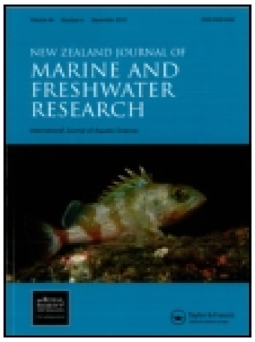

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Geomorphic change of an ebb-tidal delta: Mair Bank, Whangarei Harbour, New Zealand

KM Morgan[a]*, PS Kench[b] and RB Ford[c]

[a]*Leigh Marine Laboratory, The University of Auckland, Auckland, New Zealand;* [b]*School of Environment, The University of Auckland, Auckland, New Zealand;* [c]*Ministry of Fisheries, Wellington, New Zealand*

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The morphology and volume of Mair Bank, Whangarei Harbour, was examined at decadal and inter-annual time scales in order to assess the geomorphic stability of the ebb-tidal delta. Digitised aerial photography of Mair Bank over 56 years was analysed to determine multi-decadal changes in the position and planform configuration of major morphological units. Bathymetric survey data of the area were used to assess spatial and temporal elevation changes and to construct digital elevation models (DEMs) for quantitative comparisons. Results show that the footprint of Mair Bank has remained constant but significant changes in surface morphology have occurred. The western end of the seaward shell swashbar has migrated landward at an average rate of 10 m/year between 1950 and 2006. The largest subaerial change in sand storage volume occurred between 2003 and 2006 when volume increased from 1.107×10^5 m^3 to 1.690×10^5 m^3. In terms of material accumulation over the extent of the ebb delta, this equates to a bedlevel rise of 10 cm across Mair Bank, or a 1.3% increase in total volume. In summary, Mair Bank exhibits dynamic sediment reworking, but the gross delta feature is relatively stable in volume and position.

Keywords: morphological change; biogenic sediments; tidal inlet; delta; Northland; coastal geomorphology

Introduction

Ebb-tidal deltas are shallow inter- to sub-tidal accumulations of sand and gravel deposited on the oceanside of tidal inlets (van der Vegt et al. 2009). They are formed by the presence of strong ebb tidal currents at inlet entrances that rapidly decelerate and allow sediment deposition seaward of the entrance. These deltas are major sinks of sand and are considered to regulate alongshore fluxes of sediment and the exchange of sediment between harbours and the open coast (Bonekamp et al. 2000). Ebb-tidal deltas are effective at focusing or reducing wave energy on landward beaches and can provide a natural buffer to adjacent shorelines from incident ocean swell.

Waves and tidal currents are the main processes that drive sediment transport and shape the general planform morphology of ebb deltas (Bruun 1978; Carter 1986; Komar 1996). The combination of physical and environmental factors that include the tidal prism (Walton & Adam 1976), net amount of littoral drift entering the inlet (Carter 1986), shape of the estuary embayment and the configuration of rock headlands (Hume & Herdendorf 1992; Hicks & Hume 1996) also contribute to determine delta position and size. Hicks & Hume (1996) developed a classification of inlet and delta types in New Zealand based on the combination of these factors. Furthermore, studies have shown that these factors also control the volume of

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*Corresponding author. Email: km.morgan@auckland.ac.nz

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sand stored within an ebb delta (Dean & Walton 1973; Hicks & Hume 1991; Stauble 1998; Powell et al. 2006).

The morphology of deltas (size, topography) promotes feedbacks on the process regime of tidal inlets. Their physical presence acts as a barrier to flow and can consequently determine the flow patterns within inlets. Furthermore, delta morphology controls wave refraction patterns, sediment transport and adjacent shoreline dynamics. Minor changes in delta configuration have been shown to have pronounced effects on the erosion and accretion of adjacent shorelines (Oertel 1977). Fitzgerald (1988) also recognised the role of ebb deltas in influencing coastal processes in the vicinity of a tidal inlet through bypassing of littoral drift or by partially sheltering the adjacent shoreline from waves. Consequently, the geomorphic stability of these sand bodies are important to adjacent shoreline morphodynamics, as reduction in size, a change in position or loss of sediment volume have the potential to alter physical processes and promote coastal change.

Studies of tidal inlet systems in New Zealand have focused largely on inlet hydrodynamics (Davies-Colley & Healy 1978; Black 1983; Hume & Herdendorf 1992); site-specific case studies of inlet morphological behaviour (McCabe et al. 1985; Burton & Healy 1985; Kench & Parnell 1991); and the development of classification schemes of inlet and delta configuration (Hicks & Hume 1996). In contrast, there have been few studies of the decadal scale changes in ebb delta position and morphology in New Zealand inlets. Such studies are important to understand better the links between delta dynamics and coastal stability, fluctuations in sand resources on deltas and for engineering applications for inlet navigation.

This study examines the temporal and spatial variability of Mair Bank, the ebb tidal delta at the entrance to Whangarei Harbour. In particular, the study examines the positional and morphological changes of the major morphological units of the delta at decadal to inter-annual time scales and provides volumetric estimates of Mair Bank. Results are considered in light of recent speculation that the morphology of Mair Bank has changed (decreased in elevation and extent) because of commercial shellfish harvesting practices in the area.

Study area

Mair Bank is located at the entrance to the Whangarei Harbour on the NE coast of the North Island, New Zealand (Fig. 1A). Whangarei Harbour is meso-tidal with a spring tidal prism of 186×10^6 m (Millar 1980). Currents at the harbour inlet entrance reach 1.1–1.3 m/s during spring tides (Black et al. 1989). The lower harbour is a drowned river valley that is set against a tertiary rock headland that extends 6 km on the northern side and is enclosed by a large prograded Holocene sand barrier spit that forms Marsden Point on the southern side (Healy 1980; Black 1983; Nichol 2002). Snake Bank and McDonald Bank are the two main flood-tidal deltas located within the harbour inlet embayment, and Mair Bank and Calliope Bank are two ebb-tidal deltas positioned on the ocean side of the entrance (Fig. 1B). The hydrodynamics and sediment dynamics of the lower Whangarei Harbour have been well documented by studies incorporating physical modelling and numerical simulations (Danish Hydraulic Institute 1982; Black 1983; Longdill & Healy 2007). However, they have often been focused within the harbour embayment and centred on the morphodynamics of flood-deltas.

The focus of this study is Mair Bank, an intertidal sand and shell ebb-tidal delta that is located at the southern side of Whangarei Harbour entrance. Mair Bank is fully submerged at high tide, but at low tide has a subaerial component of tightly packed shell that extends approximately 1.1 km along its southern edge (Fig. 1C). Sandy drifts composed primarily of quartz and feldspar from the Hauraki Gulf facies (Schofield 1970) are located along the northern harbour margin of the delta and along the marginal flood

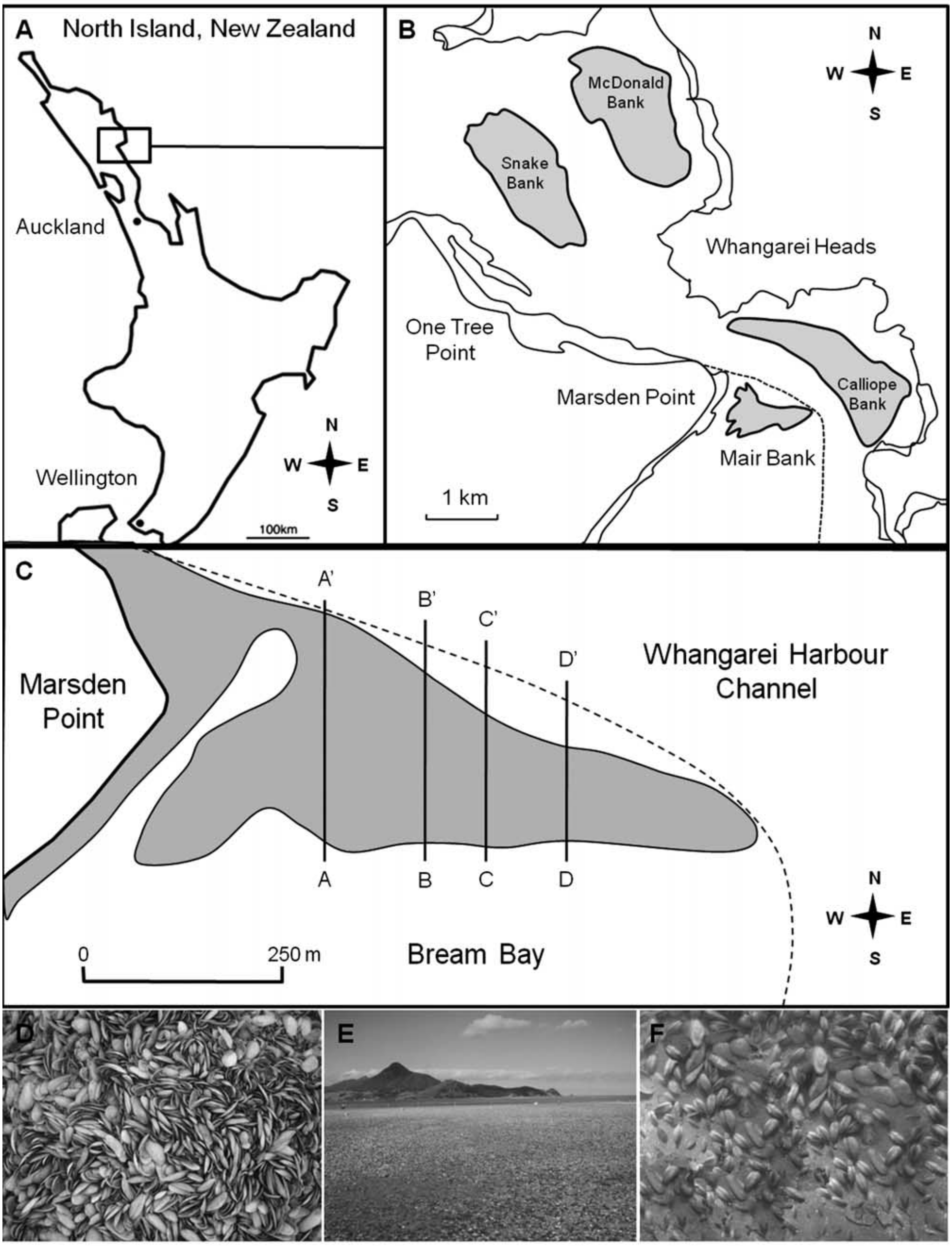

Figure 1 **A**, Location of the Whangarei Harbour on the northeast coast, North Island, New Zealand. **B**, The Whangarei Harbour entrance and the position of major associated sand bodies, including Mair Bank. **C**, General planform morphology of Mair Bank. Black lines denote the location of cross-delta profiles (transects A–D) extracted from bathymetry data for inter-annual comparison (Fig. 4). **D**, Packed detrital shell on the southern shell swashbar crest. **E**, Shell cap covering the central swash platform. **F**, Subtidal live pipi (*Paphies australis*) population on Mair Bank.

channel. The protection afforded by Mair Bank is likely to have a major role in maintaining the stability of the Whangarei Harbour entrance (Black 1983).

The sedimentary structure of Mair Bank is unique as the majority of its surface is composed of a thick shell cap (approximately 5–30 cm) produced by prolific populations of pipi (*Paphies australis*) (Figs. 1D–F) that inhabit the elevated southern edge of Mair Bank (Whangarei Harbour Water Quality Management Programme [WHWQMP] 1989). Detrital shell material armours underlying finer-grained sediments reducing actual sediment transport rates well below the potential rates of transport (Black 1983). Live pipi also appear to be an integral part in maintaining overall stability by increasing the shear resistance of Mair Bank to tidal currents and reducing overall transport. Significant declines in pipi populations have been documented to increase the 'erodibility' of Mair Bank under storm conditions (WHWQMP 1989).

To date, there have been few scientific studies of the morphology, sediments and ecology of Mair Bank (Millar 1980; Black 1983). The majority of existing knowledge has been derived from anecdotal sources, fisheries assessments (Williams et al. 2007), or through bio-environmental monitoring exercises conducted by local governmental authorities (Boyd 1983; Venus 1984; Dickie 1986; Haddon 1989). These reports concentrate primarily on only the subaerial component of Mair Bank and largely ignore the bulk of the feature that remains submerged at low tide (Dickie 1986; Haddon 1989; WHWQMP 1989).

Methods

Assessment of planform change

Assessment of planform morphological change was undertaken using a time series of aerial photographs. Available aerial images obtained of Mair Bank spanned a 56-year time period (13 March 1950, 17 June 1966, 11 February 1971, 10 January 1979 and 2006) with scales ranging from 1:15,000 to 1:25,000. Images were georeferenced using known co-ordinates of common Ground Control Points (GCP's) on Marsden Point. A reference grid (New Zealand Map Grid datum) was embedded over the imagery using ArcGIS at a scale of 1:18,500. In each aerial image, three morphological units were visually identified and their position recorded: (1) MHWM on Marsden Point, defined as the position of the 'wetted' line along the beach; (2) the northern margin of the delta that borders the main Whangarei Harbour channel; and (3) the crest of the seaward shell swashbar, defined as the highest elevation of the shell deposits that fringe the southern margin of the delta. The position of each geomorphic unit was delimited by sharp changes in image contrast on photographs. Interpretation of geomorphic units from the analysis of aerial photographs can be subject to error as geomorphic boundaries may be affected by changes in water clarity and weather conditions. However, in this analysis these errors were minimised as all images were taken at lower water stages, which precludes wave energy from the delta surface and ensures minimum water depth and optimal water clarity. Furthermore, examination of the aerial photographs indicates water clarity did not affect interpretation of geomorphic boundaries. The footprint of each morphological component of the delta was digitised for all time series and overlain onto a base orthophoto (2006) map. Observations of planimetric changes were made by calculating the distance between the sequential positions of morphological features (metres) using ArcGIS. The rate of shell swashbar migration (m/year) was calculated by dividing the distance between successive positions in the time series (metres) by the time interval (years) between each aerial image. There are multiple sources of error in interpreting aerial imagery. Errors associated with georeferencing and measurement is approximately ±3 m (Thieler & Danforth 1994). Consequently, only geomorphic adjustment greater than 3 m was considered reliable estimates of change.

Bathymetric change

A bathymetric survey was conducted as part of this study to generate high-resolution spatial elevation data of Mair Bank in December 2006, using a Northland Regional Council (NRC) survey vessel. An integrated echo-sounder and Real-Time Kinematic Global Positioning System (RTK-GPS) were used to collect and record *X*, *Y* and *Z* data points along a series of north–south orientated transect lines. Data collected from four pre-existing bathymetric surveys (May 2001, December 2001, November 2002 and June 2003) by Northport Ltd. as part of a harbour channel monitoring programme were also used in this study to provide a multi-year comparison. Data collection methodologies for this study were consistent with those of Northport Ltd. Digital elevation models (DEMs) of Mair Bank were created for each of the five survey datasets using a Triangular Integrated Network (TIN) to construct the delta surface (Stauble 1998). Spatial bathymetric change was calculated using ArcGIS and depicted on a coverage map illustrating depth changes between surveys (2001–2003 and 2003–2006). Cross-delta profiles of surface morphology were extracted from the bathymetric survey data at four positions across Mair Bank (Fig. 1C) and used for two-dimensional analysis of changes in surface morphology. Profile positions were selected to provide good spatial coverage and characterisation of surface morphology across the delta.

Mair Bank volume estimates

DEMs derived from bathymetric data were used to generate quantitative estimates of sand volume change for Mair Bank. Using ArcGIS an 'Analysis Mask' was created to define the spatial boundaries of Mair Bank so that volume calculations were based on the same areal extent for each estimate. Volume estimates for each DEM were generated using the '3D Analyst' tool in ArcGIS. Height of the base reference plane was set at three levels >8, >4 and >0 m below chart datum to determine whether volume changes varied with depth on Mair Bank.

Results

Multi-decadal scale changes in delta planform morphology

Summary changes in the planimetric extent and major geomorphic units of Mair Bank over the 56-year period of analysis are summarised in Fig. 2 and Table 1. Results show that the gross extent and planform morphology of Mair Bank, as delimited by the northern and western boundary remained relatively consistent over the 56-year time series. However, the southern boundary of the delta showed significant movement (Fig. 2). The northern boundary of the ebb delta exhibited the least degree of morphological change fluctuating in position by ±20–50 m over the period of analysis (Fig. 2). This northern limit of the delta adjoins the main ebb channel of the Whangarei Harbour entrance. The limited degree of movement of the delta margin suggests the ebb channel has remained stable over the 56-year window of analysis. The northern terminus of the marginal flood channel oscillated in position by ±120 m over the analysis period and accounted for the minimal variation in the position of the Whangarei Harbour channel (Fig. 2).

The shoreline of the Marsden Point barrier spit forms the western boundary to Mair Bank. This shoreline exhibited significant morphological variation. On the southern section of the shoreline, there was progressive landward movement of the MHWM by approximately 40 m over the period of analysis (56 years). However, the terminal end of the spit and outer inlet shoreline were found to switch between two distinct morphologies (Fig. 2). At the terminal end of the spit, the shoreline was characterised by deposition of sediment in a narrow sector of the shoreline that extended the spit apex by approximately 100 m. This condition was observed in 1950 and 2006. However, in the intervening periods

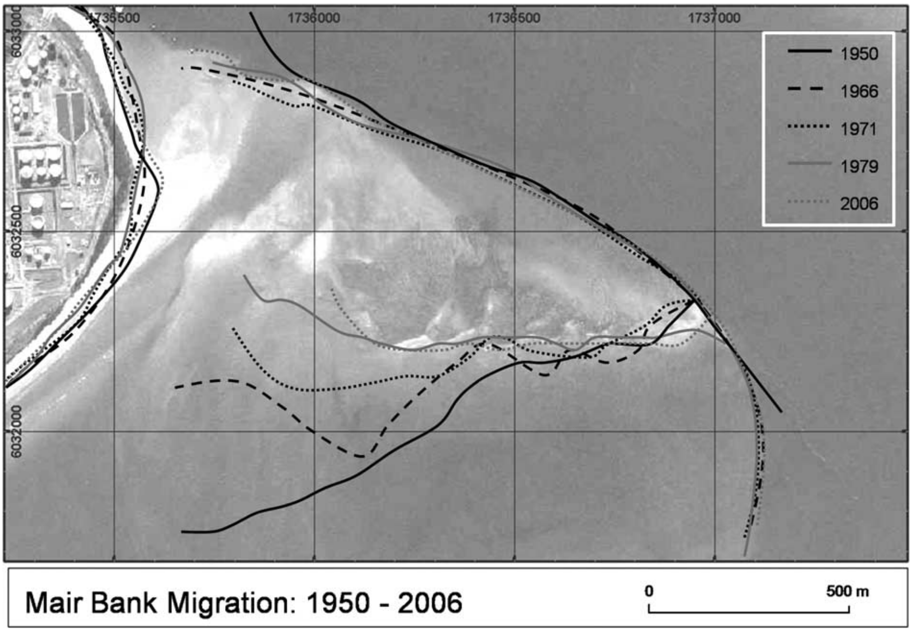

Figure 2 Multi-decadal planform change of the major morphological components on Mair Bank observed from historical aerial photography. MHWM at Marsden Point (the 'wetted' line along the beach), the northern boundary of Mair Bank, and the crest of the southern seaward shell swashbar were used as a proxy to estimate morphological change over time.

the shoreline at this location was displaced landward forming an indented planform morphology (1966, 1971, 1979; Fig. 2). The adjacent inlet shoreline appears to exhibit similar morphological changes but the chronology of change is out of phase with the spit tip. During periods when the spit terminus has accreted, the adjacent northern shoreline is at its most landward position. In contrast, when the spit terminus is at its most landward position the adjacent inlet shoreline appears to be at its most seaward position. The magnitude of these shorelines excursions is in the order of 80–100 m (Fig. 2). Results suggest that the shoreline oscillates in position at multi-decadal timescales and that there appears to be a spatially consistent balance between erosion and accretion between the two sectors of the shoreline.

Table 1 Rates of migration (m/year) of the seaward shell swashbar between 1950 and 2006 from measurements of historic aerial photography.

Year of photograph	Photograph interval (years)	Total migration distance (m)	Rate of migration (m/year)
1950–1966	16	149	9
1966–1971	5	120	24
1971–1979	8	195	24
1979–2006	27	118	4
1950–2006	56	582	10

The greatest planform changes in ebb delta morphology occurred at the seaward shell swash bar (Fig. 2). There was a significant net movement of the bar landward, although the amount of movement was spatially variable along the extent of the bar. The eastern end oscillated within a small positional window (< 100 m). Conversely, the western section migrated consistently landward. Maximum bar change on the western end was in the magnitude of 582 m landward over the 56-year time series (Table 1). Greatest movement of the western end occurred between 1950 and 1966 (approximately 400 m). Of note is the marked change in planform configuration of the swash bar in 1966, which adopted a more sinuous form. This change in pattern is mainly related to the large excursion of the western end of the swash bar between and 1950 and 1966. Significant movement was also detected between 1971 and 1979 (maximum of 150 m). Since 1979, the position of the shell swash bar has been relatively static. The extent of the shell swash bar has also declined, reducing in length by 200 m between 1950 and 2006.

Inter-annual changes in delta bathymetry

Changes in bathymetry of Mair Bank between 2001 and 2006 are summarised in Fig. 3. Results show that the central swash platform of the delta remained relatively stable over the 6-year window of analysis with only localised and low magnitude variations in bathymetry (erosion and accretion) of ±0.5 m (Fig. 3). The northern boundary of the delta, which is defined by the main ebb channel, was also stable over the analysis period with no detectable changes in bathymetry. In contrast, the southern and western boundaries of the delta displayed the greatest variations in depth over the 6-year period of bathymetric surveys. The southern margin of Mair Bank showed a progressive increase in depth of up to 0.5 m from 2001 and 2003 (Fig. 3A), and 2003 to 2006 Fig. 3B). This increase in depth was more laterally extensive along the southern delta margin between 2003 and 2006. Collectively, these bathymetric changes indicate a linear east–west aligned area of erosion across the shell swashbar in the order of magnitude of −0.5 to −1 m (Fig. 3A). However, immediately landward of this erosion zone is a laterally continuous region in which the delta surface has increased by 0.5–1.0 m (Fig. 3). The close spatial association of erosion and accretion zones is indicative of a transfer of sediment landward by approximately 140 m over the 6-year period rather than a loss of material from Mair Bank. This migration of sediment is likely to be driven by overwash swash processes. The extent of this trend was more pronounced between 2003 and 2006.

The zone of greatest bathymetric change is located at the northern entrance to the marginal flood channel. Between 2001 and 2003, this area decreased in depth by up to +3.0 m indicating rapid sedimentation of the channel (Fig. 3A). Between 2003 and 2006, this area continued to infill with a further decrease in depth of 0.5–1.0 m (Fig. 3B). However, there was localised scour (increase in depth) of up to −2.0 m on the northern edge of the channel.

The western margin of Mair Bank (that forms the eastern boundary of the flood channel) showed a progressive decrease in depth and expansion westward over the timeframe of analysis (Fig. 3). In particular, accumulation of sediment +0.5 m (and up to +1.0 m in isolated areas) occurred along the entire western margin of the delta between 2003 and 2006 (Fig. 3B). This sedimentation has constricted the channel width causing it to narrow significantly.

Topographic profiles across Mair Bank (Fig. 4) show similar gross morphology at each of the four transect sites (Fig. 1C). In particular, Mair Bank is characterised by: (1) a low gradient seaward slope ramp that extends into Bream Bay; (2) a high-elevation shell deposit (swashbar) that is up to 1.0 m above chart datum; (3) an intertidal central swash platform that ranges up to 1.0 m above chart datum; and (4) a steep drop-off into the Whangarei Harbour ebb channel (Fig. 4). In general, the delta surface has a convex morphology and the extent of the intertidal surface is largest on western transects (A, B) and reduces in width toward the east (Fig. 4). Transect C shows two ridges at the northern and southern margins of the delta suggesting overwash sedimentation processes dominate under higher tidal stages. On this profile, the central swash platform has a lower elevation (approximately chart datum, Fig. 4C). Transect A, on the western side of the delta has a

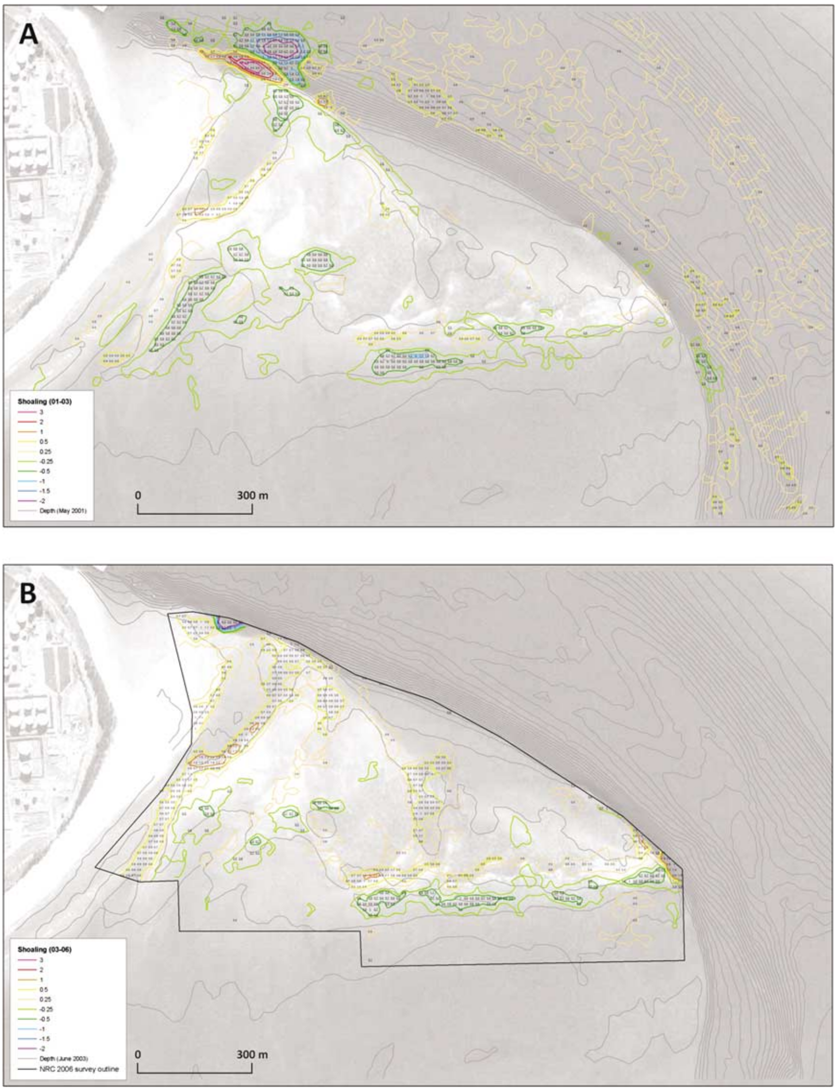

Figure 3 Multi-year bathymetric change on Mair Bank. **A**, Comparison of bathymetry between 2001 and 2003. **B**, Comparison of bathymetry between 2003 and 2006. Bathymetry change is displayed in metres.

smoother morphology and has an extended harbourside ledge before the drop-off point. The depth of this ledge fluctuated over time with periodic accretion and erosion observed.

Comparison of the time series of profiles across the surface of Mair Bank from 2001 to 2006 (Fig. 4) shows a unidirectional movement of the seaward swash shell bar northward across the central intertidal platform at all transect locations. The magnitude of this migration varied from approximately 90 to 120 m. Migration of the outer swash bar resulted in a significant decline in gradient of the seaward ramp (Fig. 4). The migration of the shell swash bar has also resulted in higher elevation shell ridges and steeper lee slopes on the northern

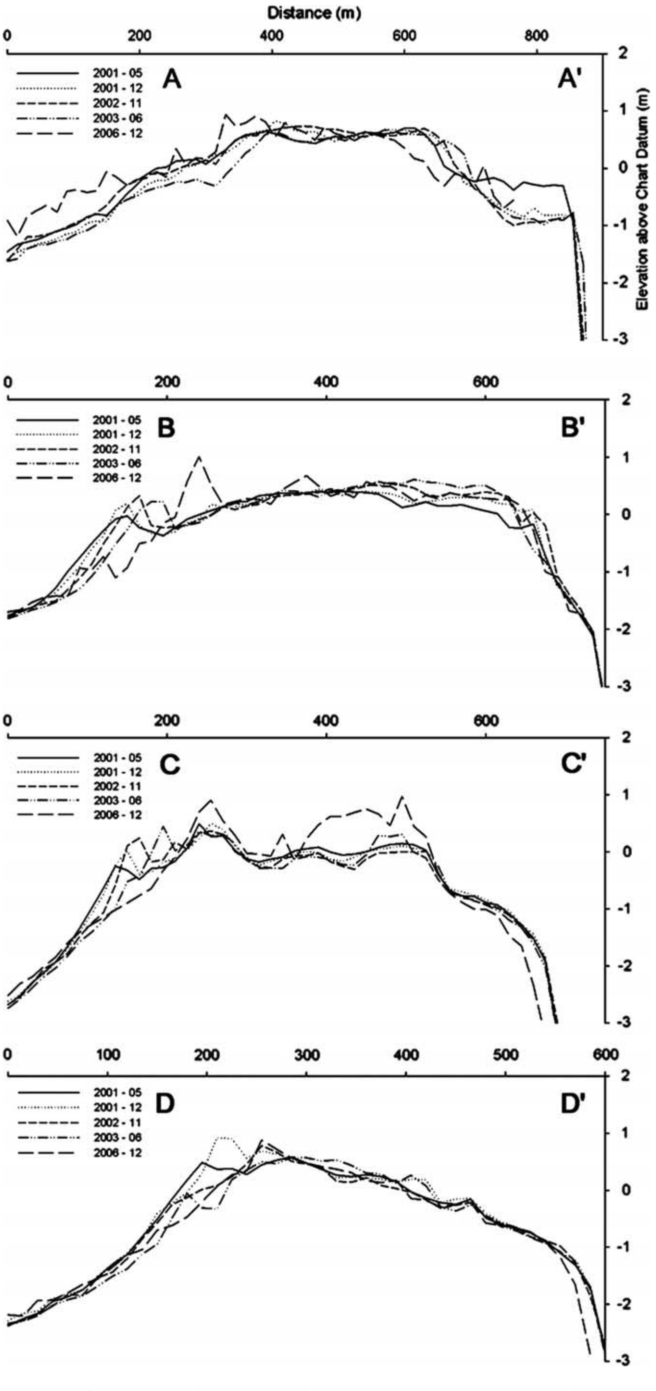

Figure 4 Cross-delta profiles of Mair Bank extracted from bathymetry survey data (Transects A–D). General delta morphology exhibits (1) a seaward slope, (2) a high elevation swashbar comprised of compacted shell, (3) an intertidal swash platform, and (4) a rapid drop-off to the main ebb channel.

side of the bar. The intertidal central swash platform retained a consistent surface morphology with the exception of Transect C, where significant accretion occurred in 2006. The comparison of transects also shows the northern margin of Mair Bank (adjoining the ebb channel) remained stable over the period of analysis (Fig. 4).

Volumetric change of Mair Bank 2001–2006

Estimates of sand storage volume of Mair Bank showed shifts in total volume relating to morphological changes of the ebb delta (Table 2). The volume of material stored above the -8.0 m R.L. increased by $+0.21 \times 10^5$ m^3 between May and December 2001. Between 2001 and June 2003, the sand volume decreased by -0.55×10^5 m^3. A sharp increase in delta volume occurred between the 2003 and 2006 surveys in the order of $+0.95 \times 10^5$ m^3 of material. This increase in volume equates to a bed level rise of approximately 10 cm across the extent of Mair Bank or a 1.3% increase in total delta volume. Changes in delta volume above the -4.0 m R.L. depth contour showed similar variations with an initial increase of $+0.19 \times 10^5$ m^3 between May and December 2001, a reduction of -0.55 between 2001 and 2003 and subsequent increase by $+0.92 \times 10^5$ m^3 from 2003 to 2006 (Table 2). Examination of volume change above chart datum shows smaller and different variations to the volume of sediment above the -8.0 and -4.0 m depth contours. The sand volume continued to increase from May 2001 to November 2002 ($+0.14 \times 10^5$ m^3). This was followed by a reduction in volume from 2002 to 2003 (-0.10×10^5 m^3) and a final increase of $+0.58 \times 10^5$ m^3 from 2003 to 2006. This final increase represents 34% of the total volume of sediment contained above chart datum.

Changes in the planform area of Mair Bank were also identified (Table 2). The area of the delta above the -8.0 m R.L. was remarkably stable over the 6-year period of analysis. However, the planform area of the delta above -4.0 m R.L. increased by 57,100 m^2, and the area above chart datum increased by 53,800 m^2 (Table 2). Collectively these results show that the sediment volume of Mair Bank oscillates by $\pm$100,000 m^3 over inter-annual timescales. The largest changes in area and sediment volume occurred above chart datum and above the -4.0 m R.L. depth contour.

Discussion

Results of this study indicate that the footprint of Mair Bank has remained relatively stable over the 56-year period of analysis. This multi-decadal stability is significant given the importance of inlet shoals in influencing inlet stability and adjacent coastline behaviour (Oertel 1977; Fitzgerald 1988). In particular, the northern boundary of the delta has exhibited least morphological change. This boundary

Table 2 Inter-annual comparison of volume ($\times 10^5$ m^3) and surface area estimates ($\times 10^5$ m^2) at different depth contours (> -8, > -4m and >chart datum) on Mair Bank.

	> -8 m Depth contour		> -4 m Depth contour		>Chart datum	
Survey date	Volume ($\times 10^5$ m^3)	Surface area ($\times 10^5$ m^2)	Volume ($\times 10^5$ m^3)	Surface area ($\times 10^5$ m^2)	Volume ($\times 10^5$ m^3)	Surface area ($\times 10^5$ m^2)
May 2001	71.687	9.445	33.952	9.407	1.060	3.707
Dec 2001	71.890	9.446	34.148	9.412	1.199	3.875
Nov 2002	71.718	9.445	33.981	9.412	1.209	3.686
Jun 2003	71.338	9.445	33.599	9.412	1.107	3.508
Dec 2006	72.288	9.448	34.523	9.425	1.691	4.245

is the southern margin of the Whangarei Harbour ebb channel and indicates geometric stability of the inlet system over the analysis period. This is supported by the findings of Black (1983) who also showed the harbour ebb channel to be stable over a 22-year period of analysis. Hume & Herdendorf (1992) attributed the natural depth and stability of the Whangarei Harbour to the sheltering capacity of an extensive headland (Busby Head) on its northeast margin and rapid ebb- and flood-currents that have entrenched the inlet position against the consolidated bedrock. Flushing of accumulated sands from the channel seaward by ebb-currents prevents the inlet channel from infilling (Stauble et al. 1988), whilst a residual shell lag armours the inlet gorge preventing lateral and vertical erosion of the throat (Black et al. 1989). A study of wave refraction patterns in Bream Bay shows the Whangarei Harbour inlet entrance emerges in a zone of low energy that provides natural stability to the inlet (Duder & Christian 1983). In summary, the Whangarei Harbour can be classified as a stable tidal inlet system and displays characteristic morphological and sediment bypassing patterns associated with this (Bruun 1966; Fitzgerald 1982; Fitzgerald et al. 2000).

However, while there is a high level of persistence of the northern boundary of the delta, results also show a high degree of morphological dynamism of other sections of Mair Bank. The southern seaward boundary (shell swashbar) exhibited movement ranging from 150 to 580 m over the period of analysis. Net migration occurred northward (landward) and accounted for the greatest change in delta morphology. Swash processes and sediment transport associated with wave breaking are an important control on the formation and morphology of delta swashbars (Oertel 1977). Therefore, swash processes are a likely driver of the landward progression of the shell swashbar on Mair Bank at decadal scales. The degree of dynamism across the extent of southern edge is spatially variable; high rates of northward migration occurred at the western end of the swashbar (580 m), whereas oscillatory shifts within a small positional window characterised the eastern end (150 m). In absence of any direct measurements of local hydrodynamic processes over the timescales considered within this study, it is difficult to provide a definitive causative mechanism of this variability. However, the observed swashbar migration indicates that despite long-term stability of the delta footprint there is a high degree of sediment flux and redistribution within the delta.

At an inter-annual scale, there has been significant change in the surface morphology of Mair Bank. Results show clear areas of isolated erosion and sedimentation driven by daily reworking and mobilisation of surfical sediments by waves and tidal currents (Black 1983). Comparison of bathymetric surveys (Fig. 3) revealed the extent of the northward migration of the shell swashbar (140 m over 6 years). Swash overwash processes occur on the southern seaward margin at higher tidal levels, which are likely driving this unidirectional shift in shell material across the central swash platform. Over this same analysis period, sediment overtopping has increased the vertical extent of the swashbar, reducing the gradient of the seaward ramp and forming a more intertidal surface feature on Mair Bank. The physical nature of this swashbar has direct implications to the shoreline morphodynamics of the Marsden Point sandspit as it acts as an effective natural buffer to wave energy. Cyclic shoreline fluctuations (40 m) in the terminal end of Marsden Point sandspit (MHWM) were identified in the results, but appeared to be independent of periods of large swashbar migration.

Changes in sediment volume were greatest above chart datum ($+0.95 \times 10^5 \mathrm{m}^3$ between 2003 and 2006), whilst material below -4 m and -8 m R.L. remained relatively constant. Results highlight the contrast between the dynamic nature of Mair Bank's surface morphology and the general stability of the delta footprint. From the sampling frequency of bathymetric surveys, it is not possible to establish any seasonal trends or ascertain the controls on delta growth or decay. However, it can be speculated that the inter-annual volume change observed is likely a response to irregularities in the magnitude of longshore littoral drift, as Hume & Herdendorf (1992) estimated the range of sediment transport along Bream Bay to vary between 19,000 and 45,000 m^3/year. Findings from a Whangarei Harbour Water Quality Management Programme (WHWQMP) study on surface area and volume estimates of Mair Bank above chart datum between July 1985 and March 1989 showed similar results to the findings of this study. In general, they showed that volume fluctuated inter-annually and that the greatest magnitude of volume change occurred at higher elevations.

At present, Mair Bank supports 99% of New Zealand's Total Allowable Commercial Catch (TACC) of pipi. The TACC of pipi on Mair Bank is 200 tonnes, which represents approximately 6.6% of the estimated biomass. Current catch landings over the past decade have ranged between 100 and 250 t/year (Williams et al. 2007), consistently operating below TACC. Based on assumptions of the density of shell, the TACC quantity represents approximately 96 m^3 of shell per annum, which is less than 1% of the inter-annual variations in sediment volume monitored on the delta. Results suggest that over the medium-term, shell harvesting has not had an impact on the gross delta morphology because of the small proportion of harvested individuals relative to total biomass and the relatively non-invasive harvesting methods used. However, it is unclear whether such rates of commercial harvest are sustainable to maintain current bank morphology in the long-term, particularly if annual catch rates increase to the TACC level.

There is still much to be gained from an increased understanding of the long-term dynamics of ebb-tidal deltas. Aerial imagery and bathymetric data can provide useful information for interpreting delta morphodynamics. However, on New Zealand coasts, findings are generally hampered by a lack of good time series data, which significantly restricts the detail of analysis and makes providing causative mechanisms for the observed changes difficult.

Conclusions

- The morphological footprint of Mair Bank has remained relatively static at multidecadal time scales, but showed significant variation in surface morphology inter-annually.
- The shell swashbar on the southern margin of the delta demonstrated the most movement. Net movement of the swashbar was northward (landward), with significant variability in the rate of movement occurring along its extent.
- The northern margin of Mair Bank (southern edge of the Whangarei Harbour channel) showed complete stability at long-term time scales.
- The volume of Mair Bank fluctuated inter-annually. Material at higher elevations (> chart datum) incurred the most change highlighting the sensitivity of Mair Bank to changes in local boundary conditions.
- Mair Bank has a rare ecology and sedimentology. Biostabilisation of sediments by live pipi (*Paphies australis*) and the protective armouring their detrital material affords is likely to be a significant contributor to the overall stability and geomorphology of the delta. However, the role that live organisms play in sedimentary processes is poorly understood.

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