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Determining Sand Volumes and Bathymetric Change on an Ebb-Tidal Delta

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ABSTRACT

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The bathymetry on and around an ebb-tidal delta at a natural headland and barrier-bound inlet on the Bay of Plenty coast, New Zealand, was surveyed using a modern, integrated echo-sounding and navigation system. The survey aims were to define the morphology of the ebb delta and nearby inner shelf, shoreface and beach and to assess the accuracy of the survey method for determining changes in bed levels and sand-storage volumes on the ebb delta. Alternate cross-shore track-lines, spaced at 100 m intervals on a box-grid measuring 2.2 by 4.4 km, were surveyed on two consecutive days; the duplicate bathymetry datasets so obtained were used to assess and survey repeatability and accuracy. Rectangular-grid, digital-terrain models were fitted to these bathymetry datasets. A triangulation surface-fitting method was adopted, although examination of volume calculations and residuals statistics showed that there was little difference between this and methods such as kriging and inverse-distance weighting. The duplicate surveys showed that the accuracy of the surface-fitting and determinations of mean surface levels varied depending on the local seabed topography. On the shoreface and inner shelf, where the topography varied broadly, the mean bed-level uncertainty was only ±4 mm, while on the ebb-delta platform with its high-relief channels and bars the uncertainty was ±54 mm. The higher error over the ebb delta resulted mainly from the track spacing; errors due to the grid-fitting and volume calculations were trivial in comparison. These results meant that repeat surveys with the same track-line spacing could only be expected to detect net sand gains over the ebb delta system exceeding 160,000 m^3. This uncertainty exceeds the annual net littoral drift at this location. A main conclusion is that to detect net sand gains or losses over an ebb delta such as the example studied, track-line spacings should be tailored to the topography with denser spacings over channels and bars. Reconnaissance surveys and/or aerial photographs should be used to plan such optimal trackline strategies. Duplicate surveys over representative morphologic zones are also recommended to confirm the survey accuracy and to test for systematic errors such as those due to the tidal correction.

ADDITIONAL INDEX WORDS: *Bathymetry, soundings, digital-terrain model, tidal inlet, ebb-tidal delta.*

INTRODUCTION

Measurements of the changes in shape and volume of sand stored in ebb-tidal deltas are required for a variety of reasons. For inlets serving as harbour entrances, the harbour's operational efficiency is limited by changing sea and depth conditions over the ebb-delta bar; thus, localised charting of the channels across the ebb delta permits safer navigation and assessments of maintenance dredging requirements. Charting over much wider areas of the delta and surrounding sea bed are necessary for scientific studies and engineering purposes where knowledge of the sedimentary processes over the delta is required. For example, bathymetry data can be used to assess the storage, exchange, and flux of sediment through a delta and is the ground-truth data for calibrating and checking numerical models of seabed deposition and erosion.

Ebb deltas have a significant impact on the local coastal sedimentary budget, because they act as valves on the coastal sedimentary supply, regulating the sand exchange between estuaries and the open coast; and they trap coastal sand swept along the shore by wave action. Also, the surface shape of an ebb-tidal delta determines how wave energy is focussed on adjacent coastal beaches and how waves propagate into the inlet, and thus, influence shoreline erosion on the adjacent beaches and within the inlet. Minerals or beach nourishment, measurements of sand storage and morphodynamics are part of environmental studies to assess sustainability of the resource and the impacts of mining. Where the sand in ebb deltas is mined for building aggregate, minerals or beach nourishment, measurements of sand storage and morphodynamics are part of impacts of mining.

At a broad scale and over longer time frames, the total amount of sand stored in an ebb-tidal delta is fairly constant, being controlled mainly by the tidal prism (WALTON and ADAMS, 1976; HICKS and HUME, 1991; HICKS and HUME, in press). In headland-dominated coastal settings, the overall shape of the sand body doesn't change much as the headland limits the lateral spread of the sand body (HUME and HERDENDORF, 1992; HICKS and HUME, in press). However, anthropogenic activities such as dredging and placing structures (*e.g.,* jetties) in the littoral zone nearby can result in changes in delta morphology. In comparison and at a more

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detailed level, there is continuous and highly variable change, both in a spatial and temporal sense, in surface shape of an ebb-tidal delta and in the volume of sand stored. This change is forced by periodic fluctuations in tidal flows and in a highly episodic and variable manner during storms by fluctuations in waves, surge and littoral drift supply.

Good measurements of the temporal changes in the surface shape of an ebb-tidal delta are necessary in order to understand and quantify the morphodynamic processes on the delta and to be able to model sediment transport. Small changes in bed level may equate with massive sediment fluxes and changes in sediment storage. It is important in the interpretation of surveys of bathymetric change to be able to differentiate the shorter-term and local variations (*i.e.*, 'noise') from the longer-term larger-scale change.

Today, with the availability of sophisticated navigation, sounding and tide measuring equipment and software to process the data, it is possible to measure and monitor changes in delta shape very accurately and with greater spatial detail, output the data in visually attractive and useful form, and then readily manipulate it. The limitations on getting a very detailed and high quality data set include matching equipment availability with windows of suitable sea state and the time and expense of doing the survey. Spatial detail is usually traded against cost, but this trade-off must ensure that the sampling error is not so large that topographic features are inaccurately registered (*i.e.*, smoothed, aliased, or missed altogether) or depth and volume changes meaningless.

In this paper, we examine a detailed bathymetric data set from a large ebb-tidal delta in the Bay of Plenty, New Zealand in order to establish how detailed a survey must be to give useful information on delta shape and processes and sand-storage volume and the implications of this for computations of sediment budgets, calibrating models, and monitoring programs.

SITE CHARACTERISTICS

The bathymetry dataset used in this study was from Katikati Inlet, the northern entrance to Tauranga Harbour in the Bay of Plenty, New Zealand. As with many of the tidal inlets on the New Zealand coast, Katikati Inlet has positional stability (HUME and HERDENDORF, 1992), being anchored on the northern shore by a rock headland, while its southern shore comprises the mobile northern extremity of the 24 km long Holocene sand barrier called Matakana Island (Figure 1). The inlet is about 400 m wide, down to 22 m deep at the throat, and drains a largely intertidal estuary of 80 km^2.

The Katikati ebb-tidal delta comprises a 'batwing-shaped' wedge of sand squatting on the shoreface (Figure 2). It is slightly asymmetric to the south, largely due to the ebb-tidal jet being trained by two rocky promontories on the headland (Figure 1). The delta protrudes some 2 km across-shore to about 20 m water depth, where its concave-seaward face merges with the flatter inner continental shelf. It is flanked by the long straight sand beaches of Waihi to the north and the Matakana barrier to the south. The beaches and the delta are comprised primarily of quartzo-feldspathic fine and very

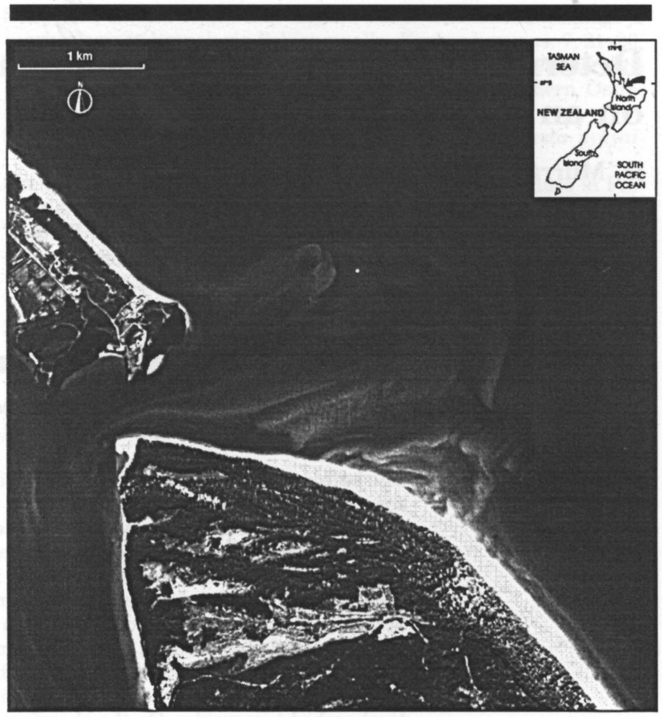


Figure 1. Aerial photograph of Katikati inlet showing the ebb-tidal delta morphology, the rocky headland at the southern end of Waihi Beach, and the Matakana Island barrier. Inset map locates Katikati Inlet in the western Bay of Plenty, North Island, New Zealand.

fine sands. There are 30 × 10^6 m^3 of sand trapped in this delta (HICKS and HUME, 1991; HICKS and HUME, in press).

While there is constant morphological change on the ebb delta, major features such as terminal lobes and lateral bars are always present in some form. The main ebb channel exits the inlet at an angle of about 70 degrees to the shore, and there is always a well formed flood-dominated channel close into the Waihi Beach shore. Across the delta, the seabed is shallow and undulating. At low spring tides, bars on the north shoulder become exposed and the crest of the central outer bar, 2 km seaward, lies only 2 m below the water surface.

The tidal range on the open coast at Katikati is from 1.27 to 1.65 m for neap and spring tides, respectively. While very strong currents run through the inlet throat, peaking at over 2 msec^{-1} on spring-ebb tides (HUME and HERDENDORF, 1992); nearshore currents away from the delta are weak (mean 0.05 msec^{-1} and maximum 0.23 msec^{-1}) and aligned principally alongshore. The wave climate in the Bay of Plenty is one of mixed storm and swell waves. The former are associated with onshore north-easterly winds which occur intermittently, associated with the passage of subtropical low pressure systems from the west (PICKRILL and MITCHELL, 1979). More rarely, decaying tropical cyclones bring high seas and storm surges. Records for the three years ending 1 March 1994 from an ENDECO wave buoy moored in 32 m water depth off Katikati Inlet give annual mean significant wave height and period as 0.8 m and 6 sec, respectively (MACKY *et*

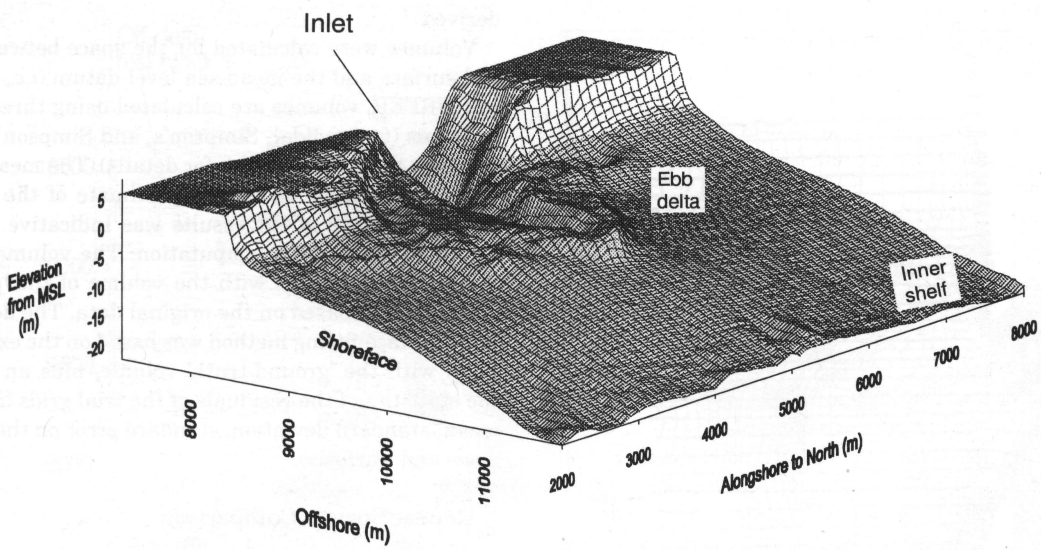


Figure 2. Digital-terrain model showing the relationship of the Katikati ebb-tidal delta to the shoreface and inner shelf. Elevations below low-tide level are shaded.

al., 1995). Storm waves recorded at the buoy typically have significant wave periods ranging from 7–12 sec, the maximum wave recorded had a height of 6.7 m, and the peak of the energy spectrum lies at a period of about 11 sec. This wave climate produces a lower-energy but more pervasive southwards littoral drift (approximately 600,000 m^3y^{-1}), which is energetically reversed during occasional easterly storms. The net littoral drift potential appears to be relatively small and can vary in direction from year to year (MACKY *et al.*, 1995).

METHODS

Data Acquisition

A detailed bathymetric survey was made of the delta and inner shelf on 8–9 December 1991. Sea conditions over this period were favourable, with an average root-mean-square wave height of 0.25 m and zero-crossing period of approximately 5 sec. Soundings were made using an ECHOTRAC sounder, and the vessel was positioned with a RACAL MICROFIX system. Profiles were run shore-normal along a preplanned boxed grid at 100 m spacings (Figure 3) that was navigated using helmsman guidance provided by the HYDRO software package linked into the echo sounder and positioning system. The survey required two days; alternate profile lines were run on each day; in effect, two separate surveys were conducted with non-overlapping lines at 200 m spacings. The average spacing of soundings along the survey lines was approximately 15 m. The survey area extended 6 km alongshore and 4 km offshore, to about 20 m water depth. The tidal-inlet throat was also surveyed.

Sounding data were corrected for tide from data recorded at an AANDERAA WLR5 tide gauge situated on the sea-bed in 8 m water depth and inside the survey grid. This minimised errors in the tide correction that can arise when water surface heights are measured at points distant from the soundings (BLAIR, 1983). The soundings were reduced to a Mean Sea Level datum which was obtained from harmonic analysis of one month of data from the AANDERAA gauge. 'Spikes' were then edited from the data using the HYDRO interactive editor. No attempt was made to smooth-out the swell.

In addition, the beach end of each of the profiles was surveyed from low water level to the top of the foredune using Emery poles and a GEODIMETER 140. The data were surveyed into bench marks and the MSL datum.

Data Processing

The survey data were analysed using the SURFER (for WINDOWS) software package (GOLDEN SOFTWARE, 1994). This uses randomly located X-Y-Z data on bathymetry to fit a rectangular gridded surface (or digital-terrain model) over the survey area. It includes utilities for computing the volume between two surfaces and to compute statistics of the errors between the actual elevations and those interpolated from the modelled surface at the sounding points (*i.e.*, the residuals). SURFER offers a variety of methods for calculating the surface grid (such as 'kriging', 'inverse distance', 'minimum curvature', 'triangulation', 'radial basis function', and so on) along with controls to tune each method towards the input data.

The data processing involved three main tasks: selecting the surface gridding method best suited to the ebb delta topography, analysing the differences between the repeat surveys, and assessing the optimal survey line spacing and direction based on the surveyed topography.

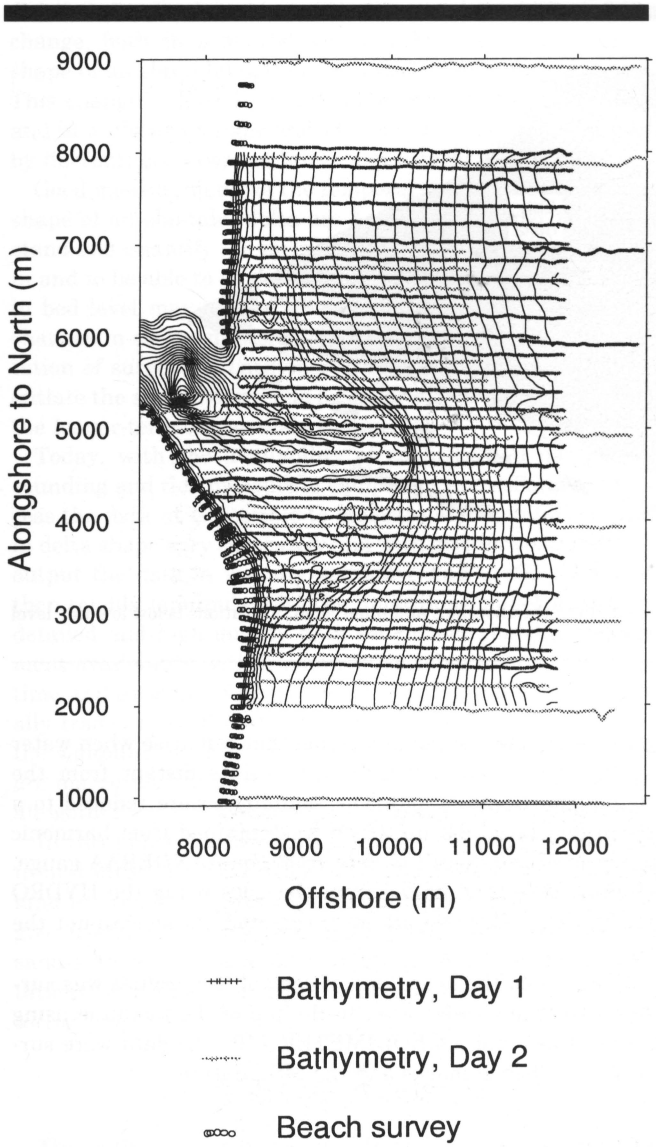


Figure 3. Layout of survey lines over ebb delta and nearby beaches, shoreface, and inner shelf. The bathymetry contour interval is 1 m.

Best Gridding Method

The first task was to identify the best surface-fitting formula for the Katikati dataset. This was accomplished by initially using the kriging method with a quadrant-search algorithm to fit a surface over the survey area using the entire dataset of soundings. This area spanned 4.5 km across-shore and 6 km alongshore. The gridding interval was 15 m in the cross-shore direction and 100 m alongshore, in keeping with the spacing of sounding points. The coordinates and elevations of this 'ground truth' grid were then used as input data for constructing comparative 'trial' grids using various grid-fitting methods packaged with SURFER. The cross-shore and longshore intervals on these trial grids were 24.9 and 80 m respectively; these were purposely different from the intervals on the original grid to ensure that the trial grid nodes did not fall on the data points from which the grids were derived.

Volumes were calculated for the space between each gridded surface and the mean sea-level datum (*i.e.*, Z = 0 plane). In SURFER, volumes are calculated using three different algorithms (trapezoidal, Simpson's, and Simpson's 3/8; refer to GOLDEN SOFTWARE, 1994, for details). The mean of the three results was taken as the best estimate of the true volume, while the range of the results was indicative of the uncertainty in the volume computation. The volumes of the trial grids were compared with the volume of the 'ground truth' grid that was based on the original data. The decision on the 'best' surface-fitting method was based on the extent of agreement with the 'ground-truth' volume, plus an inspection of the statistics of the residuals of the trial grids (*i.e.*, the range, mean, standard deviation, standard error on the mean, skewness, and kurtosis).

Repeat Survey Comparison

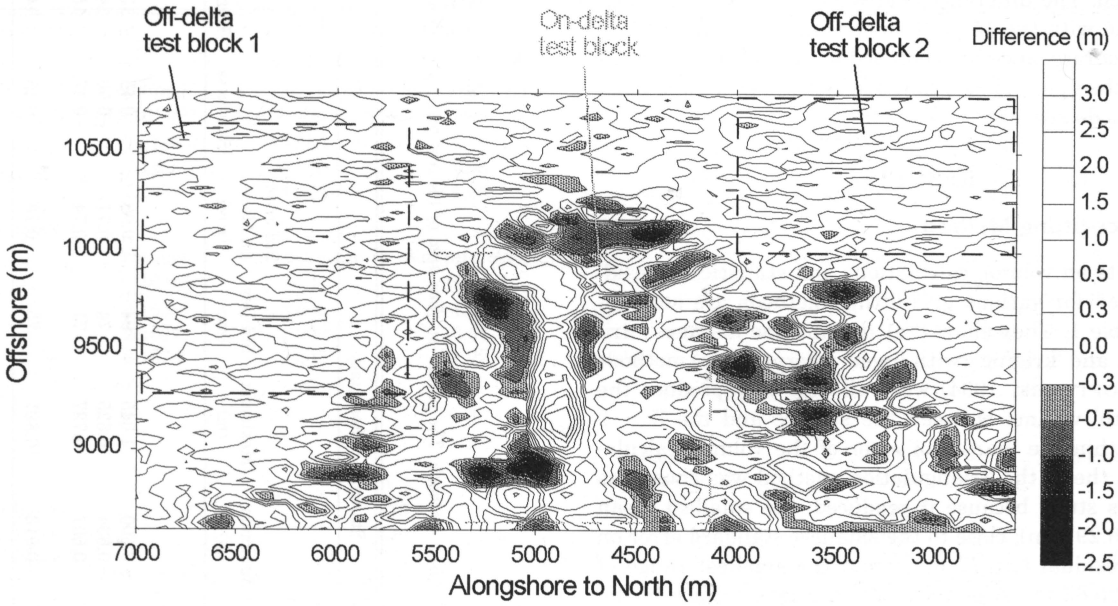
The second analysis task was to fit surfaces, using the best gridding method as identified above, to each of the two days of data and to the pooled dataset, then to compare bed levels and volumes among these three surfaces over various 'test' blocks of the survey area. By treating the two days of data as two independent surveys and by assuming negligible topographic change over the intervening day, these comparisons indicate the repeatability of the surveys, which is probably the best means of estimating the true uncertainty in measurements of the change in sand volume on the ebb delta.

The test blocks are shown in Figure 4. They included a 1,400 m square area of uneven topography (including bars and channels) on the ebb delta surface (on-delta test block), a 1,400 m square area of fairly uniform topography on the inner-shelf/shore-face on the northern flank of the delta (off-delta test block 1), a similar 1,400 × 800 m area on the south flank of the delta (off-delta test block 2), and the whole 4.4 km × 2.2 km area of ebb delta and inner-shelf/shore-face covered by both days of survey. The gridding intervals were always 30 m across-shore and 50 m alongshore.

Surface volumes were calculated as described above. Volume differences between surfaces were converted to equivalent differences in mean bed level by dividing the volume by the planar area of the blocks. A difference grid was created by subtracting the Day 1 survey grid from the Day 2 grid and was used to locate where the greatest errors in surface modelling occurred.

Optimal Survey Line Configuration

The third task was to utilise the actual survey data to identify the optimal spacing and direction of future survey lines, *i.e.*, the minimum spacing, running either across-shore or alongshore, that would yield a sand volume measurement of acceptable accuracy. This involved extracting X-Y-Z datasets at a variety of cross-shore and longshore data-point spacings from the detailed surface fitted to the original bathymetry data. In all, 25 synthetic bathymetry sets were created, with point spacing ranging from 15 to 199 m across-shore and 25 to 400 m alongshore. Grid surfaces were then fitted to each



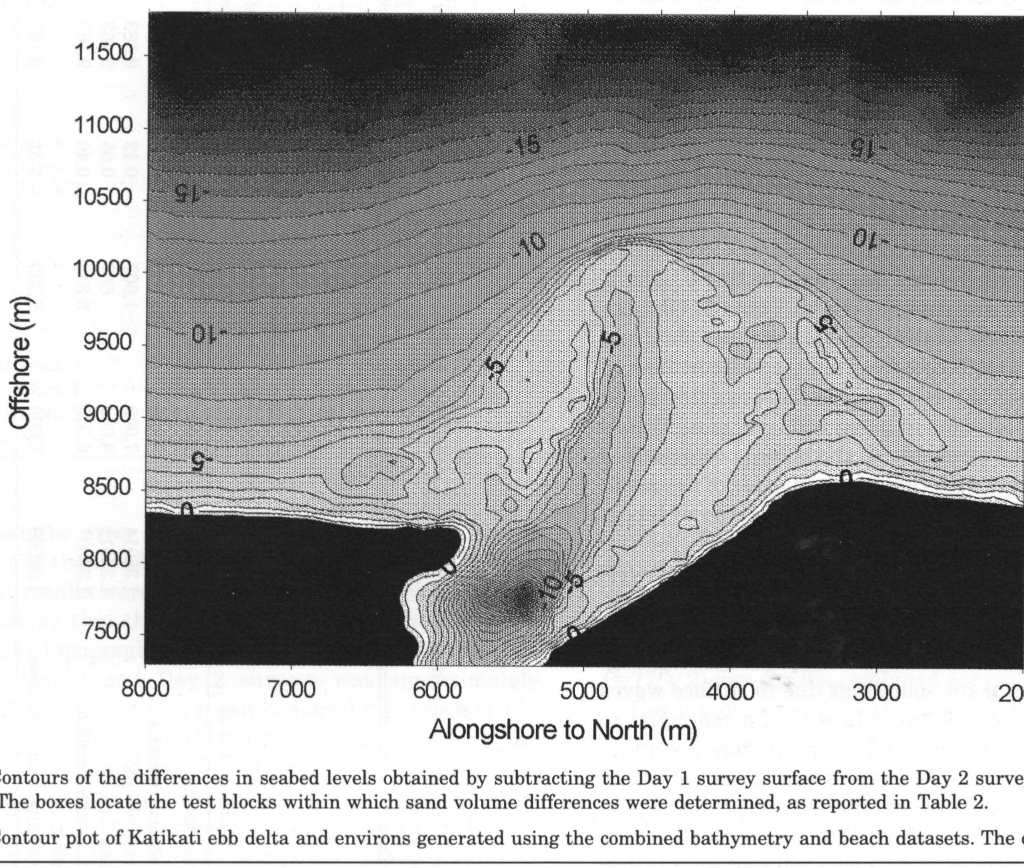


Figure 4. Contours of the differences in seabed levels obtained by subtracting the Day 1 survey surface from the Day 2 survey surface. Contour units are metres. The boxes locate the test blocks within which sand volume differences were determined, as reported in Table 2.

Figure 5. Contour plot of Katikati ebb delta and environs generated using the combined bathymetry and beach datasets. The contour interval is 1 m.

dataset, using the same node spacings and gridding procedure for each. The differences between the mean bed levels over the grid with the 15 × 25 m spacings, considered to be the most accurate, and the mean bed levels over the other 24 grids were then plotted as a function of cross-shore and longshore grid-node spacing.

RESULTS

Best Surface-fitting Method

The results on volume calculations and statistics of residuals obtained for various grid-fitting methods are summarised in Table 1. They show that the 'inverse distance', 'triangulation', and 'kriging' (with linear interpolation) methods (GOLDEN SOFTWARE, 1994) were all able to reproduce the 'ground-truth' volume between the surface and the Z = 0 plane to within the margin of error of the volume calculations. From these, the 'triangulation' method was chosen as best for this study because it produced: the smallest mean residual (−0.29 mm); close to the smallest standard error on the mean residual (±0.77 mm); and the smallest range of residuals (±0.63 m). A perfect fit of the grid surface to the data would produce zero values for these statistics. A non-zero mean of residuals indicates any net bias in the surface fitting, and so also in the volume or mean-bed-level computation, while the standard error of the mean of residuals indicates the uncertainty in this bias. Thus the results suggest that the mean bed level over the test area produced by the 'triangulation' method was biased by −0.29 ± 0.77 mm. The bias associated with the other grid-fitting methods was also of the order of 1 mm, making these methods only marginally less accurate than the triangulation method.

Repeat Survey Comparison

Results showing the calculations of volumes and differences in mean bed levels determined from the Day 1, Day 2, and combined surveys are summarised in Table 2. On both of the 'off-delta' test blocks that cover areas of inner shelf and shoreface of relatively uniform topography on either flank of the ebb delta (Figure 4), the discrepancies between the repeat surveys amount to differences in mean bed level of 6–10 mm. This is larger than the error due to the volume calculations (1–3 mm) but consistent with the standard error of the mean residual. These figures suggest that over this type of topography, the main source of the discrepancy between the two surveys lies in the grid fitting, while there is negligible systematic error between the two datasets (such as could be expected from the tidal correction) and negligible bias induced by the non-correction of water surface waves. The latter suggests that the error in point soundings due to surface waves can be treated as a random variable with a mean equal to zero. The differences between the Day 1 and Day 2 surveys suggest that the true mean bed levels over these 'off-delta' blocks was established to ±3–5 mm for 200 m spacing of survey lines. The result of the combined survey with twice the density of lines is expected to be more reliable than either single day survey. We estimate an uncertainty of ±4 (= $5/\sqrt{2}$) mm for the combined survey with 100 m spacings (as-

Table 1. *Comparison of volume calculations and statistics of residuals for surfaces fitted to test dataset using various gridding methods. The planar surface area of the test bathymetry block was 1.339 × 10^7 m^2.*

Gridding Method	Volume Calculations				Statistics of Residuals							
	Volume ($m^3 \times 10^7$)	Error in Volume Calc. (±m^3)	Difference from Ground-truth (m^3)	Equivalent Diff. in Mean Bed Level (mm)	Number of Datapoints	Mean (mm)	Minimum (m)	Maximum (m)	Std Dev (mm)	Std Error on Mean (mm)	Skewness	Kurtosis
Ground-truth	1.36012	12,000										
Minimum curvature	1.36073	13,000	−61,000	−4.55								
Inverse distance	1.36014	7,000	−1,667	−0.12	9,163	−0.41	−0.600	1.045	94	0.98	0.45	13.2
Triangulation	1.36012	6,000	667	0.05	9,163	−0.29	−0.634	0.625	74	0.77	−0.50	14.8
Radial basis function	1.36007	6,000	5,333	0.40	9,163	−0.57	−0.607	0.727	71	0.74	−0.37	15.0
Kriging (with linear interpolation)	1.36009	6,000	3,333	0.25	9,163	−0.49	−0.613	0.801	75	0.78	−0.15	14.6

Table 2. *Volumes, residuals, and differences in volumes and mean bed levels for surfaces fitted to Day 1, Day 2, and combined bathymetry datasets for greater survey area and test blocks on and off the ebb delta.*

a. Volumes

Greater area	Volume ($\times 10^7$ m^3)	Vol calc. error (m^3)	Vol calc. error (mm)	On-delta test block	Volume ($\times 10^6$ m^3)	Vol calc. error (m^3)	Vol calc. error (mm)
Day 1	7.2186	13,500	1.39	Day 1	8.4382	6,480	3.31
Day 2	7.1956	9,300	0.96	Day 2	8.1386	4,530	2.31
Combined	7.2038	14,300	1.48	Combined	8.2431	13,200	6.76
Off-delta test block 1	Volume ($\times 10^7$ m^3)	Vol calc. error (m^3)	Vol calc. error (mm)	**Off-delta test block 2**	Volume ($\times 10^7$ m^3)	Vol calc. error (m^3)	Vol calc. error (mm)
Day 1	2.1656	3,800	1.94	Day 1	1.178	3,600	3.21
Day 2	2.1677	1,200	0.61	Day 2	1.1787	900	0.8
Combined	2.1678	2,400	1.22	Combined	1.1788	1,300	1.16

b. Residuals

	n	Mean (mm)	Std dev. (mm)	Std error of mean (mm)
Day 1				
On-delta test block	679	8.79	152.50	5.85
Off-delta test block 1	630	−2.05	121.28	4.83
Off-delta test block 2	354	−2.84	122.54	6.51
Greater area	3,163	0.98	152.51	2.71
Day 2				
On-delta test block	669	8.90	168.17	6.50
Off-delta test block 1	613	−3.51	96.49	3.90
Off-delta test block 2	324	−1.17	87.71	4.87
Greater area	3,073	4.81	134.54	2.43
Combined				
On-delta test block	1,348	0.37	182.60	4.97
Off-delta test block 1	1,243	−2.28	108.98	3.09
Off-delta test block 2	678	1.37	109.33	4.20
Greater area	6,236	1.21	148.18	1.88

c. Differences

	Day 2 − Day 1		*(Day 2 + Day 1)/2 − Combined*	
	Volume (m^3)	MBL (mm)	Volume (m^3)	MBL (mm)
On-delta test block	299,640	153	45,380	23.1
Off-delta test block 1	−20,270	−10.3	−11,570	−5.9
Off-delta test block 2	−7,130	−6.4	−4,700	−4.2
Greater area	230,030	23.8	33,550	3.5

suming that the error would diminish in proportion to the square root of the number of sampling points).

Different results were found for the 'on-delta' block; Figure 2 clearly shows that the channels and bars created a much less uniform topography. There, the volume difference between the Day 1 and Day 2 surveys was approximately 300,000 m^3, equivalent to a mean bed level difference of 153 mm. This is much larger than the uncertainty due to the volume calculation and grid-fitting methods, and a large systematic error associated with the tidal correction can be ruled out (since there is no evidence for this over the 'off-delta' blocks). Thus we believe the discrepancy relates mainly to inadequate spacing of the survey lines over this area of sharply varying topography. Across the central region of the delta in particular, high-relief channels and sand bars are aligned nearly parallel to the survey lines (Figure 3), and the 200 m spacing does not sample them sufficiently. Given the ± 77 mm uncertainty in the mean bed level measured for the 200 m spacing surveys, we estimate an uncertainty of ± 54 ($=77/\sqrt{2}$) mm for the combined survey with 100 m spacings.

The inaccuracies over the ebb delta dominate the uncertainty in establishing sand volume changes over the greater survey area, which covers both the ebb delta and the surrounding inner shelf and shore face. There, the volume difference between the Day 1 and Day 2 surveys was 230,000 m^3, equivalent to a mean bed level difference of 24 mm (Table 2). Again assuming that the uncertainty might reduce by a factor of $\sqrt{2}$ with halved line spacings, this result suggests

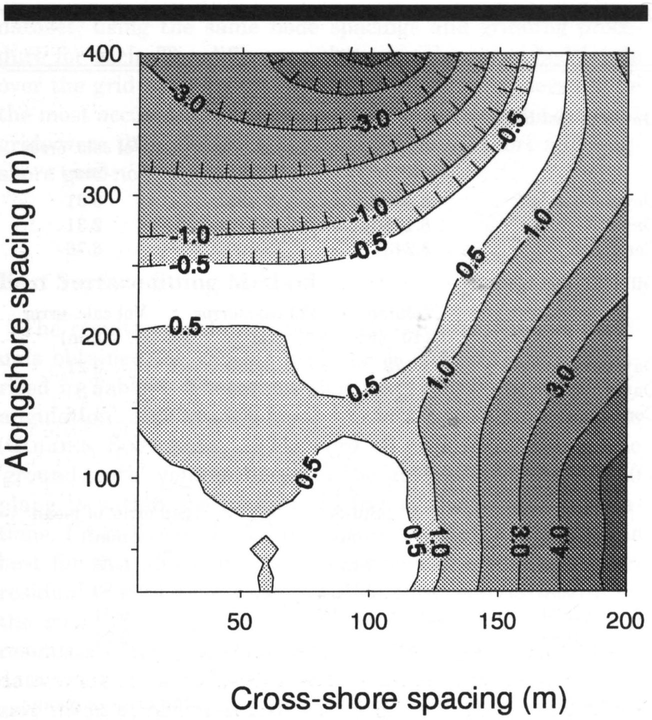


Figure 6. Contours of the error in mean bed level (in mm) over the greater survey area for surfaces gridded using synthetic datasets with various longshore and cross-shore spacings of soundings. Hachures indicate negative differences.

that with 100 m survey line spacings, net sand gains or losses over the ebb delta system can be established to ±81,000 m^3.

The source of this uncertainty shows clearly in a contour plot of the differences between the Day 1 and Day 2 surveys (Figure 4). This 'ghosts' the ebb delta form, particularly the disposition of major bars and channels (compare Figures 4 and 5). Off the ebb delta, the differences are relatively insignificant.

The conclusions are (i) that the 1991 bathymetry survey at Katikati was able to establish changes in mean bed levels to about ±4 mm over the simple topography of the inner-shelf/shoreface, but to only about ±54 mm over the ebb delta area, and (ii) that the same survey approach could not be expected to reliably detect net sand volume gains or losses over the ebb delta system that were less than approximately 160,000 m^3.

Optimal Sounding and Survey Line Spacing

The results from the 25 simulated surveys with various sounding-point spacings in the cross- and longshore directions are shown in Figure 6. This plots the differences in mean bed level in mm (over the 2.8 km by 4.8 km area) for each simulation from the mean bed level for the simulation with the densest spacing of soundings (15 m across-shore by 25 m alongshore). Positive differences indicate mean bed levels lower than this 'ground-truth' surface, while negative differences indicate the reverse.

The plot suggests that reasonable survey results should be expected with soundings spaced up to about 260 m apart alongshore and 120 m apart across-shore. At greater spacings, the inaccuracy increases rapidly. The high positive differences at high cross-shore spacings reflects a bias in the surface-fitting induced by the non-linear, concave-up shore profile, while the high negative differences with wide longshore spacings reflect bias associated with the generally convex-up profile alongshore across the ebb delta.

These results do not agree with the much higher (24 mm) differences in mean bed levels observed between the Day 1 and Day 2 surveys (with 200 m alongshore and 15 m across-shore spacings). This suggests that the base surface for the simulations, even though fitted to data at 100 m longshore spacings, was too smooth a representation of the real topography, at least over the ebb delta. Thus while Figure 6 might be useful for planning future surveys over the regular inner-shelf/shoreface, it is not useful for surveys over the ebb delta.

DISCUSSION

Survey Strategy and Accuracy

Several practical lessons arise from this study that can be applied to repeat surveys that propose to define changes in morphology and sand storage on ebb deltas of similar size and form to the Katikati delta.

The first is that it is possible to detect changes in mean bed levels and sand volumes over simple, broad seabed topographies to considerable accuracy with modern integrated echo-sounding, navigation, and sea-level recording technology, a 'saturation' survey approach, and numerical surface-fitting by computer. Given mild sea-state conditions, an adequate density and coverage of soundings and cross-shore survey lines, it appears that the error in boat-made soundings due to surface gravity waves can be treated as a random variable with zero mean and so can be ignored. Likewise, errors due to surface-fitting algorithms and volume calculation methods also appear essentially random and tend to cancel out.

The second lesson is that the reliability can diminish rapidly where the spacing of survey lines is inadequate to define sharply varying topography, such as the channels and bars found on ebb delta platforms.

It follows that the spacing of survey lines should be tailored to topography with a higher density of lines over the delta platform area. Towards this, a prior reconnaissance is suggested that would identify the wavelength and orientation of morphological features on various parts of the survey area. This might be made by boat and/or from aerial photographs (*e.g.*, Figure 1). Tracklines based on this reconnaissance information could then be entered into the tracking-guidance software for subsequent surveys.

Another factor in setting the survey spacing is the level of accuracy required. This should match the magnitude of the expected changes in morphology or sand volume over the time-frame of interest. For example at Katikati, our conclusion was that under similarly favourable sea conditions we should be able to repeat the same 100 m line-spaced survey and detect any net gain or loss of sand on the ebb delta system larger than 160,000 m^3. Our estimate of the longshore sand transport potential, obtained by applying the CERC formula to data from the nearby directional wave buoy, suggests that the average annual net littoral drift rate in the vicinity of the Katikati inlet lies within this 160,000 m^3 error margin (MACKY *et al.*, 1995). Thus, regular, annual surveys of this ebb delta system would likely show inconclusive change. Similarly, surveys before and after individual storms, for which the littoral drift at Katikati can be as high as 200,000 m^3 per storm, would at best be only able to establish the sign of any net sand volume change over the delta. Only after a spate of large storms from the same direction (as do tend to occur in the Bay of Plenty) would it be possible to measure a change in sand volume that was larger than its uncertainty.

Thus, if our aim at Katikati was to conduct repeat surveys requiring a highly accurate determination of sand level change, such as to calibrate a numerical model, then our 1991 survey would not have been a sufficiently accurate start. For this purpose, a survey line spacing of the order of 25 m would have been necessary, at least over the major bars and channels. Conversely, if our aim was to detect broad changes in sand level larger than a few cm on the nearby shoreface, then our 1991 survey would have sufficed. Also, if our aim was simply to measure the total volume of sand in storage on the ebb delta above the general trend of the local shoreface and inner shelf (3.0×10^7 m^3—HICKS and HUME, 1991), then we accomplished this with an error less than 1%.

Another lesson is that duplicate surveys are invaluable for confirming assumptions such as the effect of errors due to surface waves and the tidal correction and for establishing the uncertainty due to sounding density. The whole survey area need not be repeated, but test areas representative of various topographies should be. The additional time required in the boat, once equipment has been set up, is a small cost compared to the overall investment in a modern survey. Such duplicate surveys are considered essential where the aim of the survey is to accurately detect net sand volume changes, such as for a littoral sand budget or for calibrating or testing a numerical morphological model.

Finally, over periods longer than a few years, additional systematic errors can enter repeat surveys such as those due to changes in operators, boats, equipment, navigation systems, and so on. Such errors are difficult to detect unless some stable reference surface is resurveyed each time.

Advantages of Saturation Surveys and Numerical Surface-fitting

'Saturation'-type bathymetry surveys and numerical methods for fitting surface grids offer several advantages for analysing seabed morphologic change over the classical 'manual' approach of re-sounding the same track-lines. Foremost are the greater precision and objectivity of the modern methods, particularly for interpolating between survey lines; although as this study has demonstrated, this can become a liability when the survey density is low! Not having to reoccupy the same lines eliminates another source of error and can lead to considerable time savings. Lastly, once the survey data have been transferred into a digital-terrain model, it can be readily manipulated and graphically displayed; computer packages such as SURFER can produce often stunning visualisations that greatly assist morphodynamic interpretation.

An interesting result of this study was the minimal differences among the gridded surfaces generated by the various surface-fitting methods. In large part, this can be explained by the rectangular layout of the bathymetry dataset, the use of grid intervals similar to the data spacings, using appropriate directional 'search rules' (for example, using some data points from each quadrant for the 'inverse-distance' and 'kriging' methods), and using methods that induced minimal smoothing and preserved data integrity at grid nodes. The triangulation method which fits triangular faces over grid nodes utilises only three data points per grid node and provides a robust surface fit, providing that the sizes of the triangular faces so generated are no larger than the actual morphological faces. The triangulation method was preferred in this study for this reason and because of its slightly superior statistics on residuals.

CONCLUSIONS

While the study results and recommendations are to some extent site specific, some generalisations apply to surveys of ebb delta systems similar in size and morphology to the Katikati example.

(1) Given an adequate density and coverage of bathymetry data points, the choice of surface-fitting algorithm when constructing a digital-terrain model is relatively unimportant and induces errors in mean bed level of the order of ±1 mm only. Similar-scale errors arise from volume calculation algorithms.
(2) Given relatively mild sea conditions and cross-shore track-lines, it appears that uncertainties in measurements of mean bed level change due to the effect of surface waves can be ignored. This is because the error in point soundings due to waves can be treated as a random variable with a mean equal to zero.
(3) The accuracy of the surface-fitting and determinations of mean surface levels varies depending on the local seabed topography and the density of track-lines. The bathymetry survey method used at Katikati, with shore-normal track-lines spaced 100 m apart, was sufficiently accurate to be able to establish changes in mean bed levels to considerable accuracy (±4 mm) over the simple topography of the inner-shelf/shoreface, but to only about ±54 mm over the channel and bar topography on the ebb-delta platform.
(4) Repeat surveys with the same 100 m track-line spacing could only be expected to detect net sand gains over the ebb delta system exceeding 160,000 m^3, which, at Katikati, was not good enough to reliably detect net annual or per storm changes in sand storage on the ebb delta due to littoral drift.
(5) To obtain measurements of sand-level change on ebb deltas to an accuracy significantly better than expected sand volume changes associated with littoral drift and storms, survey track-line spacings should be tailored to the topography, with denser spacings over channels and bars.

Reconnaissance surveys and/or aerial photographs should be used to plan such optimal track-line strategies, and duplicate surveys over representative morphologic zones are recommended to quantify and confirm the survey accuracy.

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