to the long term trend which is a weak net upstream movement of sediment.

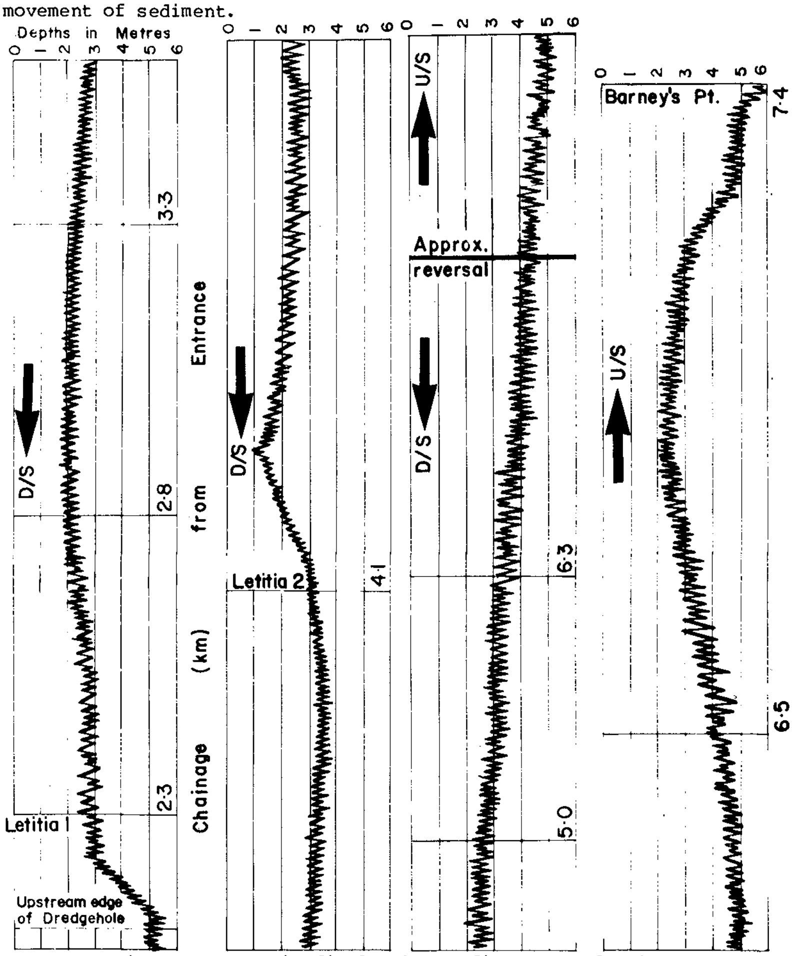


Figure 15 Longitudinal Echosounding Plot of Main Arm
Showing orientation of bedforms. Note reversal between Letitia 2 and Barney's Point.

8.2 Terranora Broadwater

Looking quickly at Terranora Creek it is apparent that the presence of the broadwater suppresses any potential change in water levels and hence there is no significant depth effect. Velocities diminish at an equal rate in proportion to the decreasing discharge. The flood velocities and gradients are always greater than the ebb due to the different shapes of the discharge curves. Hence the overall trend is a net transport into the broadwaters.

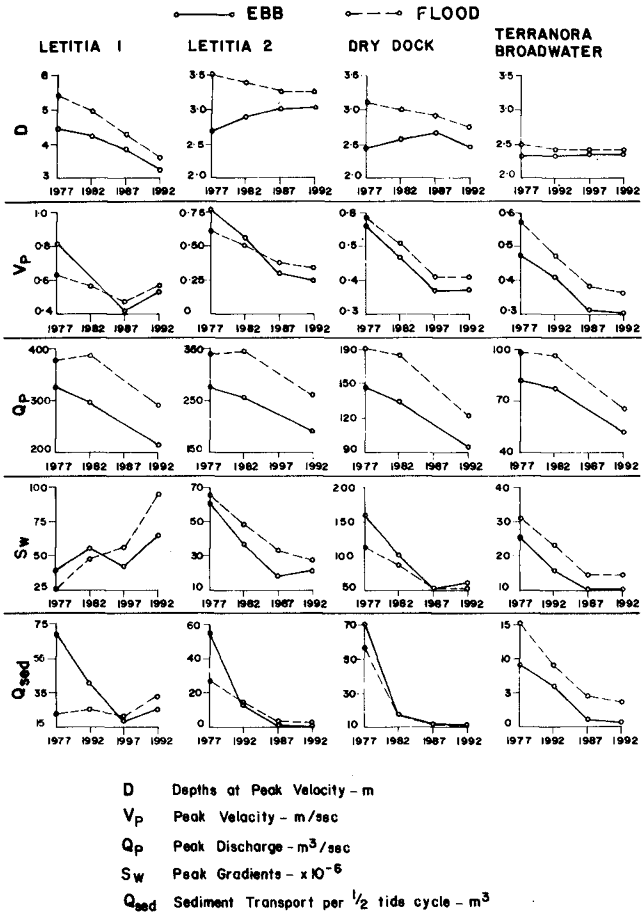


Figure 16 Variation of Hydraulic Parameters Due to Shoaling

8.3 Letitia 1

The picture is more complex at Letitia 1 because it is situated in the area of shoaling and this is reflected in the decreasing depths at both peak flows. Nonetheless a subtle enhancement of the peak flood velocities is discernable. Peak gradients increase due to the increasing head losses in the lower estuary, the flood gradient more so than the ebb. Ultimately the net transport reverts to the long term trend i.e. weak upstream movement of sediment.

9. CONCLUSIONS

(1) Tidal propagation in a shallow estuary is very sensitive to the ruling channel depth within the initial 2-3 kilometres of the estuary. The extraction of 760,000 m^3 of sand from the initial 2 km of the Tweed River had a significant effect on tidal levels and sediment dynamics throughout the estuary.

(2) The dredging affected sediment movement for a distance of 3 km upstream in the main arm and 6 kms upstream in Terranora Creek.

(3) Infilling of the dredged area initially took place at 100,000 m^3 p.a. of which 85% was marine sand brought in through the entrance and 15% was derived from reworking of upstream estuarine sands.

(4) In the long term the sediment transport throughout the estuary should trend towards a weak upstream movement of sediment.

(5) The detailed monitoring of large scale bedforms can provide practical values of gross sediment transport rates provided the bed material is sandy and the transport mode is entirely bedload.

(6) Sediment transport rates under Spring tides were five times that of Neap tide.

(7) Points of reversal of net sediment transport were predicted and observed in the Tweed River. These are considered to be indicative of non regime conditions.

(8) The hydraulic and environmental impact of large scale dredging in estuaries can be significantly reduced by location well upstream of the entrance.

(9) Further field studies are needed to verify the broad behavioural trends predicted in this study and to evaluate the effect of floods and cyclones on estuary shoal regime.

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