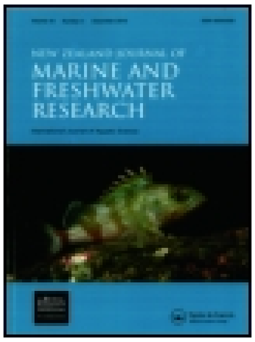

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Sediment transport near the Tauranga Entrance to Tauranga Harbour

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ABSTRACT

Sediment transport at the Tauranga Entrance was studied in relation to tidal currents and waves. Bedforms resulting from tidal flow were investigated with scuba divers and echo-soundings. The alignment and scale of bedforms indicated the direction and approximate rate of sediment transport. Sediment transport was measured directly using sediment traps, and results were compared with rates calculated by another method. Maximum sediment transport rates of 20 000–30 000 $g.m^{-1}$ per half tidal cycle occur near the inlet gorge, but rates vary considerably in time and space, depending mainly upon power of tidal currents. A model of sediment transport for this inlet has been evolved based on tidal flow streamlines, bedform features, and the measured and calculated rates of sediment transport.

INTRODUCTION

Tauranga Harbour is a large coastal lagoon impounded by a Holocene sandy barrier island and tombolo system. The Tauranga Entrance is a tidal inlet linking the lagoon to the sea (Fig. 1). Tidal range within the harbour is about 2 m, and this generates tidal currents in excess of 350 $cm.s^{-1}$ through the entrance.

Even in well-controlled laboratory conditions, sediment transport is a complex process which has, as yet, defined rigorous mathematical treatment. In tidal estuaries sedimentation is an even more complex process.

This paper reports the results of initial investigations into sediment transport by tidal currents and waves at the Tauranga Entrance in 1974–75.

TIDAL CURRENT STREAMLINES

Tidal currents and waves dominate the hydrodynamics of the Tauranga Entrance. Despite the importance of waves, the net movement of sediment is probably more dependent on tidal currents.

Tidal currents were monitored at 1 m above the harbour bed at nine of the ten oceanographic stations (Stns I–X) and at Stns M, S, T, and W in Fig. 1. The continuous records of tidal current velocity illustrate their temporal asymmetry, and indicate whether the ebb or flood tide will dominate (see Davies-Colley & Healy 1978, table 1).

Drogues have been tracked by the Bay of Plenty Harbour Board, mainly during the 1960s, to delineate patterns of tidal currents near the Tauranga Entrance. Drogues consisted of a small marker buoy connected to a large subsurface structure which moved with the "average" water particle in the water column. Using Harbour Board data the resultant streamline patterns are illustrated in Fig. 2. Notably:

(i) Most stations exhibit reversing tidal currents but at many points directional asymmetry is appreciable with maximum ebb and maximum flood currents not at 180°.

(ii) Eddy systems break off from the main tidal jet through the inlet gorge on both the ebb and flood tide. These recirculatory currents are too weak to cause bedload transport.

(iii) At the seaward end of the inlet gorge, ebb currents are stronger than flood currents while in the harbour flood currents are more powerful.

The sediment transport pattern inferred from the tidal flow pattern and other evidence is discussed below.

BEDFORMS AND BOUNDARY LAYER FLOW

Bedforms are wave-like structures formed at the mobile sediment/water interface, and characterised by their height and wavelength. Allen (1968) defines two main scales of bedform, namely ripples and dunes.

Whether ripples or dunes will develop is dependent on the boundary layer flow conditions, characterised by the grain Reynold's Number, $u_* D/v$ where u_* is shear velocity, D is grain diameter, and ν is kinetic viscosity. The boundary is smooth if the roughness elements on the bed (large grains) are submerged under the laminar sublayer of thickness $\delta_s >> D$ (Yalin 1972), and rough when these roughness elements break up the laminar sublayer. On well-sorted sand beds with a grain size less than about 0.7 mm (0.5 ϕ) flow is smooth even after the critical erosion velocity for sediment

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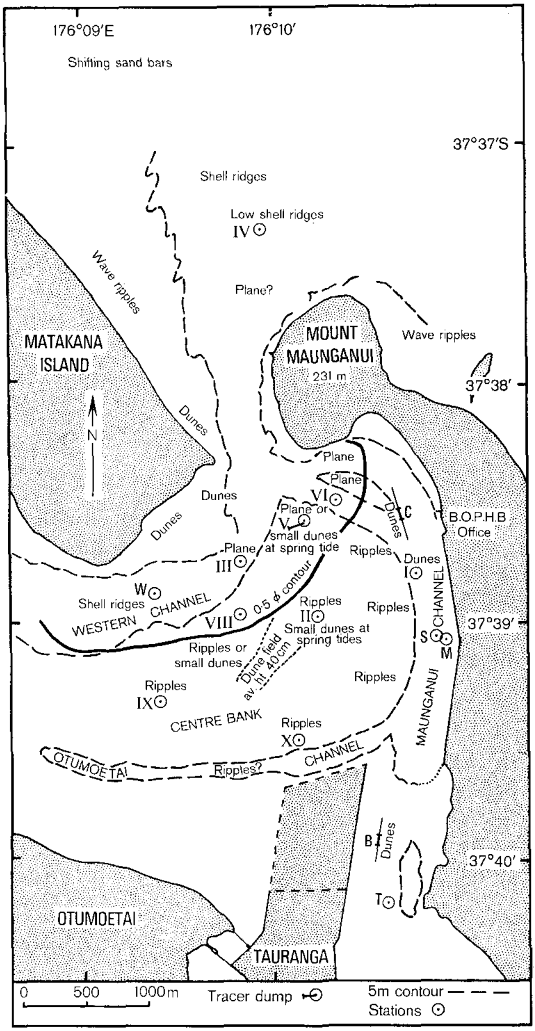

FIG. 1—Map of the study area showing the location of stations and the occurrence of various types of bedform, 1975.

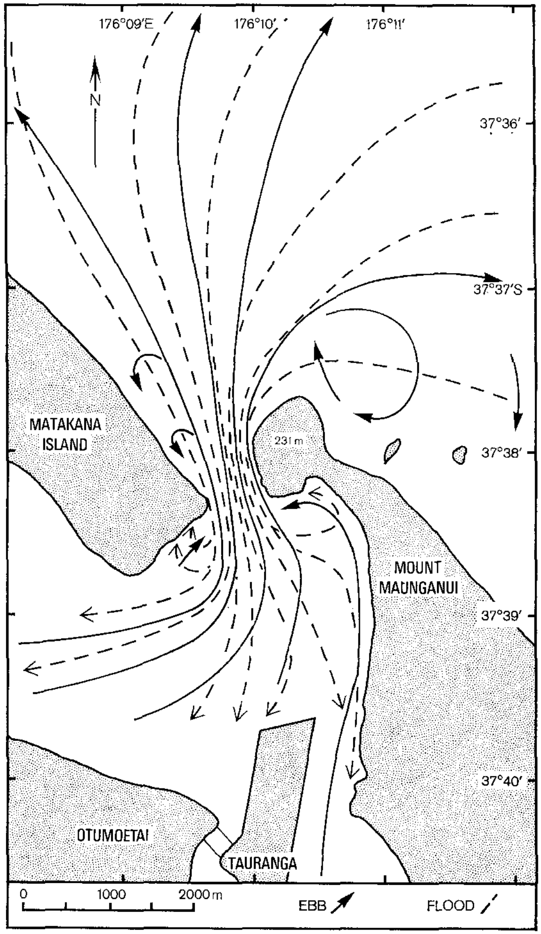

FIG. 2—Streamline diagram of peak ebb (*solid arrows*) and flood (*broken arrows*) tidal currents based on drogue tracking, mainly in the 1960's. The thickness of the lines indicates relative current strength.

transport has been reached. Bagnold (1956) has shown how a plane bed under these conditions is inherently unstable and ripples appear as the bed attempts to develop form roughness. Flow over sediment beds composed of grains coarser than 0.5 ϕ becomes hydraulically rough before critical erosion velocity is reached, and no bedforms develop until the flow is sufficiently powerful to develop dunes.

Kennedy (1969) argued that dune bedforms are related to periodic perturbations in transport of suspended sediment (which requires a rough boundary for turbulent entrainment) while ripples are related to periodicity in bedload transport.

Bedforms are normally asymmetrical in profile with a low-angle stoss side and a lee side steepness up to the angle of repose of the sediment. Grains move up the stoss side of bedforms and avalanche down lee sides. Bedforms formed by oscillating flow, such as waves and tidal currents, may reverse in direction with each reversal of the current. Wave ripples frequently have a symmetrical profile where there is little or no net sediment drift (Allen 1968).

The occurrence of bedforms observed in 1974–75 is shown in Fig. 1, with the 0.5 ϕ contour for mean grain size of the total sediment samples (carbonate plus non-carbonate content) superimposed. Ripples occur only on the finer side of this contour line, except for localised concentrations of finer material near harbour beaches.

Divers observed that, at slack water, current ripples are almost ubiquitous in areas of sediment finer than 0.5 ϕ near the Tauranga Entrance, and that they are reversed in direction when the tide turns. As the current accelerates, initial sediment motion is at the ripple crests where the fluid drag stress is greatest.

Some areas of sediment finer than 0.5 ϕ are subjected to currents sufficiently strong to develop dunes near mid-tide. Near Stn I (Fig. 1) divers observed that ripples are "washed out" and dunes begin moving when the current increases to the point where the boundary becomes rough, and fine sediment is thrown into suspension. Ripples reform in response to the waning currents near slack water and are observed superimposed on the dunes at high or low tide.

Dune-scale bedforms on the harbour bed have been identified by echo-sounding surveys using the Harbour Board's survey boat, *Kairuri II*, equipped with a Kelvin Hughes MS-36 instrument with a 14° divergence conical sonic beam. The approximate locations of known dune fields are shown in Fig. 1; others could exist. Fig. 3 shows that dunes at three locations range from 20–60 cm in height and about 6–20 m in length and are of a similar scale and morphology to those reported for tidal estuaries elsewhere by Salsman *et al.* (1966), Allen (1968), Gellatly (1970), and Klein (1970). Bedforms in Traces A and B and to a lesser extent C are asymmetrical and ebb oriented, although the runs were made near high tide. This suggests that the large scale bedforms do not reverse with turn of the tide at these localities, and that sediment transport is strongly asymmetrical, with the ebb dominating.

In Trace C the echo sounder lacked resolution for small scale detail, giving a rounded appearance to the dune profiles. A narrower beam instrument would be necessary for resolution of the details of dune morphology in water depths greater than about 5 m.

Dunes composed of shell gravel observed by divers in the deeper channels range from about 10 cm to over 1 m in height, but do not show up on echo-sounder records since water depth is too great for resolution of bottom detail.

The survey of bedforms has provided much information about sediment transport. In particular:

(i) The type of bedform indicated which flow processes were operative in the boundary layer currents. Wave ripples were distinguished from current ripples by their morphology.

(ii) The scale of the bedform, that is, whether ripple or dune, is a function of fluid power and hence of the rate of sediment transport. Allen (1968) quoted approximate ranges of sediment transport associated with the two main scales of bedform:

ripples: 1.6–16.0 $g.m^{-1}.s^{-1}$
dunes: 16–640 $g.m^{-1}.s^{-1}$

(iii) The orientation of the bedform indicates the direction of sediment transport. In the case of dune bedforms, which are not usually rebuilt to any extent in the direction of the weaker tidal current phase, the orientation indicated net transport direction of sediment over a tidal cycle.

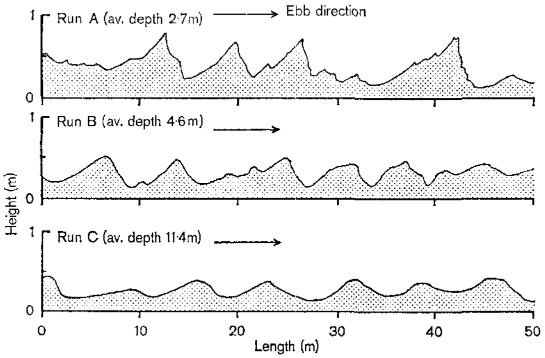

FIG. 3—Profiles across dune bedforms at three locations in Tauranga Harbour, August 1975 (Runs B and C are shown in Fig. 1, Run A is in Otumoetai Channel just west of the map limits). Note the superposition of smaller bedforms on the dunes in Run A.

SEDIMENT TRANSPORT

Three other approaches were made to the problem of estimating direction and semi-quantitative rates of sediment transport near the Tauranga Entrance:

(i) Fluorescent tracing,
(ii) Direct monitoring using sediment traps, and
(iii) Theoretical calculation of sediment discharge using Bagnold's (1956) bedload formula.

FLUORESCENT TRACING, MAY 1974

A sediment-tracing experiment was carried out near Stn V (Fig. 1) using natural harbour sediment coated with a dye which fluoresced red-orange under ultra-violet radiation. Tracer movement from the dump line (Fig. 1) was monitored by sampling on a grid system. Tracer recovery was low because of rapid sediment transport even on a tide of relatively small range (about 1 m; mean spring tide range is 1.66 m). However, almost all tracer grains recovered after two complete tidal cycles (25 h) from the dump-time had moved in the flood direction up to 800 m, proving that net sediment transport is flood-directed in this area.

SEDIMENT TRAPS

Three different devices were used for trapping mobile sediments (Fig. 4). These samplers have been described in greater detail by Davies-Colley (1977), except for the two-way sand trap or "flip-flop" sampler. This trap consisted of two separate compartments, one to trap sediment moving on the flood tide and the other to trap sediment moving on the ebb. Separating the two compartments was a gate pivoted along the dividing wall and connected to a vane projecting up into the boundary layer currents. This vane was controlled by water pressure so that the gate switched over on reversal of the tidal currents, thus directing sediment into the other compartment. The trap was installed by divers at

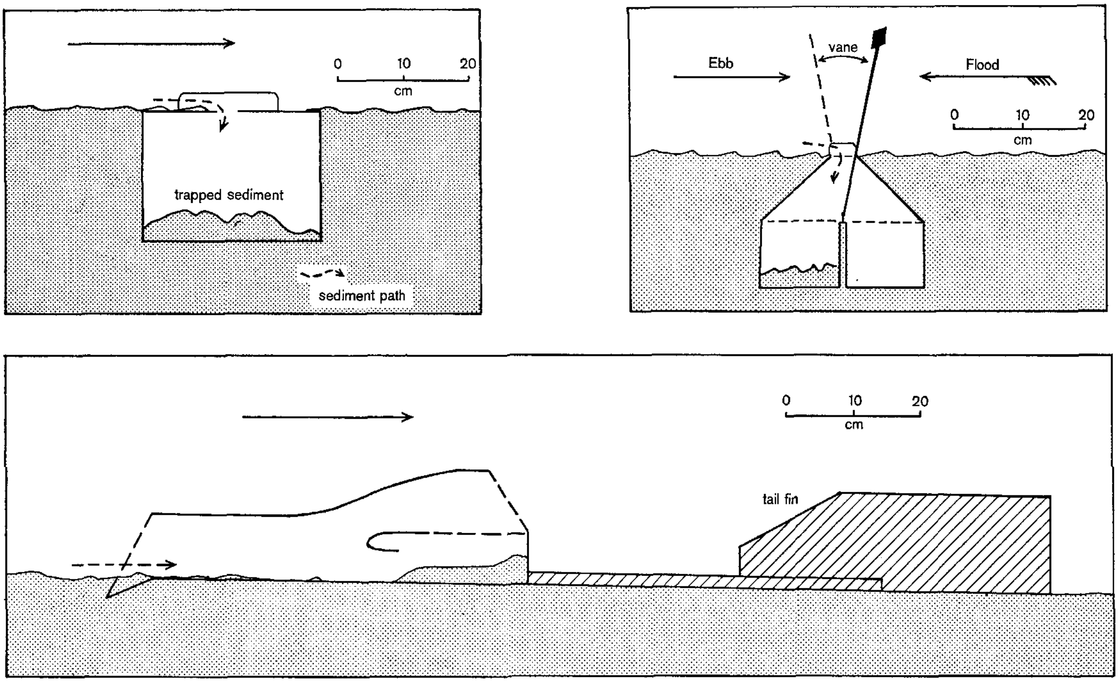

FIG. 4—Traps used to catch bedload sediments in this study: (*upper left*) Simple pit trap; (*upper right*) two-way sand trap or "flip-flop" sampler; and (*lower*) remote bedload sampler, which can be lowered on to the sea floor from a boat. The tail fin aligns the sampler to the direction of maximum flow.

slack water and left for two tidal cycles. Results are presented in Table 1 and discussed below.

CALCULATION OF SEDIMENT DISCHARGE

Sternberg (1972) presented a method of calculating rates of sediment transport in the marine environment using Bagnold's (1956) bedload discharge formula:

$$\{(\rho_s - \rho)/\rho_s\}\ gj = K\ \rho u_*^3 = K\omega$$

where j is sediment discharge, ρ_s and ρ are sediment and fluid densities respectively, g is gravitational acceleration, ω is available fluid power, u_* is shear velocity, and K is a proportionality coefficient. Sternberg's method was used with the following basic data:

(i) The standard mean spring tidal current curve, $\bar{U}_{MST}(t)$, and

(ii) The sediment mean grain size, M_z, corresponding to a critical erosion velocity U_{cr} (see Davies-Colley & Healy 1978).

The rates of sediment transport $j(t)$, with units of Mass.Length^{-1}.Time^{-1} corresponding to each measured value of $\bar{U}_{100}(t)$ (the tidal current curve as recorded at 100 cm above the bed), were integrated to give values of sediment discharge for the flood, J_{flood}, and for the ebb, J_{ebb}.

Since tidal currents are approximately proportional to tidal range, and sediment transport is proportional to the cube of current velocity, sediment transport is markedly dependent on tidal range. Thus for comparison the above calculations were carried out for both a mean spring (1.66 m) and mean neap (1.21 m) tidal ranges.

Measured and calculated values of J_{ebb} and J_{flood} are presented for comparison in Table 1. Unfortunately, sediment discharges could only be calculated at Stns I, II, V, and IX. At other stations either no full tidal cycle record of currents was available or critical erosion speed $\bar{U}_{cr}$ could not be estimated because of poor sorting or bimodality of the sediment (Davies-Colley & Healy 1978).

Station I: Ebb sediment transport was slightly greater than flood transport. Calculated rates of transport of bedload sediment are certainly underestimates of total sediment transport, since there was substantial transport of suspended sediment over dune bedforms at this station.

Station II: Flood transport dominated at this station. Agreement between sediment trap records and calculated values was reasonable, considering that the tidal range was rather higher than the mean spring range. Theoretically, no sediment transport occurs on an ebbing neap tide at this station.

Station III: No records obtained.

Station IV: No calculation was made, but one sampler record suggested slight sediment transport on both tides due to wave surge, which was also observed by divers during installation of the trap.

TABLE 1—Measured and calculated sediment transport rates, J in Tauranga Entrance, 1975. Rates are given in grams per metre per half tidal cycle, i.e., for the flood or ebb tide (tidal range at time of installation of sediment traps is given in parentheses; – = no data; * = Pit Trap set near the crest of a dune; † = trap container overfilled; ‡ = wave action observed; ? = probable malfunction of sediment trap. The stations referred to are located on Fig. 1; no data were collected at Stn III.)

Stn	Tide Phase	Pit Trap	Bedload Sampler	Flip/Flop Sampler	Calculated J	
					Spring (1.66 m)	Neap (1.21 m)
I	Flood	–	–	–	300	40
	Ebb	12 000* (1.45)	980 (1.26)	–	1200	150
II	Flood	–	–	19 000 (1.8)	12 000	250
	Ebb	–	–	1500 (1.8)	160	0
IV	Flood	–	–	150‡ (1.6)	–	–
	Ebb	–	–	560‡	–	–
V	Flood	1100 (1.1)	490 (1.1)	1100? (1.6)	30 000	500
	Ebb	210 (1.45)	120 (1.45)	130 (1.6)	300	0
VII	Flood	–	0 (1.3)	210 (1.8)	–	–
	Ebb	–	350 (1.5)	1400 (1.8)	–	–
VIII	Flood	80 (1.1)	290 (1.1)	20 000† (1.6)	–	–
	Ebb	330 (1.45)	280 (1.45)	500 (1.6)	–	–
IX	Flood	–	–	5300‡ (1.6)	40	0
	Ebb	–	3700‡ (1.6)	3300‡ (1.6)	40	0
X	Flood	–	–	310 (1.6)	–	–
	Ebb	–	–	820 (1.6)	–	–

Station V: Flood transport dominated strongly, but transports measured with the two-way sampler and those calculated disagree strongly. Other measured rates are reasonable.

Station VI: No records obtained.

Station VII: No calculation was made, but measured values suggest that movement of bedload sediment may not be very great.

Station VIII: No calculation was made. The trap records from this station clearly demonstrate how dependent sediment transport is on tidal range. Loads retained by both the pit trap and the bedload sampler on a very small range flood tide were about two orders of magnitude smaller than that retained by a two-way trap for a tide with nearly a spring range. The catches of the bedload sampler and pit trap agreed closely for simultaneous flood and ebb installation.

Station IX: The dichotomy between measured and calculated estimates at this station is probably due to the effect of wave action entraining sediment in the shallow water at this station.

Station X: The sediment discharge on the ebb was slightly larger than on the flood, but rates are surprisingly low, particularly on the ebb in view of the relatively powerful ebb current at this station.

From these discussions of estimates of sediment transport for individual stations, the following generalisations can be made:

(a) Spring tide rates of sediment movement may exceed those at neap tide by up to two orders of magnitude.

(b) Sediment transport in the dominant direction of the tide may exceed that in the reverse direction by two orders of magnitude or more.

(c) Bedload sediment traps and bedload discharge calculations, while agreeing reasonably closely, may both underestimate rates if sediment is finer than about 2 ϕ and tidal currents are sufficiently strong to suspend this sediment.

(d) In shallow water, waves may act to entrain sediment which can then be transported by tidal currents moving at well below the critical speed, U_{cr}.

SEDIMENT DYNAMICS AND SEDIMENTATION

The various evidence for sediment patterns and rates of transport derived from tidal current observations and sediment analysis (Davies-Colley & Healy 1978), and tidal current streamlines, bedform mapping, and direct measurement or calculation of sediment transport, were used to construct a model of sediment dynamics for the Tauranga Entrance. Fig. 5 presents the main results of the research—sediment flow-lines and order of magnitude estimates of sediment discharge J (vector quantity) including bedload plus graded suspension load, where

$$J = J_{ebb} + J_{flood}$$

Inside the harbour, the two main tidal channels which merge at the inlet gorge are seen to be ebb channels with ebb-directed sediment transport, whereas the main flood transport paths disperse in a radial pattern across the main shoal area. A circulation pattern is evident: sediment transported south or south-east across the Centre Bank is deflected east and then north-east into the Maunganui Channel system, whence it returns to the inlet gorge. A much smaller amount of material returns to the inlet via the lower Western Channel.

Sediment jetted out of the inlet tends to move landward under wave action towards Matakana Island. South-easterly longshore drift of sediment along this part of the open coast seems likely (Davies-Colley unpublished 1976, Healy *et al.* 1977), and this movement, augmented by flood-tidal currents, moves sediment along the foreshore of Matakana Island and back to the inlet. Sediment moving as longshore drift from further up the Matakana coast probably moves east when it impinges on the harbour bar (outlined by the 5 m contour in Fig. 5) and then reverses direction and moves west along the southern side of the bar. Some flood tide-directed transport occurs along the northern side of Mount Maunganui.

Net sedimentation rate at any point can be related to the sediment transport vector, J in a continuity equation:

$$\partial y/\partial t = (1/\gamma)\ \nabla \cdot J$$

where $\nabla \cdot J$ is the *divergence* of the vector J, γ is the sediment bulk density and $\partial y/\partial t$ expresses the sedimentation rate. Sediment transport in the present context is considered as a vector projected on to a two-dimensional x-z plane (Fig. 5), so that the above equation reduces to:

$$\partial y/\partial t = 1/\gamma\ (\partial J/\partial x + \partial J/\partial z)$$

Sedimentation ($\partial y/\partial t > o$) will occur when the bracketed quantity in the above equation is negative.

Accurate magnitude estimates of J are not available; however, examination of Fig. 5 in the light of the continuity equation serves to explain why sedimentation has occurred in some areas and, to a limited extent, predicts future patterns of sedimentation. Two extreme cases can be recognised:

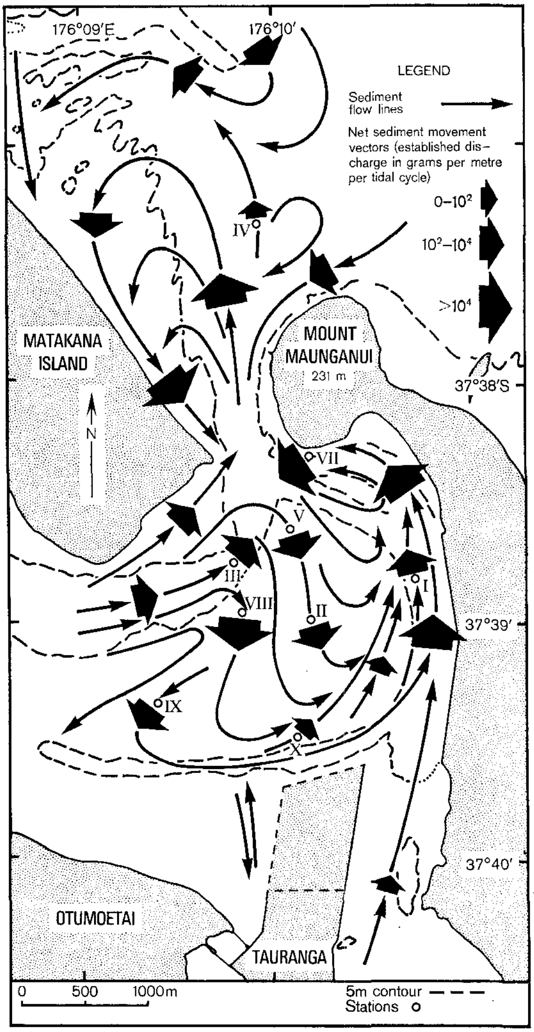

FIG. 5—Model of sediment transport patterns for the Tauranga Entrance based on tidal streamlines, bedforms, sediment discharge measurements, and theoretical calculations.

(i) J constant in direction but with changing magnitude:

(a) J increasing will produce erosion

(b) J decreasing will produce deposition

(ii) J constant in magnitude but with changing direction:

(a) Flow lines diverging will produce erosion

(b) Flow lines converging will produce deposition

Figure 5 suggests that most sediment transport in the study area is through-flow, that is $\nabla \cdot J = 0$. Thus the bathymetry of most points is in a steady state. Near the high energy tidal inlet, deviations from the steady state are (geologically speaking) rapidly adjusted when erosion or deposition occurs, leading to a return to a steady state bathymetry. The steady state may be upset by:

(i) Inputs of new sedimentary materials,

(ii) Changes in sea level, and

(iii) The effects of man.

Some morphological elements recognisable in the bathymetry of the study area (Davies-Colley & Healy 1978, fig. 3) can be explained with reference to the continuity equation for sediment flux. Panepane Point, a spit forming the eastern tip of Matakana Island, is immediately seen to be a site of deposition related to convergence of sediment flow lines. The Centre Bank shoal area, part of the flood tidal delta, is probably now in a near steady state, but originally developed due to decrease in magnitude of the sediment discharge away from the inlet, which more than compensated for divergence of the flow lines. Matakana Bank probably developed by convergence of sediment flow paths, and the ebb tidal delta was produced because of a rapid decrease in the magnitude of J away from the inlet channel. Shoaling along the west side of the Maunganui Channel is related to convergence of flow paths. The channels in the area were, of course, developed where divergence of flow lines or acceleration of transport rates produced scour.

CONCLUSIONS

The sediment dynamics of Tauranga Entrance are largely a function of tidal current asymmetry; wave action is important only in shallow areas. Three main lines of evidence made it possible to map directions and rates of sediment movement in the inlet area:

(i) Analysis of the tidal current streamlines for the Tauranga Harbour Entrance from drogue tracking; these data provided an initial basis for investigating flow patterns. The analysis showed that directional and temporal asymmetry is marked at most places,

(ii) Alignment and scale of bedforms, which indicated the direction and approximate rates of sediment transport, and

(iii) Direct estimations of sediment transport rates obtained from bedload monitoring and compared with calculations after Sternberg (1972). Maximum rates measured near the tidal gorge were about $20 \times 10^3\,g.m^{-1}$ per half tidal cycle, and occurred during spring tides. Maximum rates calculated exceeded $30 \times 10^3\,g.m^{-1}$ per half tidal cycle.

Sediment transport rates, when considered with sediment streamline patterns, suggest that most sediment transport in the entrance is through-flow, and thus that in the short term the bathymetry of most points is in a steady state.

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