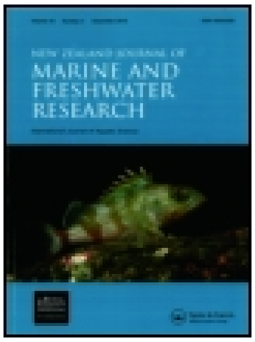

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Sediment and hydrodynamics of the Tauranga Entrance to Tauranga Harbour

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ABSTRACT

To relate the textural characteristics of the bottom sediments of a tidal inlet to hydrodynamics, 45 sediment samples from the Tauranga Entrance to Tauranga Harbour were analysed for textural parameters, and tidal currents and waves were monitored. Tidal currents dominate sediment transport processes near the Tauranga Entrance although swell waves are significant on the ebb tidal delta, and wind waves may influence intertidal sediments within the harbour. The bulk of the sediment is probably derived from marine sand from the Bay of Plenty continental shelf, but tidal currents and waves have changed its textural character. In areas of swift tidal currents, particularly in the inlet channel itself, sediment is coarser, more poorly sorted, and more coarsely skewed than that in areas of slower currents.

INTRODUCTION

Tauranga Harbour is a large lagoon system extending for about 40 km along the coast of the western Bay of Plenty, North Island, New Zealand. The lagoon has been impounded by a system of Holocene beach ridges comprising a barrier island (Matakana Island) and two tombolos connecting the volcanic cones of Mount Maunganui and Bowentown to the mainland. The harbour has two tidal inlets, one at each end of Matakana Island. The Tauranga Entrance at the south-eastern end of Matakana Island is the more important for navigation, being the entrance to the Port of Tauranga (Fig. 1). The nature and transport patterns of bottom sediments of the Tauranga Entrance as related to tidal currents and waves were investigated during this study. The only previous work on the hydrodynamics and sedimentology of Tauranga Harbour is the Wallingford Report (unpublished 1963), which was based largely on tests on harbour models.

BATHYMETRY

The essentially simple bathymetry of the inner continental shelf off the Bay of Plenty coast is interrupted opposite the Tauranga Entrance by an ebb

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tidal delta as defined by Price (1968). The delta has been formed by the loss of competency of sediment-laden currents jetting out of the inlet gorge and has been subsequently modified by wave action which has reshaped material into a harbour bar. A channel has been dredged across the tidal delta to a depth of 10.1 m below chart datum to improve shipping approaches to the Port of Tauranga (Fig. 1).

The large shoal known as the Centre Bank forms the main area of the flood-tidal delta within the inlet (Fig. 1). Most of the tidal volume exchanged through the Tauranga Entrance flows via the Western Channel, which merges with the other main channel, the Maunganui Channel, at the inlet gorge (which plunges to over 30 m depth). The artificial Cutter Channel was dredged in 1966 to deepen and extend a pre-existing blind flood channel across the Centre Bank for the purpose of improving the port approaches.

HYDRODYNAMICS

Tidal currents and wind generated waves dominate the hydrodynamics of the area. However, a variety of minor water movements also occur, including tidal wave surge, seiching, and estuarine circulation. Tidal wave surge (Phleger 1969) is the transmission of a part of the ocean tidal wave into a lagoon. In Tauranga Harbour it delays times of high water within the harbour and also delays the times of peak currents behind mid-tide. Transient estuarine circulation occurs after heavy rains when the normally low freshwater content of about 0.3% (Davies-Colley unpublished 1976) of the harbour is temporarily increased, and weak currents flow in response to salinity-density gradients. Seiching or harbour resonance has been occasionally observed in the harbour as an oscillation superimposed on automatic tide gauge records and may be produced by seisimc wave or surf-beat excitation at the harbour entrance, or by atmospheric pressure changes.

These weak or transient phenomena probably have little influence on sedimentation near the harbour entrance, and accordingly observations of hydrodynamical processes concentrated on tidal currents and waves.

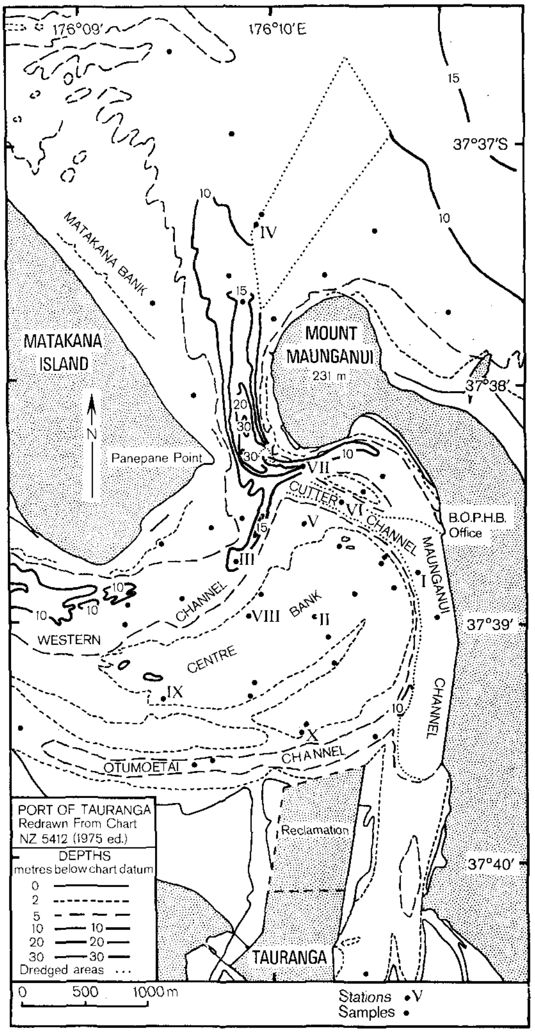

FIG. 1—Bathymetric map of the study area showing the location of sediment samples, 1974–75.

TIDAL CURRENTS

During 1974–75, tidal currents at the bottom were monitored 100 cm above the harbour bed at the stations denoted I–X in Fig. 2. Only peak ebb and flood currents were measured at Stns VIII and X, and no record was obtained at Stn VI, but at all other stations a full record of currents over one or more tidal cycles was obtained. M, S, W, and T are stations at which currents were previously monitored by the Bay of Plenty Harbour Board. The vectors in Fig. 2 represent the peak water velocities 100 cm above the bed in both the ebb and flood directions on a mean spring tide.

A small manually recorded Watts current meter mounted on a tripod 100 cm above the harbour bed was used for most measurements. Current speed was monitored as revolutions per minute, usually for five 1-min intervals. For comparability the mean currents were all expressed as expected values for a mean spring tide with the formula:

$$\bar{U}_{MST}(t) = (\text{Mean spring tide range/Observed tide range}, R) \times \bar{U}_{100}(t) \quad (1)$$

where $\bar{U}_{100}(t)$ is the bottom current measured at the time, t, on a tidal cycle with range, R, and $\bar{U}_{MST}(t)$ is the bottom current for a mean spring tide with a range of 1.66 m as measured at the Bay of Plenty Harbour Board Office. Values of $\bar{U}_{MST}$ (mean of five readings) are plotted in Fig. 3 as a function of time with vertical bars indicating 95% confidence limits.

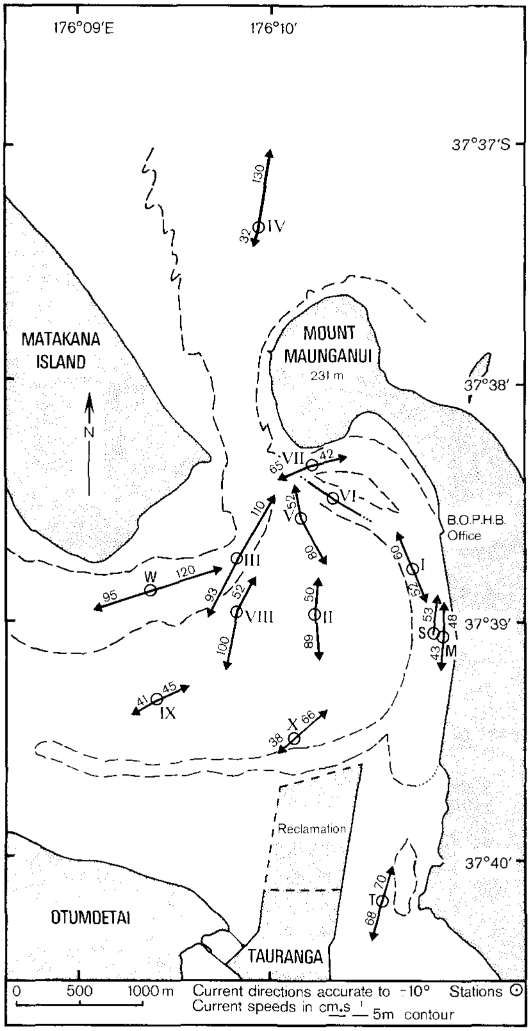

FIG. 2—Tidal current vectors at oceanographic stations for peak ebb and flood currents at mean spring tide, 1974–75.

Some records were obtained with an old type of self-recording current meter (an ONO meter) and data from these records are plotted as small circles.

The records of tidal currents show a nearly uniform phase relationship to the standard (mean spring) tide curve, peak currents occurring slightly after mid-tide on both the ebb and the flood. Most stations have a dominant tidal phase, for example at Stn III in the Western Channel, the ebb current reaches a higher peak speed than does the flood current. Very pronounced ebb dominant asymmetry occurs at Stn IV.

The effect of wind currents in shallow water can be appreciable. At Stn II, at a depth of only 0.6 m below chart datum, record A (Fig. 3) was obtained on a calm day whereas record B was taken during a 22 knot (40 $km.h^{-1}$) southwesterly wind. The ebb current in B was increased by about 10 $cm.s^{-1}$ through superposition of a wind current and correspondingly decreased on the flood until just after mid-tide (dashed line) when the wind calmed abruptly. Other stations were in water too deep for wind currents to be significant or else records were obtained on calm days.

The rather wide range (32–130 $cm.s^{-1}$) of peak bottom current speeds in Fig. 2 implies a very wide range of available current power, which is proportional to the cube of current speed. Such a marked variation in power from point to point would be expected to be strongly reflected by the texture of the bed sediments. Superimposed on some of the tidal current records in Fig. 3 are heavy horizontal lines representing the **critical erosion speed,** U_{cr} (at 100 cm above the bed), at which the sediment sampled at individual stations begins moving. Values of U_{cr} were estimated from the competency curve of J. Allen (1965) using mean grain size, M_z, (Folk & Ward 1957) at those stations with sediment satisfying the criteria:

(i) Fairly well sorted ($\sigma < 1.5\ \phi$); and

(ii) Unimodal.

Unfortunately, poor sorting and/or bimodality of the sediment precluded estimation of U_{cr} for Stns III and IV. At all stations some sediment transport occurs on spring tides for at least one phase of the tide. At Stn IV, where the flood current does not exceed 30 $cm.s^{-1}$, no flood transport occurs on a mean spring tide, since, although the critical erosion speed cannot be estimated in this case, it must be at least 37 $cm.s^{-1}$, which is the U_{cr} minimum in Allen's (1965) competency curve.

The relation of peak tidal currents at flood and ebb to the critical erosion speed indicates which phase of the tide will predominate in transporting sediment. Table 1 lists the inferred directions of net sediment transport.

WAVES ON THE OPEN COAST

Long term wave data for the Bay of Plenty coast is not available. However, waves opposite the Tauranga Entrance were observed by harbour pilots about three days in every week for a year 1974–75, and the data were used to plot the wave rose of Fig. 4.

Observed wave directions are assumed to be deep water directions, that is $L_0 < \frac{1}{2}h$, where h is the depth of water at the point of observation and L_0 is deep water wave length. Waves were observed in the dredged channel through the ebb tidal delta (Fig. 1) in depths exceeding 10 m, but as shown previously (Davies-Colley, unpublished 1976) directions of only the very largest waves are affected by shoaling transformation in this depth of water. For example waves with L_0 = 100 m, with crests aligned at 45° to the coastline in deep water will be aligned at 30° in 10 m of water.

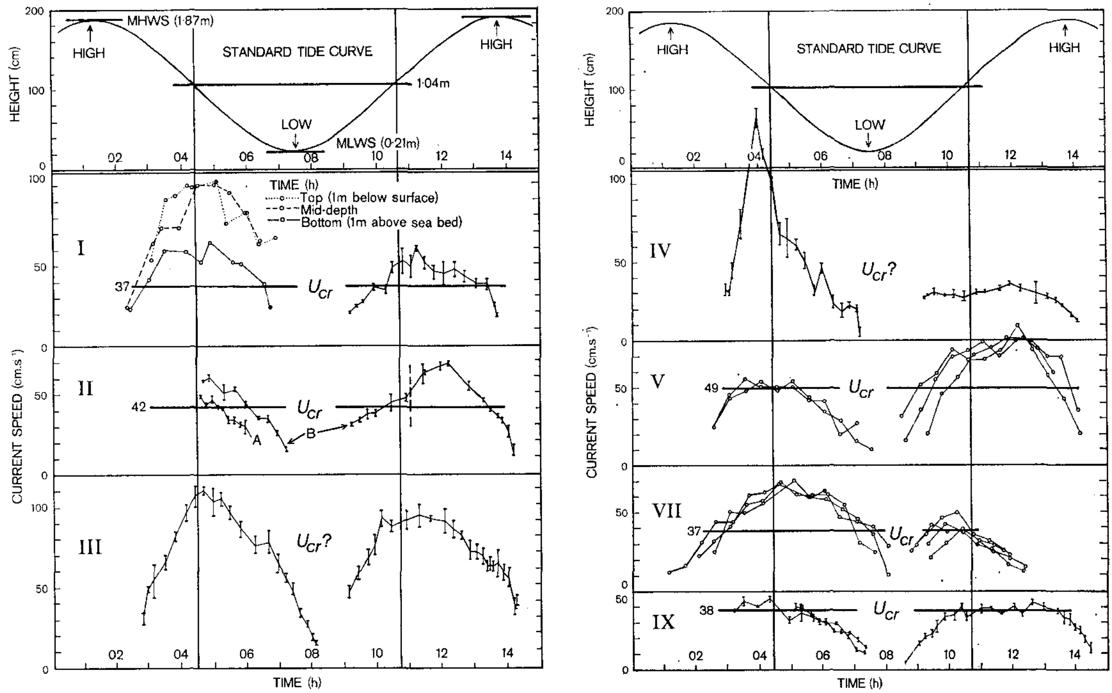

FIG. 3—Mean spring tidal currents (1 m above the harbour bed) as a function of time at seven oceanographic stations in Tauranga Harbour, 1974–75. Estimated critical erosion speeds (U_{cr}) are superimposed on the plots.

TABLE 1—Summary of parameters for tidal current stations in the Tauranga Entrance to Tauranga Harbour (Fig. 1). Capital letters in the last column indicate relatively high rates of inferred sediment transport. U_{cr} cannot be estimated at Stns III and IV, where sediment is poorly sorted and strongly bimodal, hence question mark. Dashes signify no data available.

Stn	Depth (m)	M_z (ϕ)	σ_I (ϕ)	U_{cr} (cm.s^{-1})	$\bar{U}_{MST}$ (*max*) Ebb (cm.s^{-1})	Flood (cm.s^{-1})	Net Sediment Transport
I	9	2.28	0.56	37	60	52	Ebb
II	0.6	0.87	1.12	42	50	65	FLOOD
III	11	−1.73	1.83	?	105	93	Ebb
IV	10	−1.84	2.71	?	120	31	EBB
V	3	0.27	1.54	49	52	75	FLOOD
VI	10	–	–	–	–	–	–
VII	13	1.99	0.65	37	65	40	EBB
VIII	1.1	0.11	2.04	51	52	101	FLOOD
IX	0.4	1.88	0.72	38	38	43	Flood
X	1.6	3.29	0.47	37	66	38	Ebb
W	8	–	–	–	110	95	EBB?
S	10	–	–	–	47	42	Ebb
M	10	–	–	–	55	–	EBB
T	4	–	–	–	70	55	EBB?

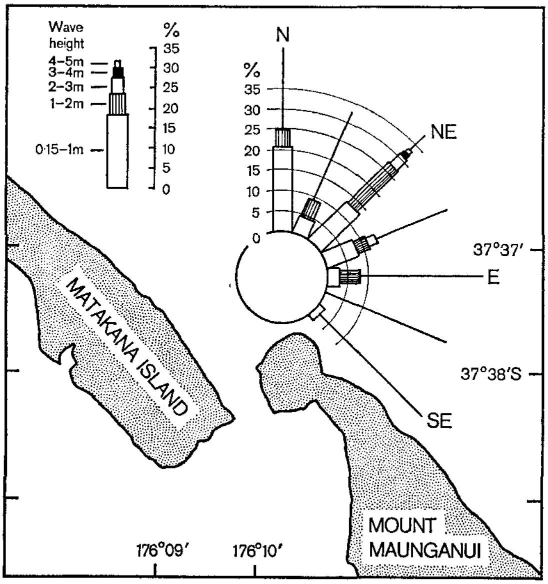

FIG. 4—Wave rose for the Tauranga Entrance showing the frequency of occurrence of various height classes and directions based on observations by Bay of Plenty Harbour Board pilots, 1974–75.

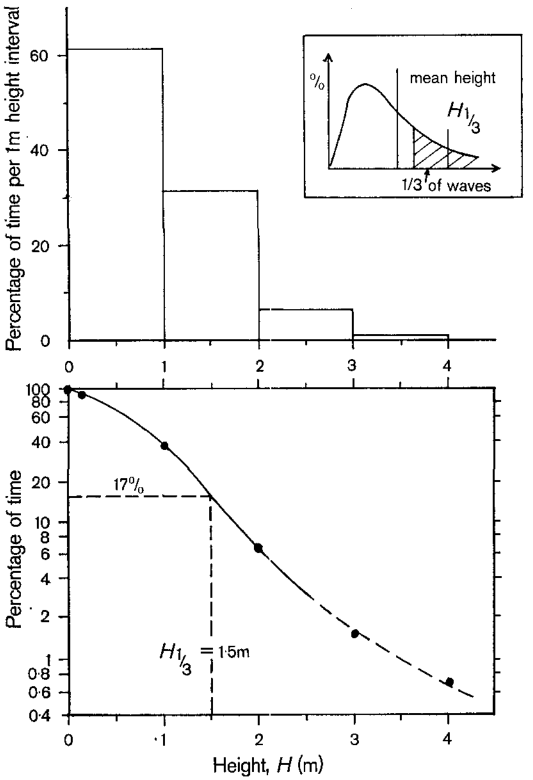

FIG. 5—(*Upper*) Wave height-frequency diagram for all wave directions at the Tauranga Entrance, 1974–75. The inset shows the Rayleigh law distribution of wave heights. (*Lower*) Exceedance curve for wave heights at the Tauranga Entrance, 1974–75.

The wave rose shows that calm conditions (waves less than 15 cm height) occur only about 11% of the time. Dominant wave direction is from the north-east, perpendicular to the coastline. A low northerly swell usually less than 1 m in height is particularly frequent, but higher waves probably arrive mainly from east of north-east. The direction of net littoral drift will depend on the direction of net 'along-shore' energy. Unfortunately, in the absence of records of wave period, littoral drift cannot be calculated easily.

The total percentage of waves from all directions is plotted against wave height in Fig. 5 (*upper*). Fig. 5 (*lower*) gives the percentage of time waves equal or exceed a given height. This exceedance curve is only approximate since the time span of the record is not long, and the Rayleigh-law spectral distribution of heights, as inset in Fig. 5, after Bretschneider (1966), makes it difficult to estimate mean height in a wave train.

The 'significant' height of a wave train (Sverdrup & Munk 1947) is the mean of the highest one-third of the waves, $H_{\frac{1}{3}}$. This concept can be extended to the exceedance graph, from whence $H_{\frac{1}{3}}$ is about 1.5 m. This is about the height (5 ft) of waves forecast from wind records in the Wallingford Report (1963) for Tauranga Harbour with a period $T \sim 6$ s and wave length, $L_o \sim 55$ m.

The bottom wave orbital velocity, u_o, at depth, h, can be calculated for $H_{\frac{1}{3}} = 1.5$ m in the equation (Bagnold 1963):

$$u_o = (\pi H/T) \;/\; \{\sinh\,(2\pi\, h/L)\} \qquad (2)$$

with deep water values adjusted for shoaling transformations. Fig. 6 shows the distribution of bottom orbital velocity with depth. Sand with mean grain size about 2ϕ will begin moving in about 18 m depth where $u_o = 18\ \text{cm.s}^{-1}$, and orbital semi-amplitude $r_o = u_o T/2 = 17$ cm. As most of the ebb tidal delta at Tauranga is shallower than 18 m, sediment on the bed of the delta is frequently mobile, entrained by waves, and moved mainly by tidal currents.

In water of 2.5–3.0 m depth the significant wave oversteepens and breaks, and intense sediment transport occurs, with grains suspended in the surging waters of the collapsed wave. Surf is frequent on the shallow harbour bar, much of which is less than 5 m in depth.

WIND WAVES IN THE HARBOUR

Westerly winds prevail in both strength and frequency at the Tauranga climate station, with south-westerly winds being of secondary importance. The east–west fetch is the longest in the southern harbour,

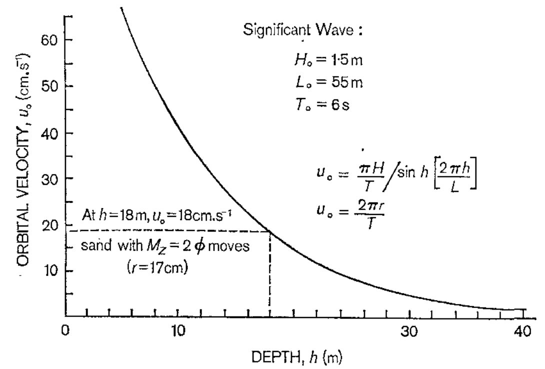

FIG. 6—Wave orbital velocity as a function of depth of water for the significant wave at the Tauranga Entrance.

thus westerlies generate the largest windwaves on the eastern harbour shores, where wave heights and directions were monitored at the Bay of Plenty Harbour Board Office (BOPHB) (Fig. 1). Wind wave heights were found to exceed 45 cm only about 2% of the time, and waves more than about 60 cm high are probably quite rare in the harbour, although occasionally they have been observed as high as 1 m under strong westerly winds at the eastern end of the Western Channel. For the significant wind wave at the BOPHB office with $H_{\frac{1}{3}} \sim 0.3$ m, ($L_o \sim 3.0$ m, $T \sim 1.35$ s) orbital velocity at the bed from equation (2) falls off very rapidly with depth, since the wave length is so short. At 50 cm depth, u_o is 56 cm.s^{-1}, at 1 m it is 19 cm.s^{-1}, and at 1.5 m it has fallen to only 6 cm.s^{-1}. Hence only in areas shallower than about 1.0–1.5 m will sand be affected by these waves. Windwave action is thus very dependent on the phase of the tide and is probably only significant on intertidal flats and harbour shorelines, and is largely negligible in subtidal areas. Waves are important in aiding entrainment in shallow waters in the vicinity of the inlet, but transport of sediment is mainly accomplished by tidal currents.

SEDIMENT SAMPLING AND ANALYSIS

Sediment samples from the locations shown in Fig. 1 were taken using a dredge designed specifically for the purpose of sampling coarse shelly material (Davies-Colley 1977). Sample positions were fixed with sextants.

In the laboratory, samples were wet sieved through a 4 ϕ (63 μm) screen to separate the mud fraction, which was then evaporated to dryness and weighed. After oven drying at 40°C, the coarse fraction was weighed and sieve analysed. The coarse fraction was then reconstituted and digested in 10% hydrochloric acid to remove shells and shell fragments before resieving. Grain-size distribution curves were plotted and parameters calculated after Folk & Ward (1957).

SEDIMENT CHARACTERISTICS

The bottom sediment of the Tauranga Entrance is mainly sand with a small gravel fraction of mollusc shells, shell fragments, and a very small proportion of pumice and rhyolite fragments. Mud content is generally very low (around 1%).

Shell content of the surface sediment of the bed in the inlet area is about 30% on average, but may be up to 80–90% in deep channels, where divers have observed lag gravel of shells with interstitial sand. Molluscs contributing to the shelly debris include *Paphies australe* (pipi), *Paphies subtriangulatum* (tua tua), *Chione stutchburyi* (cockle), and *Pecten novaezelandiae* (scallop).

The sediment is generally low in organic matter; about 0.5% by weight is typical. Most of this organic matter is contained in the fine (mud) fraction. The acid-insoluble component of the sediment is composed of about 50–55% volcanic glass, 25% sodic plagioclase, and 20% quartz with a minor content, perhaps 5%, of heavy minerals (mainly hornblende, magnetite, and hypersthene).

Most of the harbour sediment probably originated from marine sand derived from wave erosion on the Bay of Plenty continental shelf or from littoral drift along the Bay of Plenty beaches (Davies-Colley, unpublished 1976). This sand was derived originally from the acid volcanic rocks and tephra deposits of the harbour catchment and the Central Volcanic Plateau. The modal grain size of this marine sediment was probably in the fine to medium sand range (about 2 ϕ), but powerful currents in the vicinity of the Tauranga Entrance have reworked it and changed its textural character.

GRAIN-SIZE DISTRIBUTION

Figure 7 is a key diagram for the grain-size curves in Fig. 8 for sediment samples. For each sample, three curves are given:

(i) Percent by weight frequency curve for the total sample (dashed line),
(ii) Percent by weight frequency curve for the acid-insoluble fraction (continuous line), and
(iii) Cumulative percent by weight frequency curve for the acid-insoluble fraction plotted on probability paper (on which a cumulative normal curve plots as a straight line).

Percent by weight curves for grain-size distributions of total samples are generally unimodal, with varying degrees of sorting and skewness. However, Samples IV, VII, 17 and, to a lesser extent, III and 13, all from deep tidal channels, exhibit bimodality with a major second mode of gravel-sized material. Sediment in the size range between the two widely separated modes of these samples (coarse sand to fine gravel) has probably tended to be swept out of the channel areas and deposited on adjacent shoals. Meland & Norman (1969) showed that intermediate-sized grains in heterogeneous sediments are more

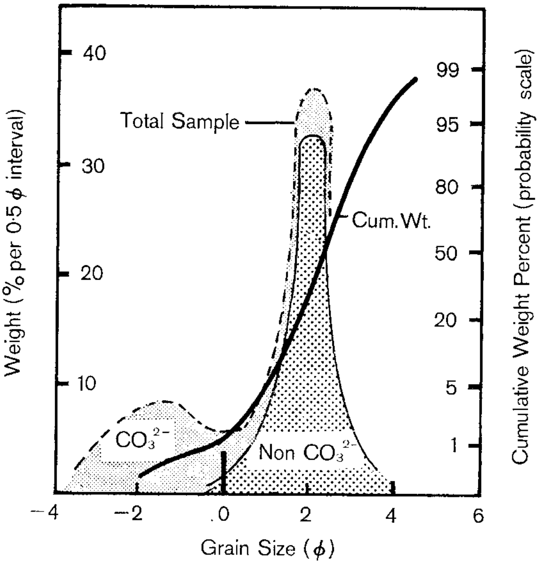

FIG. 7—Key diagram for sediment grain size-frequency curves.

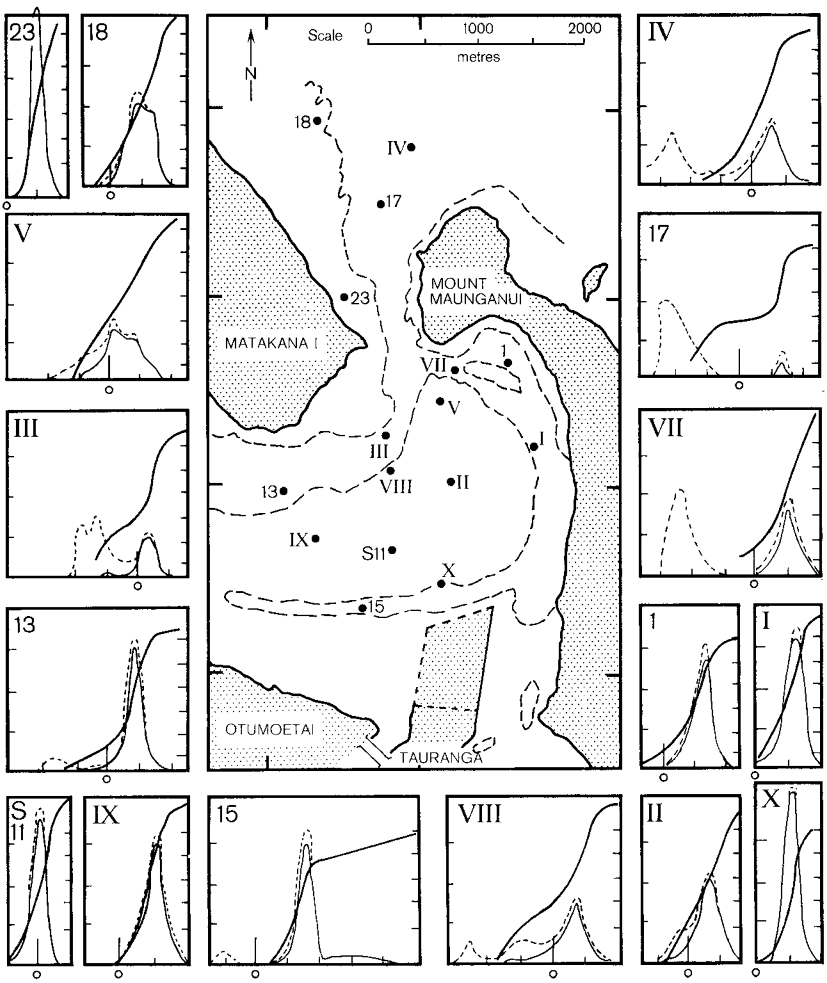

FIG. 8—Representative sediment grain size-frequency curves for samples from the study area, 1974–75.

frequently eroded and thus are transported further as saltation load than finer materials. Fine grains are probably protected from erosion by the relatively immobile coarse grains (mainly shells), while intermediate-sized grains, which project up further than fine grains, are entrained by the current. The effect of this selective transport is to floor the tidal channels with a lag of shelly sediment and interstitial sand.

Most of the percent by weight curves for acid-digested samples show relatively little bimodality and usually the dominant mode is about 2 ϕ. However Samples III and 17 have a small coarse mode of non-carbonate material, implying that at least some proportion of the associated carbonate content of the total sample is mobile in high energy areas. Sample V appears to be composed of two or more populations of slightly different modal grain-sizes, which overlap substantially, probably because they were deposited by tidal currents from different sediment sources. The sediment forming the mode at about 0.5–1.0 ϕ is possibly derived from the area of the lower Western Channel. The finer population with a mode at about 2 ϕ may be derived either from beach sand near the south-eastern shore of Matakana Island (represented by Sample 23), which is entrained by surf action and moved into the harbour with the flood tide, or from the area of the Maunganui Channel (represented by Sample I) transported by tidal currents. This hypothetical explanation has implications for sediment dispersal patterns as discussed in a further paper (Davies-Colley & Healy 1978).

Sample 18 also shows overlapping bimodality, probably produced by mixing of populations from tidal currents and wave deposition. Sample 15 in the Otumoetai Channel has a second mode of very poorly sorted, silty material which seems to be actively depositing in this area of rather low tidal current power. Hydrographic charts show that the Otumoetai Channel has been steadily infilling over a period of 122 y (Davies-Colley, unpublished 1976).

Cumulative log-probability curves (Fig. 8) for the acid-digested fractions mostly exhibit three straight-line segments or log-normal sub-populations, which represent different transport processes (Visher 1969). The well-sorted (steeply sloping) central segment is interpreted as a *saltation* population, while the relatively poorly sorted coarse segment is considered to be a *traction* population moving in contact with the bed and the poorly sorted fine population deposited from suspension. Most fine truncation points (between saltation and suspension populations) for samples in Fig. 8 fall in the range 3–4 ϕ. However, in Sample III from the lower Western Channel, which is subjected to bottom currents over 100 $cm.s^{-1}$, there is a fine truncation point at about 1.5 ϕ, suggesting that sediment finer than this is mostly in suspension at this point. Bagnold's (1956) suspension criterion predicts that suspension will occur when the dimensionless shear stress, Ξ, exceeds a critical value:

$$\Xi = \frac{\tau_0}{(\rho_s - \rho)\ gD} \geqslant \frac{C'V^2}{gD} \qquad (3)$$

where V is fall velocity of sediment grains of diameter, D, and density ρ_s (2.65 $g.cm^{-3}$ for sediment of quartz density), g is gravitational acceleration, τ_0 is bed shear stress, ρ is water density, and C' is a dimensionless constant with a value of about 0.4 (Bagnold 1956). Peak currents at Stn III exceed 100 $cm.s^{-1}$ (Fig. 2) for which τ_0 is about 30 $dyn.cm^{-2}$. Substituting values in the above inequality gives a fall velocity V of about 6.7 $cm.s^{-1}$, corresponding to a grain size of 1 ϕ, which is just slightly coarser than the fine truncation point for Sample III. In the Entrance Channel, where peak bed shear stress may be of the order of 100 $dyn.cm^{-2}$, the suspension criterion shows that substantial graded suspension of sand-sized material occurs at mid tide.

Coarse truncation points in Fig. 8 usually fall between about 1–0 ϕ, but are often poorly defined, indicating considerable mixing of the traction and saltation populations, as a consequence of the great variability of tidal current power over a tidal cycle.

MEAN SIZE AND SORTING

Mean grain-size values for acid-insoluble sediment fractions are contoured in Fig. 9 to display the areal pattern. To some extent the contours are interpolated from field observations of the bed sediment, particularly where sample density is low. The coarsest material occurs in the entrance channel and mean size decreases away from the tidal inlet, both inside and outside the harbour. Fig. 9 shows that M_z is little dependent on depth, since contours cut across the 5 m bathymetric line.

The areal pattern of the sorting parameter, σ_I (Folk & Ward 1957), which measures the dispersion of sediment grain sizes, is contoured in Fig. 10. Poorest sorting occurs in the inlet channel and on the northern tip of the Centre Bank. Inside the harbour sorting improves progressively away from the inlet. Best sorting occurs along the south-east flank of the Centre Bank. The poor sorting of the Otumoetai Channel is a consequence of the high mud content of sediment in this channel. Moderately well-sorted sediment occurs on both sides of the poorly sorted area near the inlet. Outside the harbour the σ_I pattern is somewhat similar to the M_z pattern.

This broad similarity of the areal patterns for M_z and σ_I suggests a correlation of the two parameters. The scatter plot of Fig. 11 (*upper*) for 30 of the 45 sediment samples (1–23 and 1–X, excluding Samples 2 and VI) displays a weak linear correlation (r = 0.46) significant at the 95% level. Samples 15 and 16 from the Otumoetai Channel, which are obviously anomalous, are excluded. The samples with a mean grain size around 2 ϕ are the best sorted, suggesting that this was the modal grain size of the source sediment. Sorting becomes poorer as mean grain size increases (or decreases) away from 2 ϕ. The rather low level of the correlation can probably be attributed to the bimodality of many samples, since sorting is not a well-defined parameter for strongly bimodal sediments (Spencer 1963).

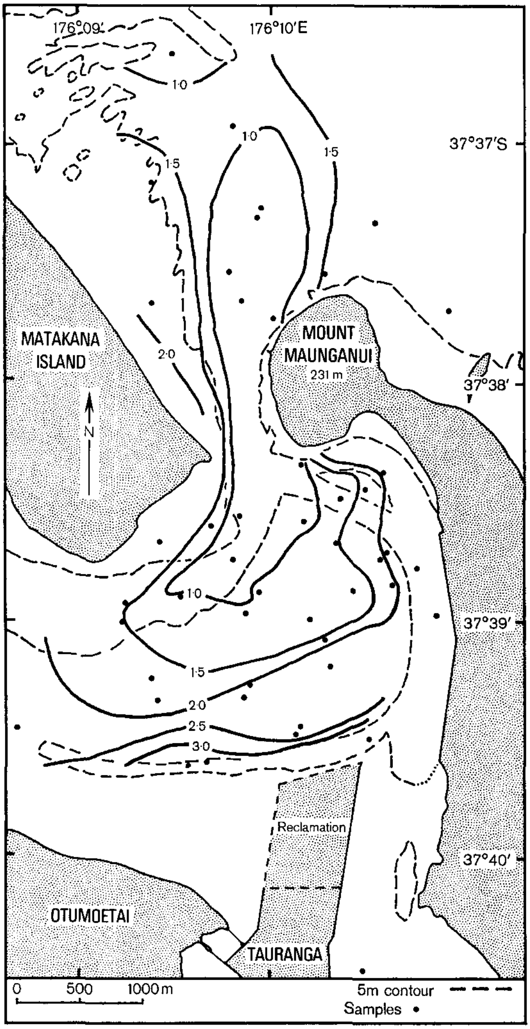

FIG. 9—Contour map for the mean grain-size parameter, M_z, of non-carbonate sample fractions, 1974–75.

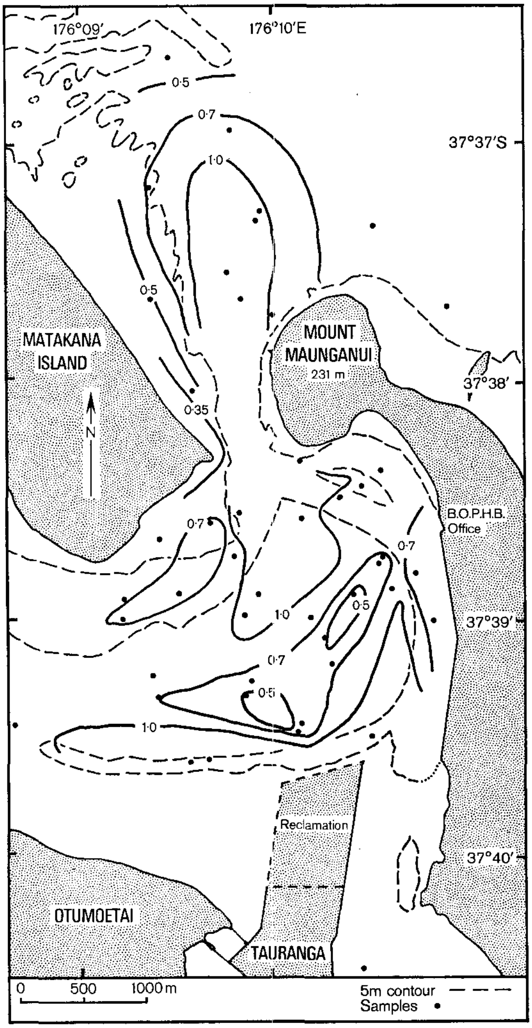

FIG. 10—Contour map for the sorting parameter, σ_I, of non-carbonate sample fractions, 1974–75.

Skewness, Sk_I, values (Folk & Ward 1957) for the acid-digested samples are mostly negative, as shown in Fig. 11 (*lower*). The Otumoetai Channel samples are exceptions, being strongly fine skewed because of a high silt fraction. All other samples range from near symmetrical to strongly coarsely skewed. Skewness is moderately correlated with mean grain size but the relatively high correlation coefficient ($r = 0.70$) is largely caused by the inclusion of samples from the Otumoetai Channel. The near-symmetrical samples tend to have mean grain sizes around 2 ϕ which further suggests that the source sediments were fine- to medium-sized sands.

Sediments with a coarser mean grain size than 2 ϕ tend to have negative skewness, resulting from removal of fine material from areas of more powerful tidal currents. Negatively skewed sediments have been reported from many estuarine environments, for example Sherwood (unpublished 1974) found that the sediments of Raglan Harbour were mainly coarsely skewed. Since beach sediments are often coarsely skewed (Friedman 1961), this coarse skewness may be a relic feature, related to a period of wave action in the sedimentological history of the marine source sediments. However, oscillating tidal currents (long-period wave currents) may also produce negative skewness by removing fines, thus having a different effect from steady unidirectional currents such as those which produce fine skewness in fluvial sediments.

DISCUSSION

According to Folk (1968), mean grain size depends on two main variables:

(i) Size range of the source material, and

(ii) Current power.

The source of most of the sediment in the study area is probably the marine sand, ultimately derived from erosion of the hinterland volcanics. Thus mean grain size should depend mainly on current power (proportional to the cube of current speed). However, the sediment is not completely graded to high fluid power because of the scarcity of coarse grains in the source sediment (although to some extent coarse grains are probably replaced by mobile shell fragments). In Fig. 12 (*upper*), mean grain sizes for acid-insoluble fractions are plotted as a function of peak tidal currents (which may be either ebb or flood directed) for the oceanographic stations. A moderate linear (log-log) correlation is revealed ($r = 0.79$, *significant at the 95% level*). However, the actual relationship of the variables may be a simple linear correlation similar to that found by G. Allen (1971) for the sediment of the Gironde Estuary, France. Whatever the precise form of the relationship of mean grain size to peak tidal current speed, the correlation displayed in Fig. 12 (*upper*) explains the areal pattern of M_z in Fig. 9, in which mean grain size is at a maximum in the inlet channel where maximum currents occur.

The sorting parameter, σ_I, is generally dependent on four main factors according to Folk (1968):

(*i*) Size range of the source material,

(ii) Type of deposition,

(*iii*) Rate of deposition, and

(iv) Current power and variability of current power.

Before deposition in the harbour, the source sediments probably underwent considerable progressive sorting by wave action on the continental shelf, which limited the size range available. Deposition of the modern sediments was relatively slow, and sorting processes have had considerable time to act, which in itself would tend to produce relatively good sorting. However, the extreme variability of tidal currents, both in time and space, has swamped any such trend and given rise to rather poorly sorted sediments. σ_I values are plotted as a function of tidal current speed in Fig. 12 (*lower*); there is considerable scatter ($r = 0.64$, significant at 90% level but not at 95%) but a relationship is suggested such that sorting becomes progressively poorer as tidal currents increase. Sample IV has been excluded from the correlation calculation because it probably contains a significant mobile carbonate content which produces poorer sorting of the total sample. The correlation of σ_I with current speed explains the areal pattern in Fig. 10. The *increase of σ_I as tidal currents increase is related to* the washing effect of tidal currents on sediment originally derived from rather well-sorted marine sand with a modal grain size of about 2 ϕ. Progressive removal of fine material from this sediment leaves the remaining material increasingly poorly sorted, coarser, and increasingly coarsely skewed.

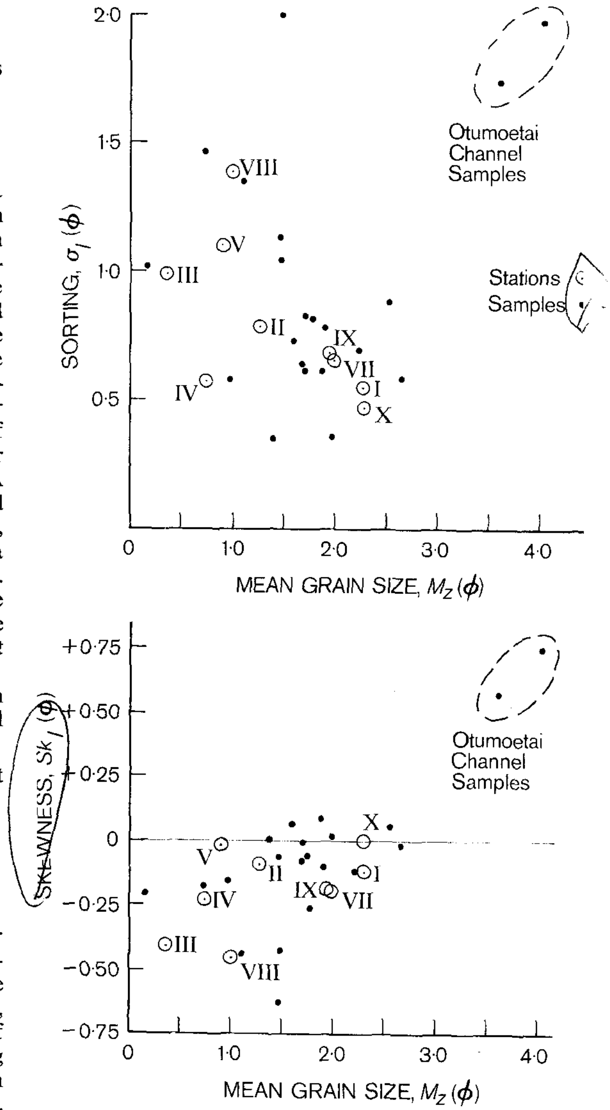

FIG. 11—Scatter plots of the mean grain-size parameter, M_z, against (*upper*) the sorting parameter, σ_I, and (*lower*) the skewness parameter, Sk_I, Tauranga Entrance, 1974–75.

CONCLUSIONS

The textural characteristics of the bottom sediments near the Tauranga Entrance to Tauranga Harbour can be related to the hydrodynamical processes operative on the bed. Tidal currents dominate sediment transport near the tidal inlet, although swell waves are significant on the ebb tidal delta. Inside the harbour, wind waves are probably only important on

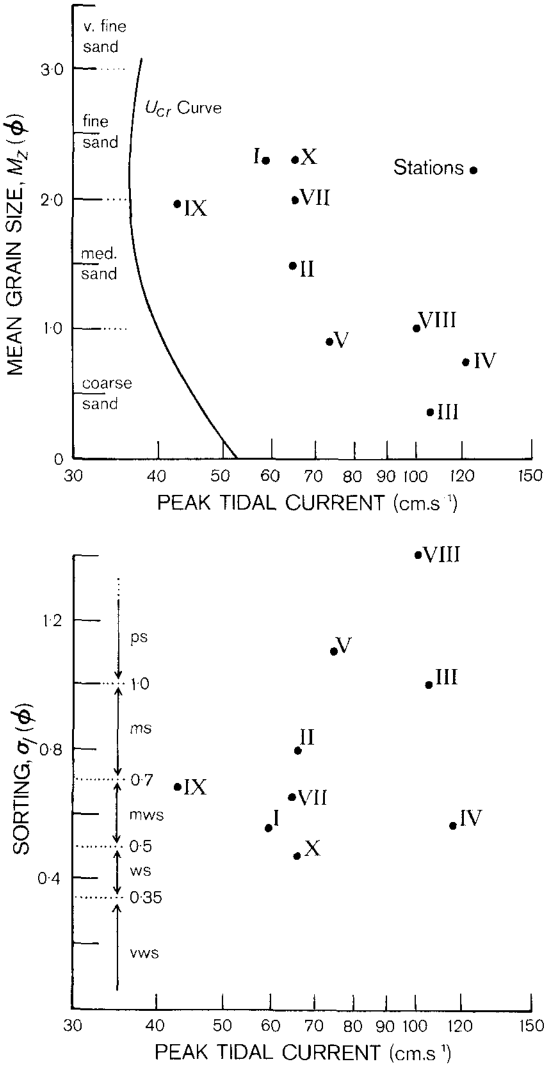

FIG. 12—Scatter plots of peak tidal currents (either ebb or flood) at stations in the study area against (*upper*) mean grain size, and (*lower*) sorting, Tauranga Entrance, 1974–75.

intertidal flats and harbour beaches. The non-carbonate fraction of the sediment is probably derived from marine sand from the Bay of Plenty continental shelf, and the action of tidal currents and waves in the vicinity of the inlet has changed the textural character of this sediment. In particular, sediment in the deep tidal channels is characteristically bimodal, with a fine mode of sand and a coarse mode of shelly gravel. Intermediate-sized material has probably been eroded from the channel and deposited as a mixture of populations on adjacent shoal areas. Sand-sized sediment is frequently moved in graded suspension in the lower Western and Entrance Channels, which are characterised by powerful tidal currents.

The areal patterns of mean grain size and sorting reveal a relationship to power of tidal currents. As tidal currents increase, removal of fine material causes the sediments to become coarser, and the grain size distributions become increasingly poorly sorted and increasingly coarsely skewed.

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