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Morphology and Size of Ebb Tidal Deltas at Natural Inlets on Open-sea and Pocket-bay Coasts, North Island, New Zealand

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ABSTRACT

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Sand volumes and morphologies of 17 ebb tidal deltas off natural inlets on the New Zealand North Island coast, in both open-sea and pocket-bay settings, were investigated. Four basic ebb-delta forms were identified. 'Free form' deltas, typically 'bat-winged' in shape, occur on open shorelines. 'Constricted' deltas are similarly shaped but occur in shoreline angles lacking space for the free form to fully develop. 'High-angle half-deltas' are typically shore-normal or 'L-shaped' and occur in embayment corners where the ebb jet flows against the rocky headland, resulting in a significant shoal forming only on the beach side of the inlet. 'Low-angle half-deltas' are almost shore-parallel sand 'wedges' that form between the ebb jet and the beach where the ebb jet is forced by rock controls to flow at a low angle to the beach. Sand storage volumes ranged from 3.8×10^4 m^3 to 1.2×10^{10} m^3. The main controls on ebb delta sand volume (V) are the tidal prism volume (P), the angle between the outflow jet and the shoreline (θ), and the wave climate. The empirical equation

$$V = 1.37 \times 10^{-3} P^{1.32} (\sin \theta)^{1.33}$$

accounts for 83% of the variance in sand volume in the dataset. Deltas on the high-energy west coast tended to be smaller than east coast deltas with similar tidal prisms. The supply of littoral drift also appears to influence delta volume in some cases. These results may be used to help assess permissible rates of sand mining from ebb deltas, to estimate ebb-delta sand entrapment associated with changes in the tidal prism, and to re-design the alignment of inlet channels in order to control ebb-delta sand volumes.

ADDITIONAL INDEX WORDS: *Sediment processes, tidal inlet, tidal prism, sea-level rise, sand mining.*

INTRODUCTION

Tidal deltas, the bodies of sand at the seaward and bay ends of tidal inlets, are major sand sinks along the coast of New Zealand's North Island, as indeed they are along many of the world's coastlines. The ebb tidal deltas, in particular, are being increasingly seen as prospective sources of sand for use by industry and/or for beach nourishment. Ebb deltas, however, are major and dynamic elements of the littoral sediment budget, and they can strongly influence coastal processes in the vicinity of the tidal inlet, for example, bypassing of littoral drift and partial wave sheltering of the adjacent shore (*e.g.*, FITZGERALD and HAYES, 1980; FITZGERALD, 1988). Therefore, before mining ebb deltas for sand, it is prudent to understand the basic factors that determine their size and shape, the sustainability of their sand supply, and the role that they play in the stability of the nearby coastline.

Little of this basic information is available for New Zealand's ebb tidal deltas, almost all of which are associated with natural inlets. Studies of tidal inlets overseas, many of which are artificial or are trained and stabilised with structures, have shown that ebb delta volume depends on the tidal prism (a function of the tidal range and the geometry of the enclosed bay), inlet geometry, shoreline configuration, offshore bathymetry, wave climate and littoral drift, sediment size, and freshwater runoff (*e.g.*, WALTON and ADAMS, 1976; HUBBARD *et al.*, 1979; MARINO and MEHTA, 1987, 1988; FITZGERALD, 1984, 1988). For inlets of the United States coasts, WALTON and ADAMS and MARINO and MEHTA found that ebb delta volume increased with increasing tidal prism, decreasing inlet width/depth ratio, and decreasing wave en-

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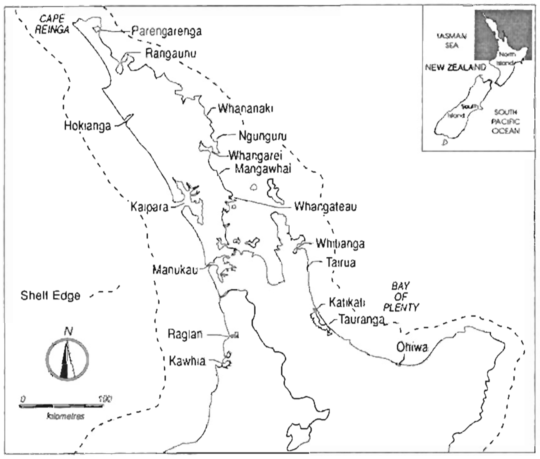


Figure 1. Location map showing ebb tidal deltas investigated in this study.

ergy. They inferred that, given other factors staying more-or-less the same, as wave energy decreases the ebb shoal builds further seaward and hence is larger.

This paper presents results from an investigation of 17 ebb tidal deltas on the coast of North Island, New Zealand (Figure 1). The objectives were to measure the volumes of sand comprising the ebb delta shoals, to determine the factors controlling ebb delta size and shape, and to explore the implications of the results for coastal processes and management. Preliminary results from this study have been presented in HICKS and HUME (1991).

METHODS

Delta Locations

The seventeen locations included in this study represent all the North Island tidal deltas that have existing useful bathymetric data. As such, they cover a wide selection of locations, configurations, and physical conditions, ranging from the large headland-bound open-coast inlets on the high-energy west coast to small embayment-corner inlets on the relatively sheltered east coast (Figure 1 and Table 1). Most of these inlets have been included in previous studies concerned with inlet classification, geometry, and/or stability (*e.g.*, HEATH, 1975, 1976; HUME and HERDENDORF, 1988a, b, 1992, 1993). All occur at barrier-enclosed estuaries, as defined by HEALY and KIRK (1982) and as used in the classification scheme of HUME and HERDENDORF (1988b).

Delta Bathymetry and Sand Volumes

The bathymetric data were mainly in the form of fairsheets, most from Royal New Zealand Navy Hydrographic Branch surveys undertaken over the past 40 years or so, but in some cases also from surveys conducted by NIWA Oceanographic (New Zealand Oceanographic Institute). Digital data were available for Whananaki and Ngunguru, which were surveyed in 1992 by NIWA Ecosystems. The quality of these surveys varied from delta to delta in terms of their scale, spatial coverage, and density of soundings. Generally, the larger the delta, the better the quality of the survey. At a few locations, larger scale contour charts were used to 'patch-in' the bathymetry of offshore areas not covered by fairsheets. At some inlets, particularly the larger ones (*e.g.*, Manukau) which provide access to ports, several historical bathymetric surveys were available; in such cases, the most detailed survey was used. In most cases, the fairsheets (usually having a chart datum at the lowest astronomical tide level) lacked detail on intertidal areas (survey boats avoid bars for safety reasons) and there was little data on shore levels. In these cases, all intertidal areas and dry land were assigned zero levels.

The approach for analysing ebb delta shapes and volumes involved fitting digital terrain models to the existing bathymetry and to an inferred 'no-delta' surface, then differencing the two surfaces to give a model of the 'residual delta' surface (Figure 2). The MS-DOS software package SURFER (GOLDEN SOFTWARE, 1989) was used for this purpose.

For the existing bathymetry, soundings data from the fairsheets were digitised and input to a gridding model that calculated the elevation at each grid node from the elevation of the three nearest data points in each quadrant, weighted according to the inverse square of their distance from the grid node. Grid spacings ranged from 25–500 m, depending on the delta size. A cubic-spline procedure was then used to double the density of grid-lines by interpolating between grid points. The 'no-delta' surface was created by first drawing interpreted 'no-delta' contour lines on the original bathymetry charts across the area of seafloor covered by the ebb delta and inlet. These 'no-delta' contours were then digitised and the resultant 'no-delta' data subset was merged with

Table 1. *Characteristics of tidal inlets and their ebb deltas investigated in this study. Information sources discussed in text. Inlet types, after* Hume *and* Herdendorf *(1988b), are: 4 = single spit; 5 = tombolo; 6 = barrier island.*

	Inlet Type	Ebb Delta Sand Volume (10^6 m^3)	Ebb Delta Shape Type	Mean Spring Tide Range (m)	Mean Spring Tidal Prism (10^6 m^3)	Throat Width @ MT (m)	Throat Area @ MT (m^2)	Throat Depth (mean) @ MT (m)	Ebb Jet Angle (Deg)	Beach Slope to −10 m	Annual Littoral Drift (m^3)	Ebb Delta Length/ Breadth Ratio	Sand Size d_{50} (mm)	Wave Energy Factor H^2T^2 (m^2 sec^2)	Daily Mean Runoff (m^3/sec)
Hokianga	4	16.4	I	2.77	228	1,090	13,000	11.9	72	0.0102	175,000	0.60	0.19	159	38
Kaipara	4	12,300	I	2.68	1,990	5,600	82,000	14.6	57	0.0125	175,000	0.29	0.16	159	16
Katikati	6	30.2	I	1.6	95.8	380	4,680	12.3	60	0.0058	70,000	0.70	0.28	81	9.4
Kawhia	4	31.6	I	2.9	121	600	11,000	18.3	73	0.0078	175,000	0.52	0.20	159	30
Mangawhai	6	1.93	I	1.8	6.55	216	500	2.31	75	0.0175	60,000	0.48	0.23	29	1.6
Manukau	4	1,250	I	3.38	918	1,900	46,000	24.2	88	0.0074	175,000	0.61	0.13	159	28
Ngunguru	4	0.781	III	1.71	3.83	109	310	2.84	83	0.0109	5,000	1.9	0.14	4	2.8
Ohiwa	6	12.4	II	1.6	28.1	308	1,880	6.10	85	0.0070	70,000	0.26	0.23	81	6.5
Parengarenga	4	21.1	I	2.13	73.0	500	7,000	14.00	86	0.0096	30,000	0.59	0.19	25	7
Raglan	4	7.10	I	2.8	46.0	640	3,600	5.63	87	0.0081	175,000	0.50	0.20	159	18
Rangaunu	4	49.2	II	2.0	134	1,012	6,490	6.41	42	0.0135	20,000	0.82	0.18	25	6.2
Tairua	5	2.15	III	1.6	5.02	130	430	3.31	48	0.0037	5,000	0.80	0.40	16	15
Tauranga	6	47.3	II	1.6	131	480	6,260	13.0	42	0.0088	70,000	1.1	0.28	81	37
Whananaki	4	0.415	III	1.8	1.46	79	130	1.60	77	na	5,000	1.8	0.14	4	1.6
Whangarei	4	168	III	2.1	155	790	14,600	18.5	55	0.0111	20,000	1.6	0.17	22	12
Whangateau	4	0.277	IV	2.2	10.5	174	660	3.79	5	0.0097	13,000	1.7	0.14	22	1
Whitianga	4	0.0384	IV	1.6	12.6	240	1,300	5.42	18	na	1,000	3.8	0.40	4	2.3

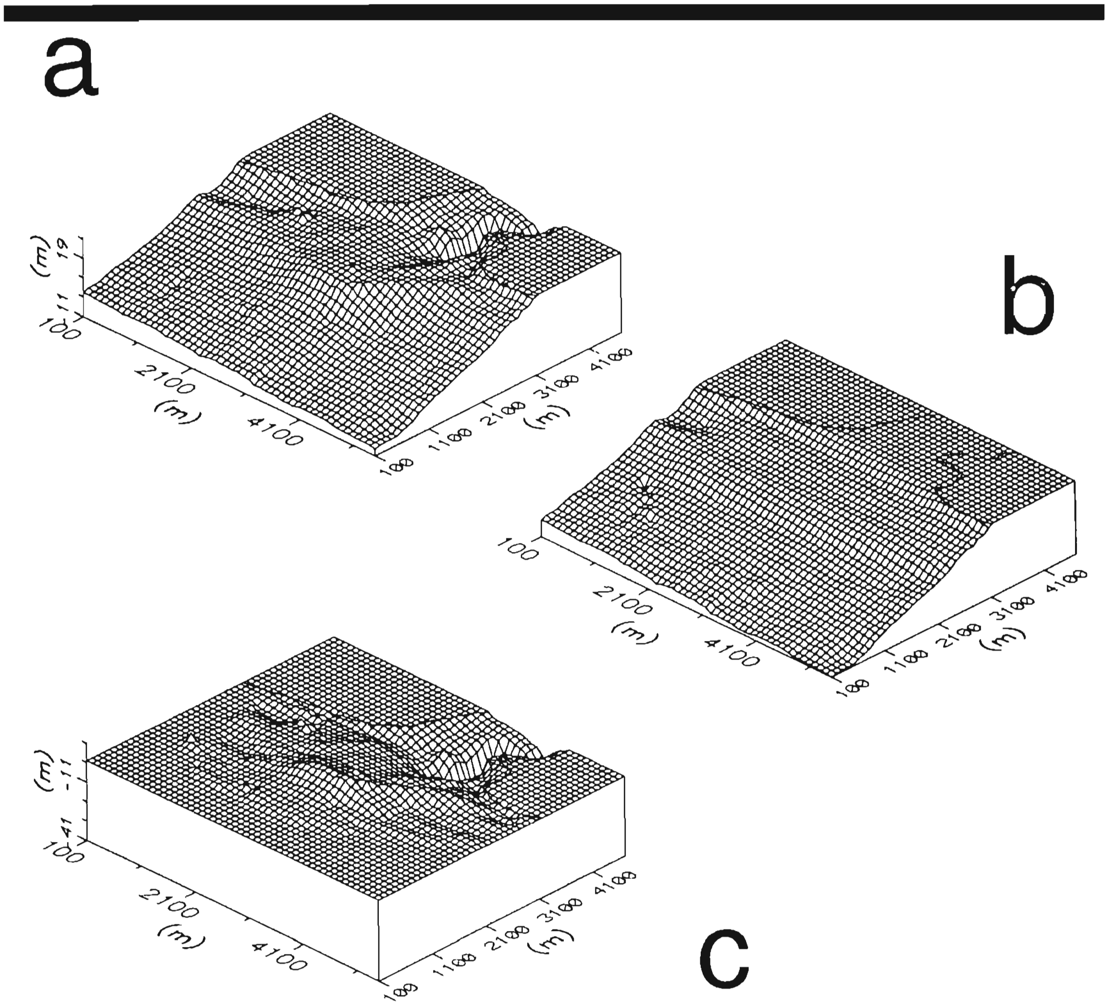


Figure 2. Plots of the ebb tidal delta at Hokianga Harbour: (a) existing bathymetry, (b) interpreted 'no delta' bathymetry, (c) residual topography associated with the ebb delta and inlet throat.

the bathymetry data from the areas of shore and seafloor outside the delta-inlet area.

To facilitate compilation of the random x-y-z data files used by the gridding program, the shore and seabed over and around the ebb delta were digitised into separate files comprising: (i) the existing bathymetry over the ebb delta area; (ii) the existing bathymetry through the inlet; (iii) the existing seafloor bathymetry and land topography beyond the boundaries of the ebb delta and inlet; (iv) the 'no-delta' contours over the ebb delta area; and (v) the 'no-inlet' contours over the inlet area. The existing surface was then generated by combining files (i)–(iii), while the 'no-delta' surface was created from files (iii)–(v).

The shapes of the actual delta and of the 'residual delta' were plotted on perspective diagrams and as contour charts. The 'residual delta' contour charts are isopach maps of the delta deposit and were used to scale delta length/breadth ratios. Delta length and breadth were measured from the 0.5 m or 1.0 m isopachs rather than from the 0 isopach, as experience indicated that the outline of the delta only became distinct at isopachs larger than the 'noise level' of the surveying and grid-fitting. Delta length was measured along the ebb outflow axis. The volume of the ebb delta was found by calculating the positive (or 'cut') volume between the 'residual delta' surface and the z = 0 surface. The negative residual volume, corresponding to the channel scoured into the 'no-delta' shore at the tidal inlet, was ignored because this volume depended arbitrarily on how far into the inlet the control volume extended.

The main error source in the volume determinations involved interpretation of the 'no-delta' bathymetry. This interpretation was straightforward and involved little error for tidal inlets on straight clastic coastlines, where the nearshore contours either side of the delta and the beach contours either side of the inlet could be joined more-or-less as straight lines. The approach became more subjective and uncertain where the inlets occurred at the corners of embayments or beside headlands, particularly where the seabed contained rocky shoals or where small deltas merged with longshore bar systems. We estimate that there could be up to a 25% error in the sand volume estimate at the larger inlets, such as Manukau; however, at small deltas such as Whangateau, where it was difficult deciding where the longshore-elongated ebb delta stopped and the regular longshore beach-bar began, we estimate a factor-of-four uncertainty. In comparison, errors in the terrain modeling and calculation routines were trivial: variations on the gridding method, including different grid sizes, search methods, and smoothing routines, induced less than 5% variation in delta volume estimates.

For interest, some ebb delta volumes were recalculated using the method of DEAN and WALTON (1975), which is basically a manual equivalent to the computer technique used in our study. The results from the two methods agreed to within 1–2%; however, the computer technique is preferred, being less laborious, more objective, and permitting the ready creation of surface graphics such as contour plots and profiles.

Parameters Controlling Delta Shape and Size

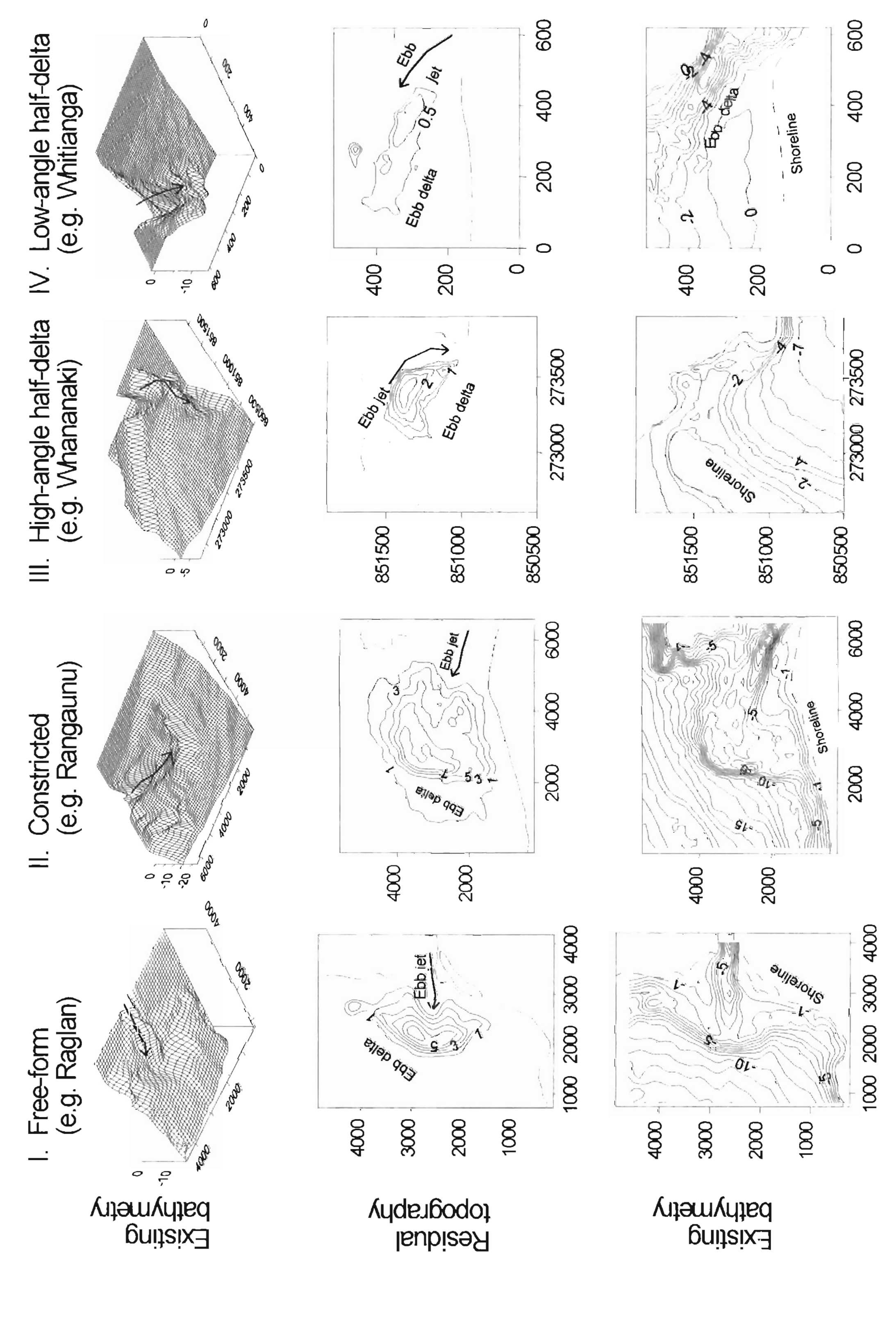
Parameters potentially controlling ebb delta shape and size (Table 1) included tidal range (a_0), tidal prism volume (P), inlet throat width (W), throat cross-section area (A), throat mean depth (D), wave energy (Ew), littoral drift rate (L), ebb tidal jet angle (*i.e.,* the angle θ subtended by the inlet axis and the shoreline), beach slope (*i.e.,* the mean nearshore slope out to the 10 m isobath for 'no-delta' conditions), sediment median grainsize (d_{50}), and freshwater runoff into the inlet (R).

Generally, the data on tidal range and prism and inlet geometry were based on tidal gaugings (HUME and HERDENDORF, 1992) and are relatively accurate. The information on wave energy and littoral drift rate were generally estimates, accurate to a factor-of-two at best. The wave energy parameter was derived as H^2T^2 (which is actually a relative wave energy), where both H (significant wave height) and T (dominant wave period) were, in most cases, estimated very crudely from information on deep water waves given by PICKRILL and MITCHELL (1979), with some adjustments for headland sheltering. Because of the patchy quality of the wave information, each delta was assigned to a simple wave climate: either west-coast high energy or east-coast moderate energy. The littoral drift rates similarly vary in quality: some derive from measurements and estimates reported in the literature, while others are simply guesses based on comparisons with nearby locations of similar aspect where some knowledge of littoral transport is available. The nearshore slopes were scaled from the bathymetry fairsheets. The sediment size data were derived mainly from SCHOFIELD (1970) and are for beaches adjacent to the tidal inlets. The ebb jet angles were measured from aerial photographs.

Freshwater runoff values were either derived from HEATH (1976) or estimated. Two methods of runoff estimation were employed in this study. Wherever possible, records of runoff from gauged catchments, either within the inlet's catchment or nearby, were used to estimate the total river inflow to the inlet on the basis of its catchment area. Where no runoff records were available or were available only for a small part of the inlet's catchment and where there was a strong rainfall gradient over the inlet's catchment, the runoff estimate was based on the mean rainfall of the catchment and a representative runoff factor. Mean catchment rainfall was integrated from isohyets stored on NIWA Freshwater's POLAR geographic information system. The runoff factor was found from the rainfall (obtained by the same technique) and runoff at the nearest suitable gauged catchment.

Analysis

The perspective and contour plots of 'residual' deltas were used to group the deltas in terms of their shape and length/breadth ratios. Correlation


I. Free-form
(e.g. Raglan)
II. Constricted
(e.g. Rangaunu)
III. High-angle half-delta
(e.g. Whananaki)
IV. Low-angle half-delta
(e.g. Whitianga)
Existing bathymetry
Residual topography
Existing bathymetry
Ebb delta
Ebb jet
Ebb
Jet
Shoreline
Ebb delta

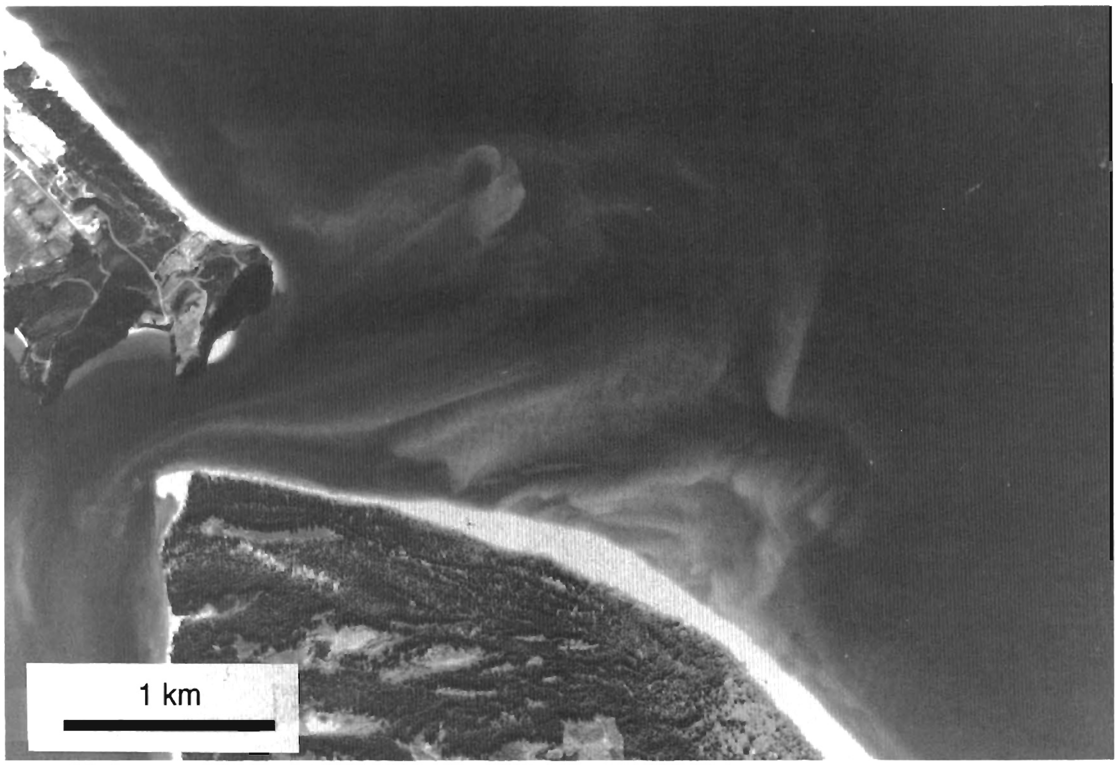


Figure 4. 'Free-form' ebb delta at Katikati Inlet on the moderately exposed Bay of Plenty coast. Note the assymetric 'batwing' outline of the delta. The predominant littoral transport direction is from top to bottom (north-south).

and regression analyses were used to identify the physical factors determining delta volume. Data were log-transformed to improve uniformity and normality of data scatter.

RESULTS AND DISCUSSION

Delta Shape

Basic Types

Four basic shapes of 'residual' ebb delta can be identified in the dataset (Figure 3), distinguished largely on the basis of the delta length/breadth ratio. These shapes appear to be related mainly to delta size and to shoreline configuration through its control on wave exposure, shape of the space available for the delta to occupy, and alignment of the ebb tidal jet.

The first delta type (Type I in Table 1) is a longshore-elongated, reasonably symmetrical 'batwing'-shaped delta that occurs off inlets on relatively straight, exposed shorelines experiencing significant littoral drift (Figures 3 and 4). This shape occurs with or without the presence of headlands, provided that the headland length

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Figure 3. Examples of the four general morphological types shown by North Island ebb deltas: (I) free-form; (II) constricted; (III) high-angle half-delta; (IV) low-angle half-delta. For each type, the three plots show, from top to bottom: perspective diagram of the existing bathymetry, contour map of sand depths on the ebb delta (positive residual topography), and contour map of existing bathymetry. All dimensions are in metres. Elevations on the existing bathymetry plots are with respect to the 'lowest astronomic tide' datum. Arrows show the paths of the ebb tidal jets.

Figure 5. 'Constricted' ebb delta at Parengarenga Inlet. The offset northern headland constrains growth of the northern arm of the delta, preventing development of a 'free' form.

is short compared to the delta length (*i.e.*, there is little offset between the sand barrier and the rock headland; the headland acts as a jetty, controlling the tidal throat but not the lateral extent of the delta) and hence is termed 'free-form'. The west coast deltas (Kawhia, Raglan, Manukau, Kaipara, Hokianga) and Mangawhai, Katikati, and Ohiwa deltas on the east coast are examples of this type. Their length/breadth ratios are less than 0.7.

The second delta type (Type II in Table 1) is of similar basic shape but is less elongated alongshore and occurs where the inlet occupies a broad shoreline angle (Figures 3 and 5). In such cases, the offset between the rock headland and the barrier restricts the lateral spread of the delta. The

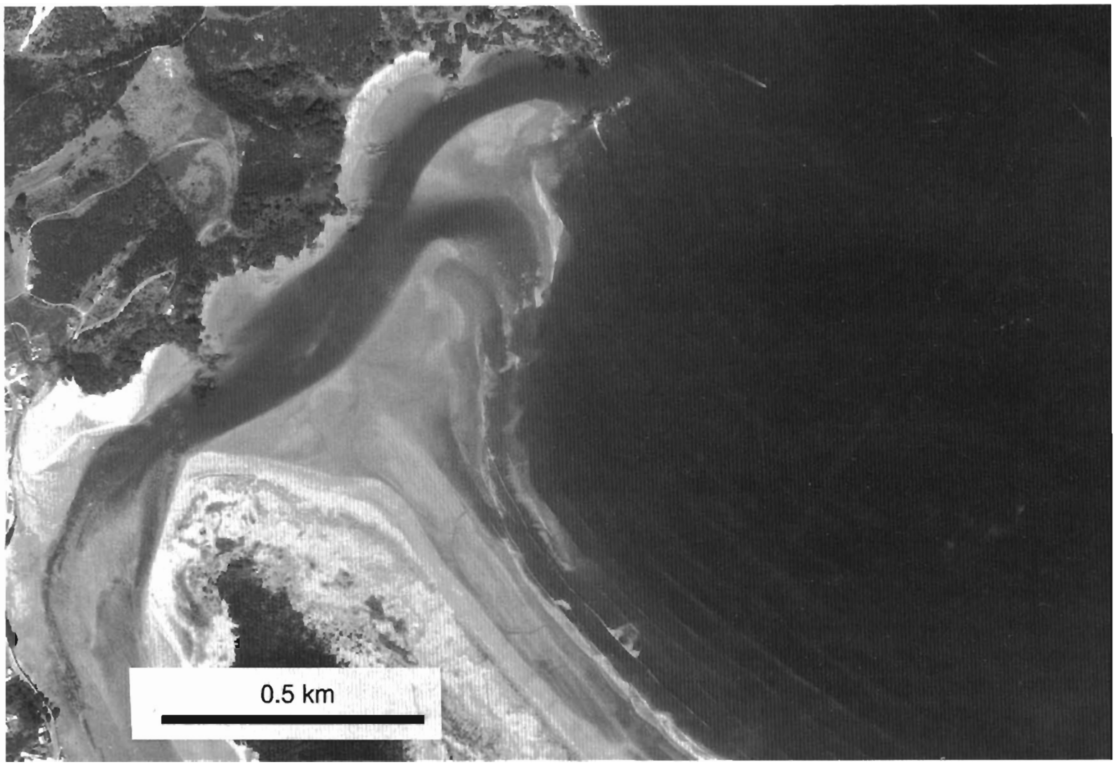

Figure 6. 'High-angle half-delta' at Ngunguru Inlet. Note the ebb tidal channel lying hard against the headland and running approximately normally to the barrier shore, with the ebb delta developed off the distal end of the barrier.

term 'constricted' is applied to this type. Parengarenga, Rangaunu, and Tauranga are examples. Their length/breadth ratios range from 0.6 to 1.1.

The third delta type (Type III in Table 1) is essentially a 'half-delta', taking the form of a near shore-normal or 'L-shaped' bar (Figures 3 and 6). They occur where the ebb jet runs hard against the headland, resulting in a significant shoal forming only on the barrier side of the inlet. The term 'high-angle half-delta' is used for this type. They are particularly common in the pocket-beach coasts of east Northland and Coromandel. Whangarei, Whananaki, Ngunguru, and Tairua are examples. Their length/breadth ratios range from 0.8 to 1.9.

The fourth delta type (Type IV in Table 1) takes the form of a longshore-elongated wedge-shaped deposit (Figures 3 and 7). The delta is pinched between the beach and an ebb tidal jet forced to flow at a low angle to the barrier shoreline either by an acute-angled embayment configuration or rock controls along the banks of the inlet throat (while a deposit may sometimes also form on the ocean side of the ebb jet, its relief is minor compared to the deposit on the shoreward side). We term this type a 'low-angle half-delta'. Their length/breadth ratios are greater than 1.7; Whangateau and Whitianga are examples. In both of these cases, the ebb jet angles are very low (5 and 18 degrees, respectively) and the ebb deltas are basically widened swash bars.

Because much of an ebb delta is sub-tidal and our topographic data are generally sparse over the intertidal area, these delta shapes may not always correspond well with the morphologies apparent on aerial photographs. Hence, our classification may not correspond completely with morphological classifications based largely on air-photographs (*e.g.*, OERTEL, 1975).

Factors Controlling Shape

The primary factors appearing to control the shape of the ebb deltas investigated are volume of tidal outflow, shoreline configuration, and to a

Figure 7. 'Low-angle half-delta' at Whitianga Inlet. Note the low angle of the inlet channel with respect to the barrier shore, and the ebb delta restricted to a small sand bar on the inner bank of the channel.

lesser extent wave energy. These controls have been previously recognised for sandy coastal plain settings (*e.g.*, HUBBARD *et al.*, 1979; FITZGERALD, 1984). A distinctive feature of the New Zealand ebb deltas, however, is the importance of bedrock configuration. On a broad scale this influences the location of the inlet (*i.e.*, all the New Zealand inlets lie against rocky headlands) and the configuration of the adjacent sandy shoreline, while at a finer scale bedrock outcrops can also control the orientation of the main ebb channel.

Another significant feature of the New Zealand ebb deltas is the degree to which the controls of their shape can be interactive. For example, the relative exposure to waves can be influenced by headlands and by the size of the ebb delta which itself is largely related to the volume of the tidal prism. Also, the shoreline configuration directly controls the shape and size of the space available for the ebb delta to occupy and can also, through its control on the alignment of the ebb-tidal jet, further influence the interaction of waves and the jet flow. The net effect of these interactions, particularly for natural inlets in embayed coasts, is a wide spectrum of ebb-delta shapes. A progression through this spectrum, from Type I to IV, represents greater control by the hard shoreline and increasing tidal dominance, the latter mainly by virtue of wave shelter provided by headlands.

The 'free-form' Type I deltas, that have built off straight shorelines (*e.g.*, Ohiwa, Kaipara) or extend well seaward of headlands (*e.g.*, Hokianga), are moulded principally by the ebb-tidal jet and the incident waves. Their equilibrium shapes show a close relationship between delta length/breadth ratio and tidal-energy/wave-energy ratio, with bigger waves limiting the offshore extent of the delta by driving delta sediment shoreward and also spreading it alongshore (Figure 8a). The 'constricted' Type II deltas form where offset headlands constrict delta growth and afford wave shelter (Figure 8b).

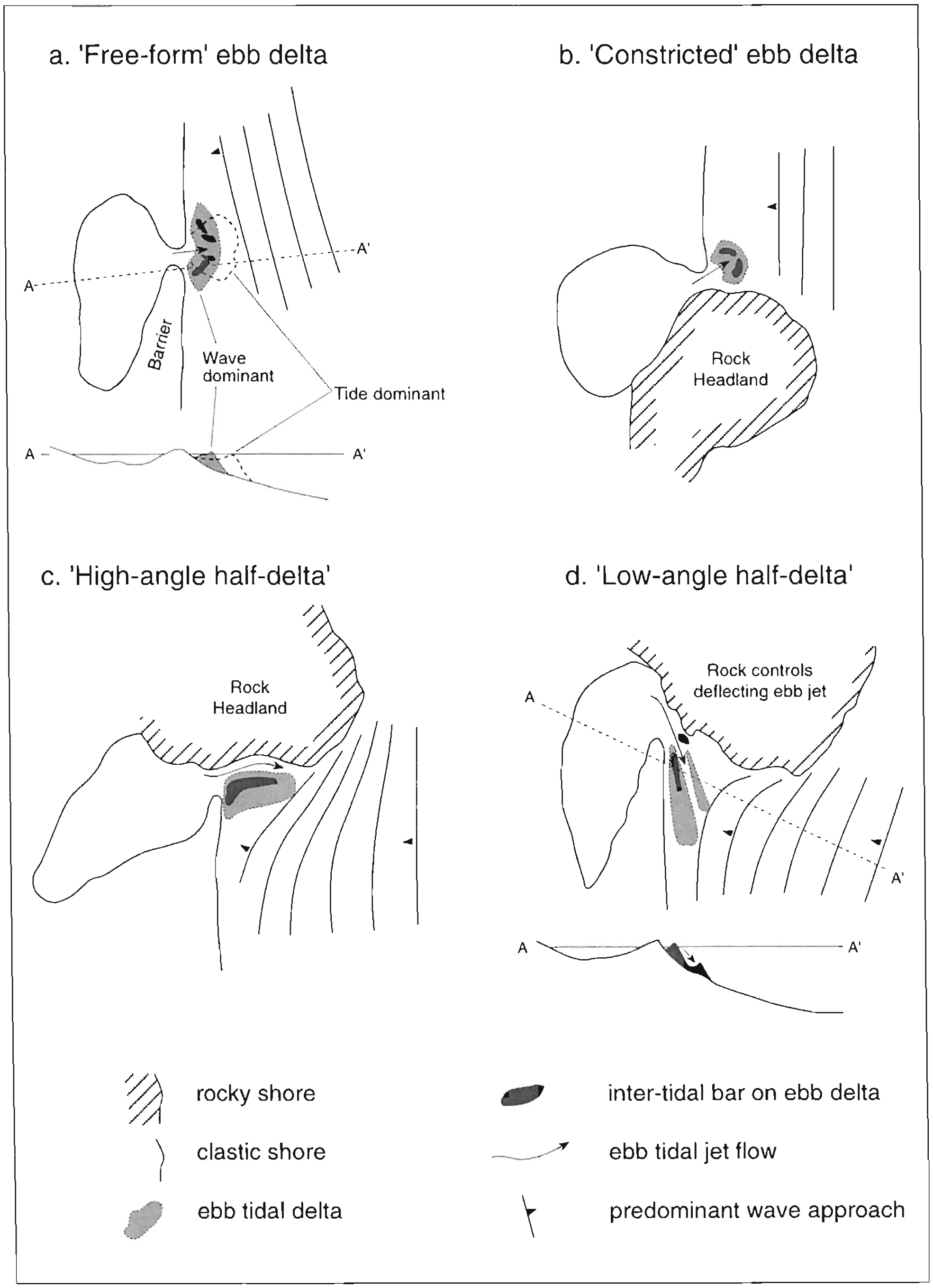

Figure 8. Schematic diagrams depicting controls on ebb delta size and shape.

Table 2. *Results of log-linear regression of ebb delta sand volume (V) on tidal prism (P) for partitions of the dataset split according to wave climate and after removal of outliers. The regression model is of the form: log V = a + b log P (or $V = e^a P^b$). Included also are the regression models of* Walton *and* Adams *(1976), for inlets in a variety of wave environments on the United States coast, and* Marino *and* Mehta *(1987), for inlets on the east coast of Florida.*

Datagroup	Regression Intercept a (95% C.I.)	Regression Slope b (95% C.I.)	Regression Coefficient r	Standard Error of Estimate + or − (× or /)	Regression Model
All	−8.58 (−15 to −1.5)	1.41 (1.01 to 1.81)	0.89	1.47 (4.35)	$V = 1.9 \times 10^{-4}P^{1.41}$
East coast	−6.32 (−17 to 4.8)	1.28 (0.62 to 1.93)	0.81	1.57 (4.83)	$V = 1.8 \times 10^{-3}P^{1.28}$
West coast	−20.1 (−43 to 2.6)	2.00 (0.83 to 3.16)	0.95	1.11 (3.04)	$V = 1.9 \times 10^{-9}P^{2.0}$
East coast minus outliers	−3.08 (−6.17 to 0.0)	1.12 (0.94 to 1.30)	0.98	0.41 (1.51)	$V = 4.6 \times 10^{-2}P^{1.12}$
West coast minus outliers	−18.6 (−30.8 to −6.4)	1.94 (1.31 to 2.56)	0.99	0.44 (1.55)	$V = 8.4 \times 10^{-9}P^{1.94}$
Walton and Adams					$V = 6.6 \times 10^{-3}P^{1.23}$
Marino and Mehta					$V = 5.6 \times 10^{-4}P^{1.39}$

The 'half-delta' shapes result when the inlets occur in right- to acute-angled embayment corners. In the 'high-angle half-delta' case (Type III) with the ebb jet exiting approximately normal to the barrier shore but 'hugging' the rocky headland, there is only space for deposition of sand entrained by the ebb jet on the barrier side of the inlet. Elongation of the delta in the direction of the ebb flow is assisted by the wave sheltering and refracting effects of the headland, with delta length increasing as headland length (and therefore wave shelter) increases (Figure 8c). In the case of the 'low-angle half-delta' (Type IV), the ebb-jet is forced at a low angle to the barrier shore, so the incident waves act more across it than against it. Consequently, sand entrained by the ebb jet is more easily spread alongshore, while waves can more easily sweep the sand shoreward after it has deposited from the ebb jet (Figure 8d). As the ebb jet angle decreases (and the ebb jet becomes more parallel to the wave crests), the ebb delta may become indistinguishable from longshore bars.

At all delta types, but particularly the 'half-deltas', wave refraction across the ebb delta shoal can lead to a return drift of sand back towards the inlet. This return drift, which is invariably assisted by strong flood tide flows across the beach side of the delta, results in a transport loop.

Delta Size

Sand volumes calculated for the ebb deltas (Table 1) range over six orders of magnitude, from 3.8×10^4 m³ at Whitianga to 1.23×10^{10} m³ at Kaipara. Analysis of partial correlation coefficients among all parameters in the dataset showed that the main determinant of delta volume (V) is the size of the tidal prism (P). Regression analysis of the relationship between the logarithms of V (in m^3) and P (also in m^3), as shown in Figure 9, yielded the following least-squares best-fit equation for the whole dataset:

$$V = 1.88 \times 10^{-4} P^{1.41} \quad (1)$$

The regression coefficient, r, for this equation is 0.89; the standard error of the estimate equates to a factor of 4.3; and the 95% confidence interval on the exponent 1.41 ranges from 1.01 to 1.81. Very similar regression results were obtained by Walton and Adams (1976) and Marino and Mehta (1987, 1988) for tidal deltas on the Atlantic, Gulf of Mexico, and Pacific coasts of the United States and on the east coast of Florida, respectively (Table 2, Figure 9). This strong influence on ebb delta size by tidal prism size appears to be because (1) the momentum and hence offshore extent of the ebb tidal jet is directly related to the ebb discharge, and (2) the delta deposit scales with the length of the ebb jet, as has been demonstrated experimentally (*e.g.*, Sill et al., 1981) and analytically (*e.g.*, Özsoy, 1986).

Although the regression coefficient for equation (1) is significant, the large factorial standard error and the obvious scatter in Figure 9 point to other controls on sand volume besides the tidal prism. Other partial correlations suggested that ebb delta volume also increases with decreasing wave en-

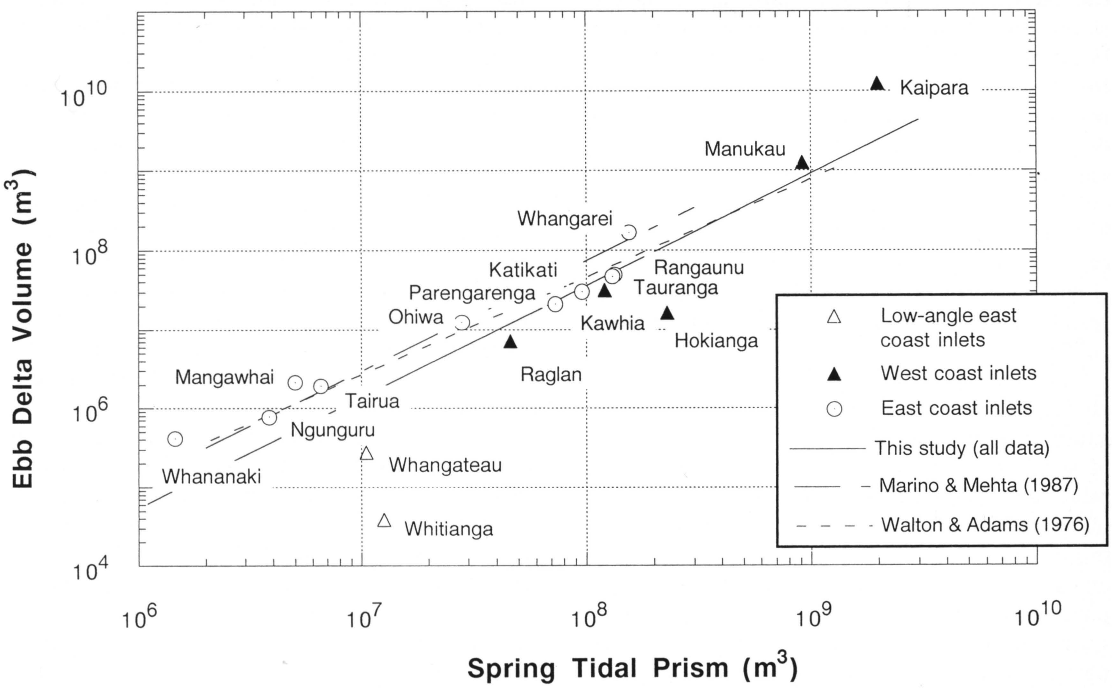

Figure 9. Relationship between ebb delta sand volume and tidal prism. Symbols distinguish inlets on the higher wave energy west coast, the lower wave energy east coast, and cases where the angle between the ebb jet and the barrier shoreline is low.

ergy (Ew), decreasing sand grainsize (d_{50}), and increasing sine of tidal jet angle ($\sin \theta$). A multiple regression analysis on these parameters yielded the following model:

$$V = 1.37 \times 10^{-3} P^{1.32} (\sin \theta)^{1.33} \qquad (2)$$

The r value for this is 0.91 and the standard error represents a factor of 3.5, only slight improvements over equation (1). The wave energy and grainsize parameters made no significant contribution to the model and were dropped.

Almost identical regression statistics to those for equations (1) and (2) were obtained by substituting inlet-throat cross-sectional area (A) for tidal prism in the regression analyses. This is to be expected given the high correlation (r = 0.99) of throat area with tidal prism for these inlets, as found previously by HEATH (1975) and HUME and HERDENDORF (1988a, 1992, 1993). The equations are:

$$V = 61.0 A^{1.51} \qquad (3)$$

$$V = 207 A^{1.40} (\sin \theta)^{1.27}. \qquad (4)$$

For equation (3), r = 0.87 and the standard error represents a factor of 4.8; for equation (4), r = 0.89 and the standard error represents a factor of 4.1. Equations (3) and (4) may be used as alternatives to equations (1) and (2) for predictive purposes as throat area is relatively easy to measure at inlets lacking bathymetric or tidal prism data.

The multiple regression analysis was repeated using dimensionless variables wherein V/P was related to W/D, A/a_o^2, $\sin \theta$, L/P, R/P, $d50/a_0$, and Hs/a_0. Again, only the ebb jet angle made any significant contribution to the regression model, which was:

$$V/P = 0.35 (\sin \theta)^{1.42} \qquad (5)$$

The regression coefficient for this model is 0.52 and the standard error equates to a factor of 4.4.

The angle between the ebb jet and the barrier shoreline appears to influence delta sand volume in two ways. First, the more shore-normal the ebb outflow, the greater the water depth and the more space there is available for a deposit to grow atop the 'background' nearshore topography. Second, as the ebb jet angle becomes more acute, there is less direct conflict of tidal and wave energy. Since the ebb jet flows more parallel to wave crests, the waves can more efficiently return shoreward sand deposited from the ebb jet. These effects are most apparent at Whitianga and Whangateau (the two outliers below the general V vs. P trend on Figure 9) where the ebb channels are forced by bedrock controls to emerge at very low angles, deposition is confined to shallow nearshore areas, and the resultant 'low-angle half-deltas' are very small in volume.

The limitations of the multiple regression models (2), (4), and (5) should be appreciated. Considering their standard errors, the limited range of some input parameters (*e.g.*, sand size), the relatively few data points (and hence few degrees of freedom), and the large uncertainties with some input parameters (notably delta volume, wave energy, and littoral drift rate), the exclusion of a parameter from the final models does not necessarily discount the possibility that it influences delta volume. Other considerations, too, are whether there has been sufficient time and sand available in the littoral system for the ebb deltas to build to equilibrium size.

WALTON and ADAMS (1976) and MARINO and MEHTA (1987, 1988) believe that at least some of the data scatter in their delta volume *vs.* tidal prism relationships results from a trend for decreasing delta volume with increasing wave energy (for a given tidal prism). This can be explained by at least two effects: (1) wave radiation stress reducing the effective momentum of the ebb jet and thus its offshore penetration, and (2) waves driving sand deposited from the ebb jet back onshore into shallower water and hence requiring less sand to build the delta to its equilibrium depth.

The same trend is suggested when our data are separated into either west coast 'high-energy' or east coast 'moderate-energy' wave climates (Figure 9), particularly when Hokianga is removed from the west coast group (as discussed in the following section, the Hokianga delta is possibly starved of sand and may not yet have grown to its equilibrium size) and Whangateau and Whitianga are removed from the east coast group (both are 'low-angle half-deltas' with very low ebb outflow angles). Regression equations for these two groups have slopes and intercepts that are significantly different at the 5% level (Table 2), although the few degrees of freedom for our west coast group limits the value of these statistics.

MARINO and MEHTA (1987) interpret from their Florida dataset a trend for increasing delta volume (for a given tidal prism) with decreasing inlet width/depth ratio (although their data show no correlation between V/P and W/D that is significant in the statistical sense). Conceptually, this relationship might be expected since a deeper inlet channel is liable to be associated with an ebb jet that extends further offshore and inlets exposed to greater wave energy tend to have shallower entrances (*e.g.*, FITZGERALD and FITZGERALD, 1977). A similar trend is not shown by the New Zealand data, however, probably because it is masked by other effects.

An inverse relationship between ebb delta sand volume and sand size is expected, since coarser sediment settles more rapidly from suspension in ebb-tidal jets (ÖZSOY, 1986) and is also held closer and more steeply against shores by wave action. Such a relationship was suggested in this study by the partial correlation analysis, but lacked a sufficient level of significance to justify inclusion in the regression models. The small range in sand size (0.13 to 0.40 mm) severely limits our ability to recognise this influence.

The Hokianga ebb delta has a sand volume approximately one tenth of that expected of a west coast delta with the same tidal prism (Figure 9), suggesting that it has not yet grown to its equilibrium size. We hypothesize that this is because it has been relatively starved of littoral drift sand while the huge Kaipara delta updrift to the south has grown, capturing much of the littoral drift being transported along the North Island west coast during the Holocene. This hypothesis may also explain why no obvious sink can be found for littoral drift sand at the northern tip of the North Island. The extensive shoals of Pandora Bank, west of Cape Reinga, are largely bedrock; modern fine detrital sands characteristic of the North Island west coast littoral drift system occur there only in thin belts near the shore and around the shallower, higher energy parts of the bank (SUMMERHAYES, 1969a,b). Further indicators that the Kaipara ebb delta is trapping littoral drift are: (i) approximately 80% of the volume of the ebb delta lies on the updrift side of the inlet, and (ii) the seabed sediment out to the delta margin, 14 km offshore, is fine sand similar in size to the Kaipara beach sand (MCDOUGALL and BRODIE, 1967; L. CARTER, *personal communication*).

Implications for Coastal Management

The New Zealand ebb deltas collectively represent a potentially huge reservoir of sand for industry and beach renourishment. Equations (1) or (2), or the equivalent relationships between sand storage and inlet throat area (Equations 3 and 4), can be used to estimate sand volumes at inlets not covered in this study and also the total volume of the sand resource on littoral cell and national scales. In the absence of more detailed information, such as might be obtained from a numerical model study, an estimate of the amount of sand in storage at an ebb delta is probably the best indicator of the amount of sand that can be mined safely from it before the stability of the adjacent shoreline is compromised by interrupted sand by-passing and diminished wave shelter.

The influence of the ebb jet angle on delta size and shape suggests that these features could be modified by using jetties to direct the inlet outflow angle. For example, by deflecting a shore-normal outflow to a low angle, the new delta should have a much smaller volume, with the surplus sand being available for mining or beach nourishment.

The effect of rising sea-level on ebb delta volume should depend on how the tidal prism changes. Little change in tidal prism should occur in a steep walled inlet or one where sedimentation keeps pace with the rising sea-level. However, the tidal prism could increase appreciably for a shallow inlet with extensive intertidal areas and/or a low-lying hinterland. In such cases, the ebb delta could be expected to grow until a new equilibrium was established with the larger tidal prism. Littoral drift by-passing could wane while these ebb delta adjustments were occurring, with detrimental impacts on the downdrift coast. Downdrift effects could be particularly severe on coasts with a strong littoral drift regime, such as along the North Island west coast, and where ebb deltas trap a significant proportion of the total sand resources of the littoral cell. FitzGerald (1988) describes cases from the North American east coast and the Friesian Islands where historical changes in tidal prism have resulted in changes to ebb delta volumes.

Manipulation of equation (2) may be used to estimate the changes in ebb delta volume expected with changes in tidal prism and/or ebb jet angle (assuming that equation (2) represents an equilibrium relationship). From equation (2), the differential of delta volume is:

$$dV = dP\,\partial V/\partial P + d(\sin\theta)\,\partial V/\partial(\sin\theta) \quad (6)$$

and the partial derivatives are:

$$\partial V/\partial P = 1.81 \times 10^{-3} P^{0.32} \sin\theta^{1.33} \quad (7)$$

and

$$\partial V/\partial(\sin\theta) = 1.82 \times 10^{-3} P^{1.32} \sin\theta^{0.33} \quad (8)$$

thus

$$dV/V = 1.32\, dP/P + 1.33\, d(\sin\theta)/\sin\theta \quad (9)$$

For example, at Manukau Inlet, which has a delta volume of 1.25×10^9 m^3 and an ebb outflow angle of 88° and with no change in outflow angle (*i.e.*, $d(\sin\theta) = 0$), a 10% increase in tidal prism associated with a sea-level rise would require the delta to grow by 13%. This amounts to 160 million m^3 of sand, equivalent to almost 1,000 years of the present littoral drift sand supply at Manukau. Even allowing that some of the sand added to the ebb delta would derive from scour of the tidal inlet, these estimates clearly show how even a modest relative increase in tidal prism at large inlets might lead to profound impacts on the littoral sediment budget and the stability of coasts downdrift from inlets (as found previously by, *e.g.*, FitzGerald, 1985, 1988).

By setting $dV = 0$, equation (9) also may be used to estimate the reduction in ebb jet alignment required to offset the increase in sand storage that would be associated with an increase in tidal prism:

$$d(\sin\theta) \approx -dP \sin\theta/P \quad (8)$$

For example, given that an inlet has an outflow angle of 60° and a predicted 20% increase in tidal prism associated with a sea-level rise, then the delta volume would not increase if the inlet outlet was trained to an outflow angle of 44°.

At an inlet where no change in tidal prism resulted from a rise in sea-level, reduction of the ebb outflow angle with training jetties could be used to decrease the equilibrium size of the ebb delta and so free-up sand for stemming the retreat of nearby beaches. For example, at 2,600 m long Pauanui Beach beside Tairua Inlet (Figure 1), a 0.5 m rise in sea-level might be expected to induce a beach retreat of 27 m (based on Bruun's 1962 equation, using a foredune-crest to closure-depth distance of 700 m and elevation difference of 13 m). This retreat could be offset with the addition of 9×10^5 m^3 of sand to the beach sediment budget. From equation (9), this sand volume could be obtained from the Tairua ebb delta (present sand volume equals 2.15×10^6 m^3) if its outflow angle was trained to be 31° instead of its present 48°. The impact of the inlet training on navigation and the changed pattern of wave shelter around the inlet shoreline would, of course, be additional issues to consider.

CONCLUSIONS

The primary controls on the shape of the New Zealand North Island ebb deltas are wave and tidal energy and shoreline configuration. These controls are highly interactive, particularly on embayed coasts where the bedrock controlled shoreline configuration influences wave shelter and the alignment of the ebb tidal jet. 'Free-form' deltas occur on relatively straight coasts; they become progressively elongate alongshore as the ratio of wave to tidal energy increases. 'Constricted' deltas occur at shoreline angles receiving some wave shelter and where there is insufficient space for a 'free-form' shape to develop. 'High-angle half-deltas' are typically shore-normal deposits that occur only on the barrier side of inlets in embayments where the ebb jet flows against a headland. 'Low-angle half-deltas' are more shore-parallel features that form on the barrier side of an inlet where the ebb jet is directed at a low angle to the barrier by a rock shore.

The major controls on ebb delta sand volume are primarily the volume of the tidal prism and secondarily the angle of inlet outflow with respect to the shoreline. Delta volume also appears to increase with decreasing wave energy, with west coast deltas tending to be smaller than east coast deltas with similar tidal prisms. Sand volumes ranged over six orders of magnitude, from 3.8×10^4 m^3 at Whitianga to 1.23×10^{10} m^3 at Kaipara.

Rising sea-level should cause ebb delta sand storage to increase if the rise results in a larger tidal prism. This sand entrapment could potentially place coasts downdrift from large inlets in a severe sand-deficit situation. Manipulation of the inlet outflow angle with training jetties offers a possible means of controlling sand storage at ebb deltas, perhaps to 'free-up' littoral sand to offset the effects of sand mining or a rise in sea-level.

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