Coastal erosion hazard assessment
Whale Bay, Raglan

A report prepared for J. Hemi

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1. Introduction

The draft RNZCPS essentially provides a coastal erosion hazard distance (CEHD) formula (equation 1) that incorporates five components:

$$CEHD = LT + ST + SLR + DS + CU \qquad (1)$$

Where:
LT = *longer-term 100^{+} yr shoreline change.*

ST = *Shorter-term shoreline fluctuation.*

RSLR = *Retreat of shoreline associated with 100+ yrs of sea-level rise (SLR) induced by global warming.*

SS = *Slope stability.*
This component accounts for subsequent retreat of an erosion scarp following storm cut that is necessary to achieve a stable slope;

CU = *Combined uncertainty*
The Guidance Manual stressed the need for a robust uncertainty assessment.

Each of these components will be assessed such that additional requirements in the Guidance Manual and the Draft RNZCPS are incorporated.

2. Historical shoreline data

Although not stated in the Guidance Manual or Draft RNZCPS, the use of a 100^{+} year prediction period requires analysis of a historical shoreline data set preferably extending back into the 19th century; this is because shoreline behaviour can contain substantial variability including trends. If shorter data-sets are analysed increased uncertainty values would be required in keeping with the Precautionary Approach (NZCPS 1994, Policy 3.3.1). Note that a 100 yr prediction period is not the same as a 100 yr return period which relates to the probability of an event of a certain magnitude occurring in any particular year; this can be estimated using a high resolution data-set of much shorter length and assumes trends are not present.

For the initial 2005 Whale Bay erosion assessment, shorelines back to 1944 were derived from vertical aerial photographs. For the present re-assessment, survey maps have been included which extend the shoreline history back a further 67 years to 1877. In addition, several high resolution contour maps of the lagoon area have recently been surveyed. The set of survey plans consist of: 1877 (ML 3819); 1917 (ML 10971); 1928 (ML 14486) and 1972 (ML20686). The set of vertical aerial photographs consist of: 1944 (SN 266); 1957 (SN 1051); 1967 (SN 1889); 1974 (SN 3730); 1979 (SN 5479); 1989 (SN 11250-1); 1993 (SN 13129-30); 1997 (SN 9615); 2002 (SN 9990C), and 2007 (SN 50634C). Contour maps were surveyed in October 2006, October 2007 and December 2008.

These various data sources were geo-referenced New Zealand Map Grid 2000 (NZMG2000), a standard co-ordinate system, thereby enabling direct temporal comparison. Precise co-ordinates for the survey plans were obtained from Harrison and O'Sullivan Ltd (Licensed Cadastral Surveyors and Land Development Consultants) using LINZ resources. Geo-referencing errors ranged between 0.5 and 0.9 m. The high water mark (HWM) at the time of survey was carried out is used as the shoreline indicator on these survey plans. This indicator can cause problems for shoreline analysis as it incorporates several unresolvable environmental factors such as tide and waves which can cause the mark to vary by up to several metres. Furthermore, marine-based shoreline indicators all contain a seaward bias when compared with the location of the vegetation-front typically used as the shoreline indicator for aerial photographs. The coastal practitioner must take these potentially significant influences into account when carrying out historical shoreline analyses.

The aerial photographs were taken by New Zealand Aerial Mapping Ltd or GeoSmart Ltd. Unlike the 2005 investigation that analysed scanned contact prints, the present re-assessment used scanned negatives which, while considerably more time and funding to acquire, give substantially greater detail thereby enabling more accurate geo-referencing and feature detection. The scans were transformed to orthophotos by New Zealand Aerial Mapping Ltd. Orthophotos have had distortions caused by lens effects and relief removed. The shorelines were then detected under my direction using a state-of-the-art stereo viewer at NZAM offices. Stereo technilogy permits 3D viewing, thereby providing greater precision in detecting the vegetation front on aerial photos. Combined errors (root sum of squares) involved in deriving shoreline location were estimated by NZAM photogrammetric staff to range between 0.91 to 2.94 m, with the variations depending primarily on photo scale and ground control point detection.

The contour surveys were carried out by Skyworks Waikato Ltd using a Total Station theodolite. Elevation datum was Moturiki Datum 1953 and spatial datum was NZMD2000. The combined (root sum of squares) error for the contour survey is 0.8 m spatial and 0.05 m vertical.

3. Historical shoreline analysis

Neither the Guidance Manual nor the Draft RNZCPS provide details of the actual method(s) of analysis to be applied to the shoreline location data, although the Guidance Manual stresses the need for careful consideration of assessment methods. The practices used in this assessment are considered to be the most robust available at the present time.

All shorelines have been overlaid in Figure 1. Of particular note are the more landward location of the early shoreline in the vicinity of the boulder bank-spit, and also the more seaward location of the early central shoreline (adjacent to the site of the proposed building site), compared with later aerial data. These differences are explained later in terms of shoreline response to variation in sediment supply

To identify the shoreline behaviour in more detail, time-series graphs were prepared for all survey plan and aerial-based shoreline data along three transects located in the southwestern part of the lagoon. These transect locations are marked on Figure 1 with CEN being the central transect located between the proposed building site and the lagoon step, N50 being 50 m to the north of CEN and E50 being 50 m to the east. The shoreline time-series corresponding to these transects are shown in Figure 2. In addition a regression analyses were performed on the aerial-based shoreline data sets, and these output are also shown in Figure 2. Note that the mathematical terms and concepts used below are described in standard statistics texts or manuals such as Shaw and Wheeler (1985) or Wilkinson (1996).

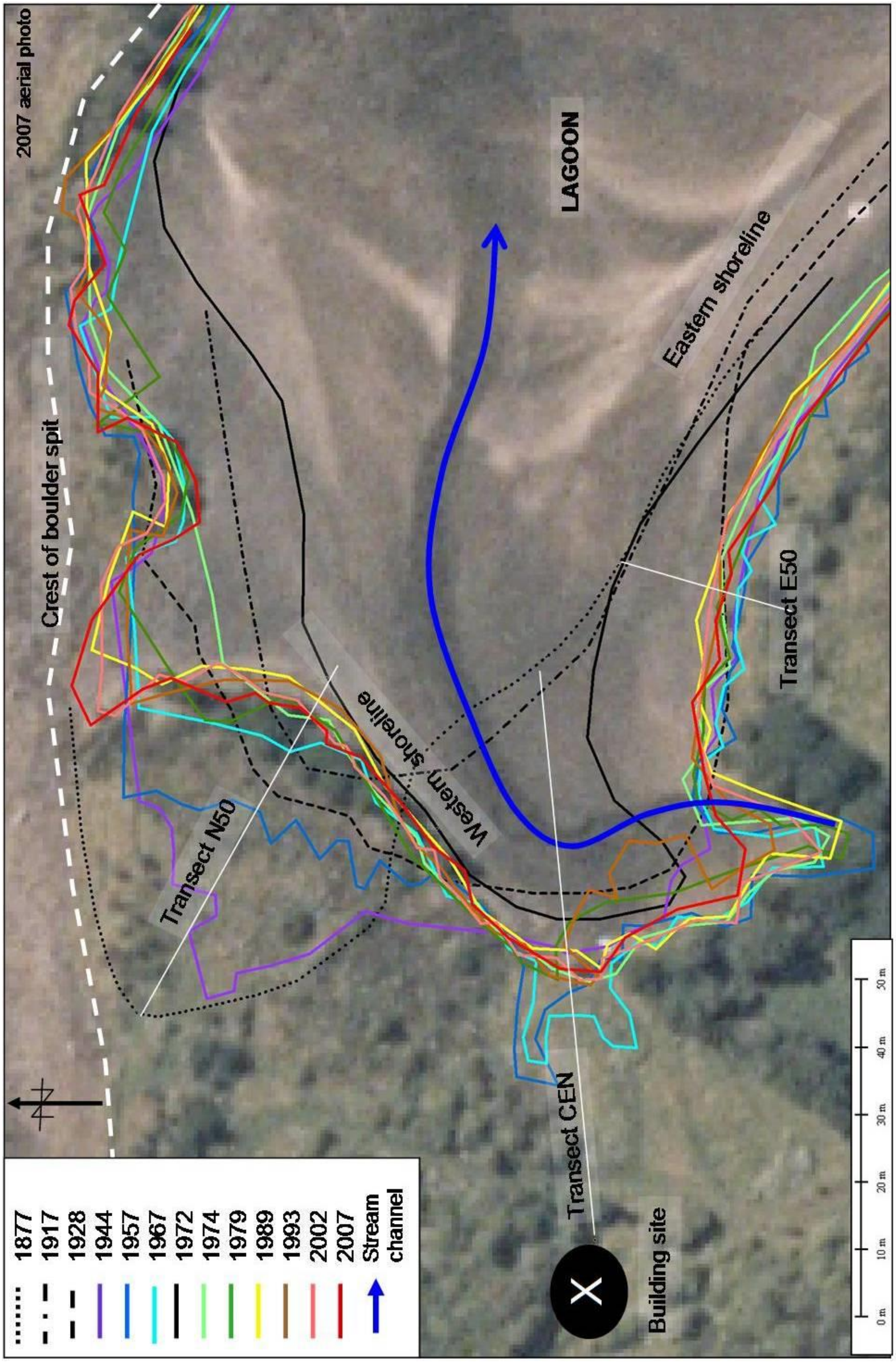


Figure 7.1 All historical shorelines superimposed upon 2007 aerial photo. Shoreline analysis transects have also been marked along with other features referred to in the text.

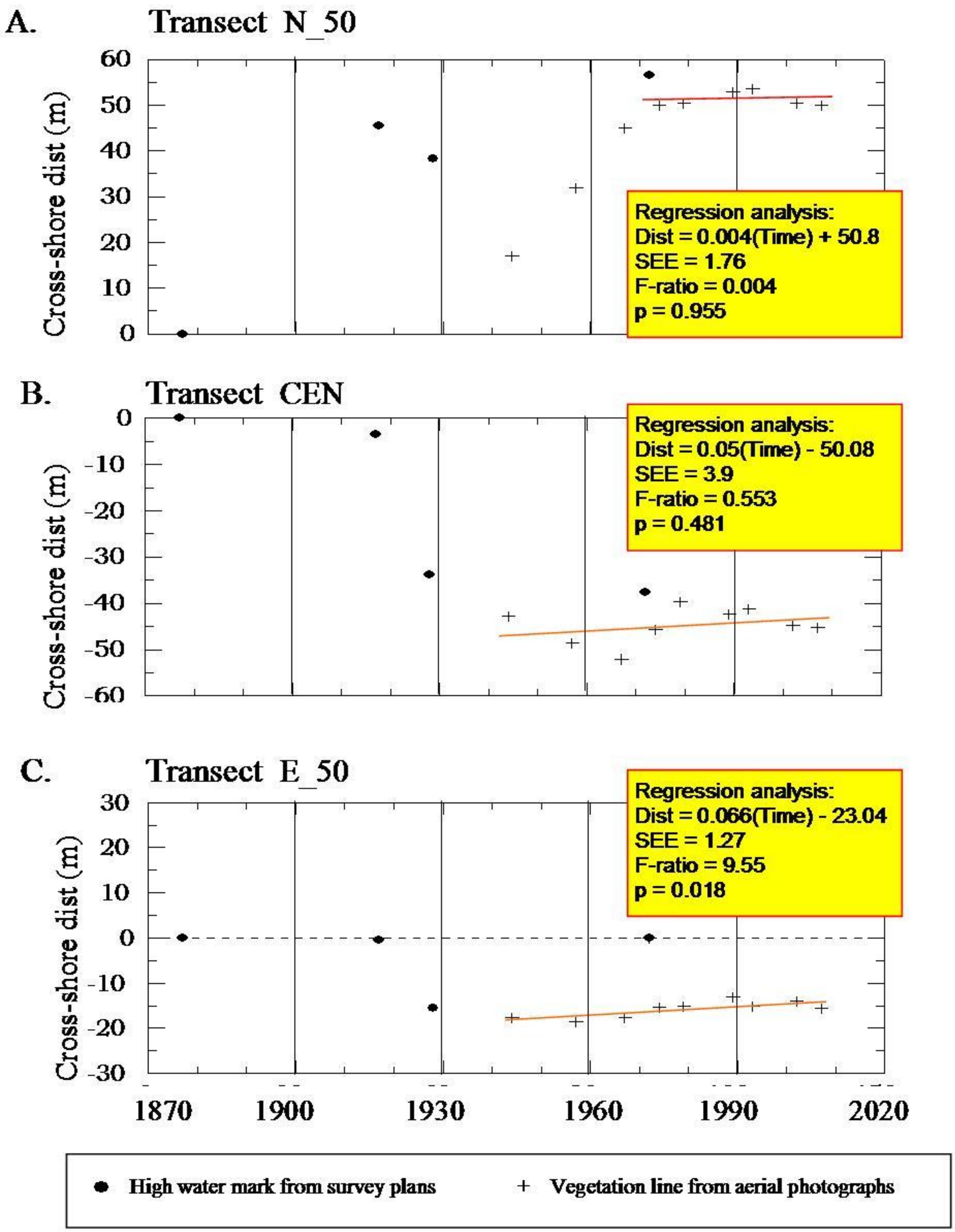


Figure 2 Shoreline time-series for transects CEN in line with the building site, N_50 some 50 m to the north, and E_50 some 50 m to the east, together with the regression analysis for aerial data subsequent to any earlier trend.

The N50 time-series (Figure 2A) confirms significant seaward movement of the shoreline in this area after 1877. Of note is the apparent lag between the trends depicted by the survey plan data points for N50 and the aerial-based data. The offset reflects the longer time taken for vegetation to grow following accretion compared to the HWM adjustment. Furthermore, the expected systematic difference between two types of shoreline indicator noted earlier is clearly illustrated when comparing the 1972 survey plan's HWM with the 1974 aerial-based vegetation front, with the latter being located some 6 m to landward.

Regression analysis applied to the more recent post-trend data for N_50 show a stable shoreline (slope = 0.004) characterizing the more recent history

The shoreline fluctuation at N50 can be determined by doubling the standard error of estimate, i.e. 2 x 1.8 = 3.6 m to each side of the regression-based average. Doubling the standard error of estimate allows us to be 95% confident that this interval will contain the range of possible shoreline positions. Note that the assumption that residuals be normally distributed was met for all three transects using the normal probability straight line test.

The CEN transect's shoreline history is plotted in Fig 7.2B and shows the early shoreline retreating some 40 m. The post-trend regression analysis defines an underlying shoreline trend of 5 cm/yr. However, this is statistically insignificant as the probability of the F-ratio statistic was 0.481 and this needs to be <0.01 for the trend to be significant. The shoreline fluctuation at CEN was the largest of any transect at 2 x 3.9 =7.8 m.

The shoreline history for transect E50 is depicted in Figure 2C. Both the survey data sets and the aerial data set show relative stability with the latter's 15 m landward offset being consistent with the expected systematic difference between the HWM and vegetation line. Regression analysis on the aerial data define a 7 cm/yr accretional trend which is statistically significant (p = 0.02). However, the fluctuation value for E_50 of 2 x 1.27 = 2.5 m was the lowest for any transect.

While the more recent shoreline history indicate relative stability of the lagoon margin and hence an LT value of zero could be used in the CEHD formula (equation 1), the early erosive trend on the critical CEN transect is problematic as if the regression analysis were to be performed on the full 130 yr data set (adjusted for differences in the shoreline indicator), a negative (erosional) long-term trend value would be derived. The only way to avoid incorporation of an overall negative longer-term value into the CEHD is if the processes responsible for causing the earlier behavior can be identified and deemed not likely to result in additional landward erosion in the future. With this in mind, an investigation into sediment dynamics within the lagoon was carried out.

4. Lagoon sediment dynamics

Erosion hazard assessments along the west coast of the North Island have identified medium term oscillatory behaviour at periods of approximately 20 to 50 years. While the coastal literature is sparse on explanation, my own research has linked such behaviour to variation sand supply. Such variations characterize the west coast with sediment systematically migrating both northward (toward North Cape) and southward (toward Paekakariki) from Cape Egmont. Sediment pulses have been linked with episodic increases in river sediment, changes in rivermouth configuration, e.g. spit breaching, episodic bypass around littoral barriers, or offshore sand wave migration. It is therefore very likely that sediment volume within Whale Bay fluctuates over time and this may explain the contrasting shoreline configuration evident earlier in the study period.

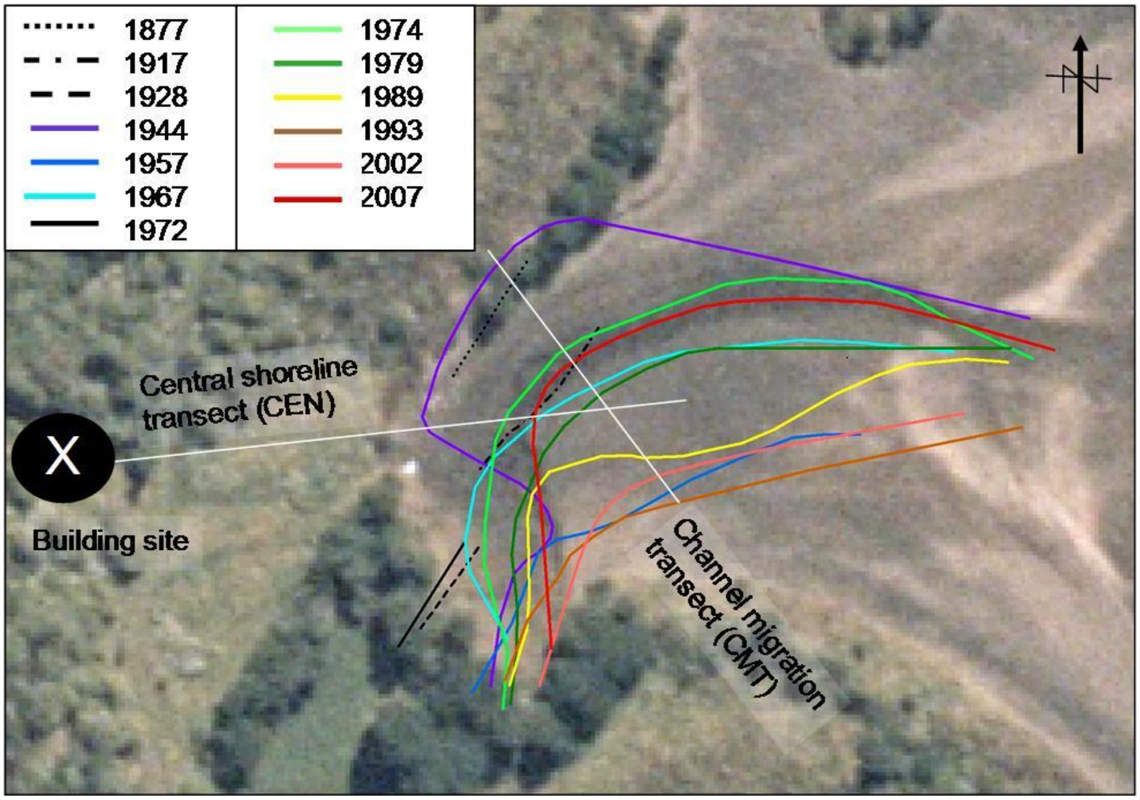
Stream and rivermouth morphology are particularly susceptible to change associated with variation in sediment availability, so channel behaviour can be a useful indicator of sediment level. As there is a perennial stream at the southwestern end of the lagoon, this investigation begins by identifying its channel behaviour.

Historical channel locations have been marked on Figure 3A. Data were collected along a transect that intersecting the CEN shoreline transect some 30 m seaward of the access track step and has been marked in Figure 3A. This transect, hereafter referred to as the Channel Migration Transect (CMT), was chosen as it was found to define the most dynamic part of the channel.

The channel intersection distances from the easternmost 1993 channel (datum) have been plotted in Figure 3B. Note that the 1928 and 1972 survey plan channels were not shown intersecting the CMT. The channel locations have a migration range of 43.5 m along the CMT, and with the mean distance being 19.3 m from the easternmost (1993) channel location. The more comprehensive aerial data indicates two migration cycles occurred during the 1944 to 2007 period.

Comparing the lagoon morphology with channel migration, shows the higher channel offsets, i.e. greater CMT distances, correspond with a sediment *lobe* developing on the eastern side of the channel. Such morphology is indicative of sediment arriving from the east. By contrast, when the migration distances were low, the lobe diminished as the channel took a more direct route into the lagoon. These two contrasting states are illustrated by aerial photos in Figure 4. Note that the HWM in the 1972 survey plan has been included as it further defines the eastern lobe, as well as defining a somewhat subdued lobe on the northern side of the channel. It will be recalled from Figure 3B that the channel had on offset maxima in the early 1970s.

A. Channel locations



B. Channel migration history

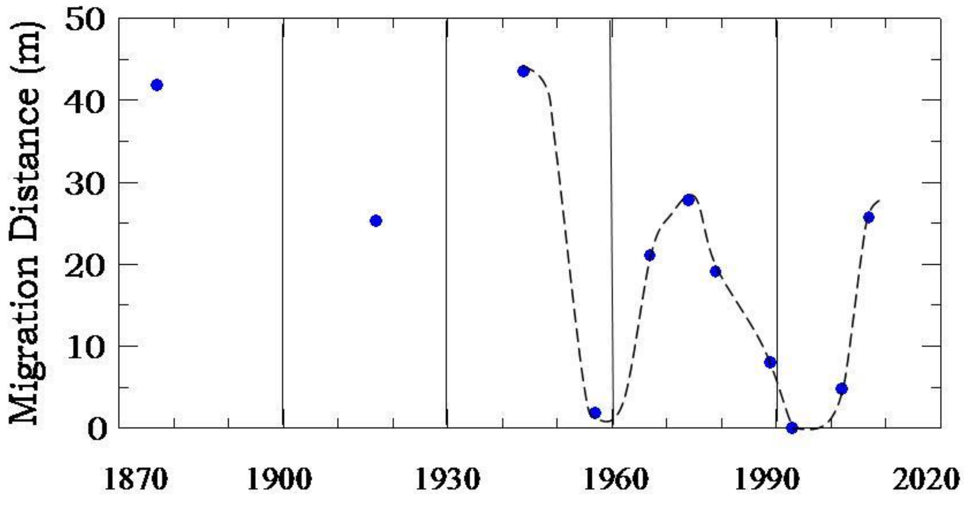


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Figure 3 Channel locations (A) and channel migration distances (B) along the channel migration transect marked in A. The distance datum is B was the easternmost (1993) channel

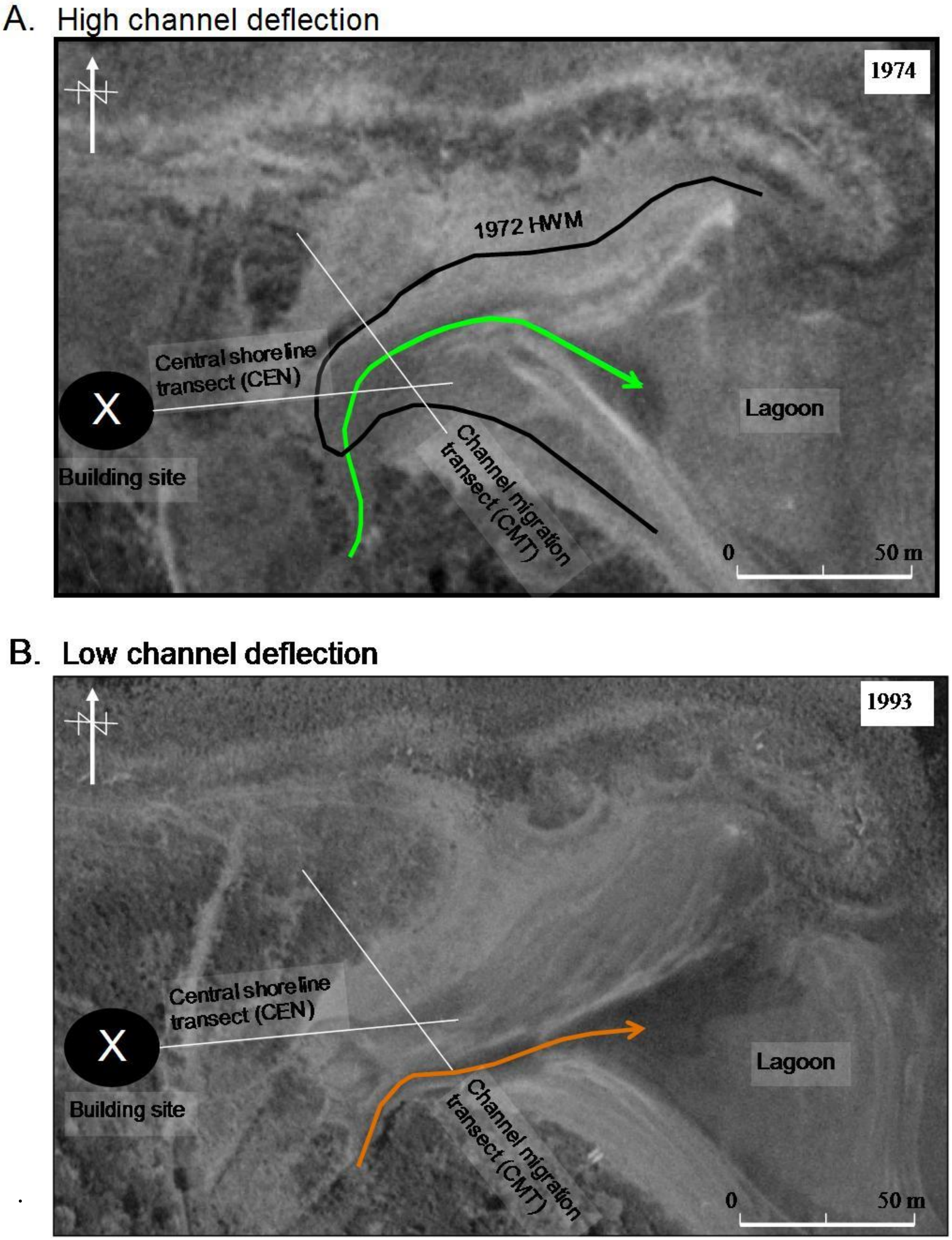

Figure 4 The 1974 aerial photo and 1972 survey plan's HWM in A illustrate high channel deflection or offset morphology, while the 1993 aerial photo (B) provides an example of minimal offset configuration with the channel taking a more direct route into the lagoon. The transects used earlier in Figures 1 and 3 have been included to assist with interpretation

More definitive evidence that higher channel offset corresponds with increased sediment supply, and in addition, that this influx entered the lagoon from the open coast, was obtained from the analysis of recent contour surveys data of the lagoon and adjacent open coast. A large *slug* of sand was monitored migrating northward around the Mt Karioi headland during 2005-06 and reported by Mead and Phillips (2007). Their paper noted that the sediment had a significant negative effect on the quality of surfing waves in this area, an effect not observed by surfers during at least the previous 20 years (Mead pers comm.) indicating that the arrival of such a sediment volume was a rare occurrence. The 2006-08 contour surveys carried out as part of our geo-physical research at Whale Bay did not coincide with the open coast surveys, and thus may have missed the period of maximum sediment input. However, the lagoon surveys did at least cover the latter part of this event with some 2,330 m^3 of sediment accumulating between the October 2006 and October 2007 surveys, while an additional 494 m^3 had accumulated by November 2008. Furthermore, observations since 2005 show minimal wave-induced or wind-blown sand entered the lagoon over the top of the boulder bank adjacent to the western lagoon beach; so the accumulated sediment reached this area via wave-induced transport through the lagoon mouth.

There is thus compelling evidence based on morphology and sediment volume, that the higher channel migration distances (increased channel offset or deflection) in Figure 3B, correspond with occasional influxes of littoral sediment.

To determine under which morphological state (high or low channel deflection), the western lagoon shorelines are more prone to erosion, the channel migration data were correlated with shoreline data from transects N50 and CEN. The correlation coefficient for CMT*N50 = -0.806 with $p = 0.05$. This result means that there is a significant negative association such that as the channel offset increases (higher lagoon sediment supply), so too does erosion along the western shoreline. Note that as in the shoreline regression analysis (Fig 7.2A) only the post-accretion trend shoreline data points were used. The corollary is that the western shoreline is more likely to accrete under lesser channel offset (lower sediment supply). The former effect can be explained by wave surge being topographically constricted and directed into the western shoreline. During the latter effect, the channel's more direct path to the sea provides less topographic control off wave surge and shoreline erosion. In addition, a larger area of exposed sand is available for wind erosion, and hence subsequent sand deposition and accretion of the western shoreline.

By contrast, the shoreline data adjacent to the proposed dwelling site showed no such statistical association with channel behaviour. In this case the correlation coefficient was only 0.208 which is highly insignificant and indicates the shoreline adjacent to the house site is unaffected by such sediment dynamics within the lagoon.

Given the lagoon sediment dynamics derived from the above analysis, can the atypical shoreline behaviour evident in the early survey plans be explained, i.e the early accretional trend at N50 and the early erosional trend at CEN? Under a prolonged period of high sediment supply, the eastern lobe would be expected to extend further west, and the stream channel would also be deflected. The 1877 HWM shoreline marked on Figure 1, and the associated channels marked in Figure 3A, show that the shoreline configuration was indeed consistent with the sediment dynamics-based explanation, with the eastern lobe extending further than the 1972 (HWM) lobe, which corresponds with a sediment influx, and the lobe having deflected the stream channel further west.

The 1877 survey does therefore appear to have been taken during a period of particularly high sediment supply. A description of such extreme sediment accumulation appears in the memoirs of V E Pegler (Vernon, 1981, p37): *Late last century due to a change of wind or tide or both, the rocks along the beach from Manu to Whale Bays were covered with sand, and instead of rocks a sandy beach ran from the land to the breakers.*

In summary, the aerial-based shoreline data (1944 to 2007) show relative stability despite intervening variation in littoral sediment supply. The more seaward location of the CEN shoreline which is closest to the proposed dwelling, evident in the earlier survey plans, appears to have been associated with a major influx(s) of littoral sediment, and as such, cannot cause additional landward erosion as had been pondered at the end of Section 3. It is therefore appropriate to use an LT value of 0. In addition, the ST retreat value of 7.8 m, as derived by the regression analysis of the CEN transect data, will be used in equation 1.

5 Climate change

The Guidance Manual considered profile translation models are an appropriate method of determining shoreline recession associated with 100^+ yrs of sea-level rise (SLR). However, these models only apply to certain types of coast. The most well recognized model is that of Bruun (1983) which reasons that an elevated sea level enables wave action to erode the upper beach and that this sediment is then transported offshore and deposited such that the eroded quantity balances the quantity deposited. The seaward limit of profile being translated is the outer limit of cross-shore sediment exchange (closure point), which is typically several hundred metres offshore. The model only applies to sandy coasts with no variation in sediment supply, conservation of longshore transport volume and no lithological (rock) control. Clearly the assumptions associated with the Bruun Model are not met by the Whale Bay environment.

A somewhat less stringent profile translation model is that of Komar et al. (1999) which only translates that section of profile landward of the low tide mark. This approach is based on the argument that it is the inter-tidal beach is that most likely to be affected by process changes associated with a rise in sea-level. However, the sand cover in the Whale Bay lagoon only extends down to MSL thereby excluding direct application of this approach. At Whale Bay, the Komar translation model could only be applied to the sand-based upper lagoon profile, as it is only within this region of sand-sized sediment that processes are likely to be affected by the predicted rise in sea level. However, an added complication at Whale Bay is that the morphological behaviour of the western lagoon, that section of particular significance to this erosion assessment, is constrained by the stream channel, so this feature would make a more relevant lower limit for profile translation. The Komar formula (equation 2) was therefore applied to a representative profile (Figure 5) that extended from the time-averaged channel intersecting the CEN transect to the proposed building site.

$$R = S/\tan\beta \qquad (2)$$

Where R is the profile translation distance in the landward direction, S is the predicted rise in sea-level, and $\tan\beta$ is the slope of the average profile.

While the Guidance Manual recommends using SLR values of 0.6 and 0.9 m out to 2010, when being applied in an erosion assessment, the long-term shoreling change component already accounts for a portion of these values and not to exclude this portion would amount to double counting or as it is often described, *double dipping*. This is because there has been a historical rise in sea level of about 2 mm/yr during the aerial shoreline record upon which the regression analysis was based. This amounts to 0.2 m over a 100 yr prediction period. The SLR values to be applied in equation 2 are thus 0.4 and 0.7 m. Using these values, together the average upper beach profile slope of 0.028, shoreline retreat values come to are 14.3 m and 25 m respectively (see Figure 5). However, these values make no allowance for other possible consequences of global warming and these will now be discussed further.

Sediment supply to Whale Bay may increase due to process changes within its own stream catchment and also from littoral sources due to increases in both the episodic and mean annual supply from rivers to the south, and also from coastal cliff erosion. These increases will help compensate for the shoreline sediment loss that the Guidance Manual

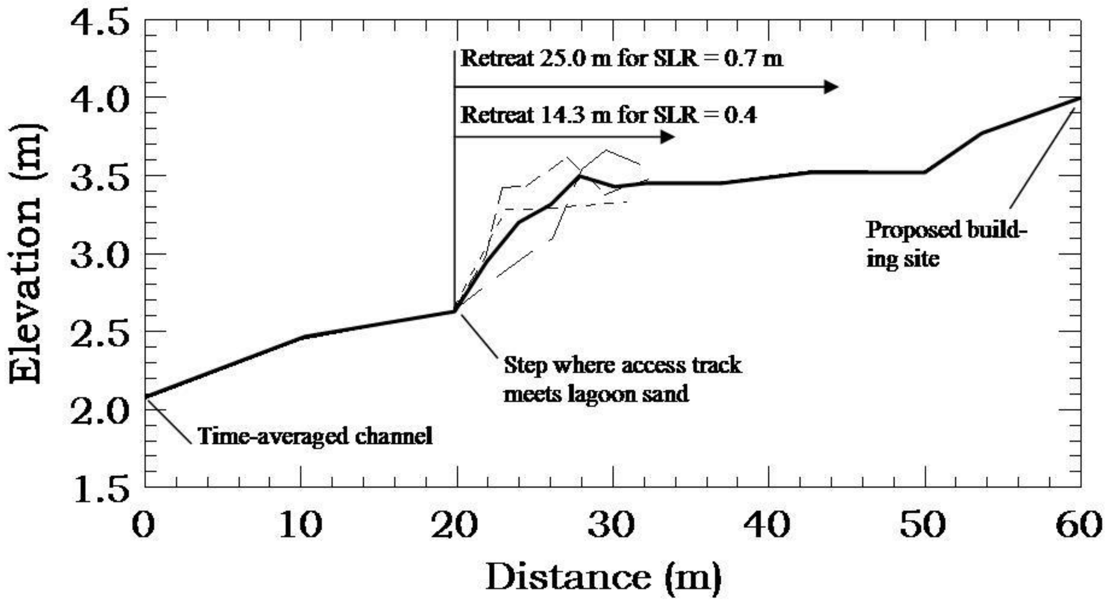

Figure 5 Representative profile extending from the time-averaged channel to the proposed building site. Shoreline retreat distances as predicted by equation 2 using SLR = 0.4 and 0.7 m (see text) have been marked. For interest, profile variation immediately landward of the step is shown. Translation processes are likely to ensure such variation persists

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expects to occur due to increased wave attack associated facilitated by increasing water level, storm wave height and storminess.

Any changes in lagoon sediment supply that are associated with Climate Change are unlikely to have significant negative shoreline effects as it was shown in Section 4 that the shoreline adjacent to the proposed building site remains relative stability despite intervening variation in (littoral) sediment supply. The extreme influxes described in Section 4 that were responsible for more dramatic historical shoreline changes (Section 3) are not expected to occur from climate change.

In Section 4.7, it was also noted that a further response to increased river/stream discharges may be a tendency for channels to becoming orientated more directly toward the sea. It is well recognized that when elevated sea level (storm surge and tide) coincide with high river/stream flows, spits tend to be overtopped and breached. If this were to occur at Whale Bay and channel offset be systematically reduced, then results in Section 4 suggest that less erosion would occur along the western shoreline (N_50) adjacent to the proposed site.

The erosion issues associated with Climate Change raised in the Guidance Manual therefore tend to be *compensatory*, especially when the site-specific sediment dynamics identified by this study are taken into account.

6. Slope stability

Episodes of erosion along sandy shorelines including the western Whale Bay lagoon tend to leave a steep scarp or cliff-like feature. The scarps top then retreats until a stable slope angle is achieved, and such retreat needs to be considered in erosion hazard assessments.

A suitable model to determine the scarp retreat distance is that of Clark and Small (1982) which is based on the slope replacement theory, it can be expressed as equation 3.

$$SS = h/2(\tan \propto) \qquad (3)$$

where SS is the landward distance the scarp top must retreat to achieve slope stability, h is the height of the erosion escarpment and $\propto$ is the angle of repose.

From Figure 5, it is evident that the maximum scarp height is likely to be no more than 1 metre. The predominant sediment of the lagoon margins in the vicinity of the building site is sand which has an angle of repose of 34 degrees. Applying these values to equation 3 gives a scarp top retreat value of 0.74 m. A value of 1 m will be used for SS in equation 1, the increase being to account for pockets of more cohesive materials of terrestrial origin which have lower angles of repose.

7. Uncertainties

The Guidance Manual (p38) states that consideration needs to be given to insufficient shoreline data, deficiencies with assessment methods, future greenhouse gas emission scenarios and lack of knowledge. Uncertainty associated with each CEHD component will now be considered.

The shoreline data used to assess the long-term shoreline trend (LT) was the most comprehensive available and processed using the most accurate methods available. Use of the vegetation-front as shoreline indicator only requires sampling every few years as vegetation acts and a high pass filter for events lesser magnitude compared with the response by the more seaward located HWM. Adequate care was taken to allow for the greater variability of the HWM indicator and also of the systematic difference between the two types of shoreline indicator. The methods of analysis were mathematically rigorous, the reasoning conservative, and the sediment dynamics defined by the study explain the past 130 yrs of shoreline behaviour. The only relevant uncertainty value for this component is associated with measurement errors associated with geo-referencing and detection of the shoreline indicator. The greatest of these was associated with the

1967 aerial photo (2.9 m), and this will used to represent LT in the combined uncertainty computation, i.e. CU_{LT} = 2.9. However, in addition to being an overrepresentation of the measurement error, this value also contains a considerable non-quantified safety margin due to the averaging process used in the regression analysis which effectively reduces this value.

The shorter-term fluctuation component value was based on the same data as the longer-term component so the conservative measurement error of 2.9 m will be used in the CU computation, i.e. CU_{LT} = 2.9. However, the non-quantified safety margin once again benefits from the averaging in the regression process which ensures the measurement error is conservative. Furthermore, the standard error approach ensures that a near maximum likely landward fluctuation (7.8 m) has been used in the assessment equation (1). This compares with the use of the greatest inter-survey change value of 6.3 m which is often used in erosion hazard assessments.

The assessment has adhered to the Guidance Manual's recommended SLR value of 0.6 m for a 100 yr planning time frame. This reduces to 0.4 when historical SLR was removed. The manual also recommended assessing the potential consequences of an additional sea-level rise of at least 0.3 m, thereby accounting for alternative emission and/or ice response scenarios. The associated shoreline retreat was determined using an appropriate profile translation model which, for a SLR of 0.3 m, gave a value of 10.7 m, and this value is considered adequate for the CU_{RSLR} . component. Note that the representative profile and channel base location were determined using the same high accuracy methods as used by Skyworks Waikato for the contour surveys. Furthermore, the impact on shoreline erosion at Whale Bay range of possible climate change hazard drivers discussed in the Guidance Manual was also assessed. The impacts were found likely to be compensatory, especially when the lagoon sediment dynamics identified in Section 4 were taken into account.

The SS value was increased by ~0.26 m for uncertainty. However, there were several other considerations which further increase the non-quantified safety margin. The slope stability component uses the maximum possible scarp height and thus a maximum associated retreat. Further, the use of 34 degrees as the angle of repose assumes erosion scarps do not contain plant roots which enhance revegetation thereby increasing stable slope angles and thus reduces associated scarp top retreat. Observed erosion scarps at the site invariably did contain vegetation.

In the past, there is been a tendency to simply combine error terms using addition. However, such terms are often derived from variables which are independent, so to assume that they are likely to occur at the same time (which addition infers) is statistically incorrect and gives an overly conservative combined uncertainty value. Combining independent terms should be carried out using the *root sum of squares (RSS)* method defined by equation 4.

$$CE = \sqrt{(E_1^{\ 2} + ... + En^2)} \qquad (4)$$

Where CE = combined error (shoreward directed), E_1 = first error term, and En = n^{th} error term.

Applying the error terms for LT, ST, SLR, SS (which are independent) to equation 4 gives a combined uncertainty value of 11.5 m for use in equation 1.

8. Coastal Erosion Hazard Location

This assessment has derived the following component values which combine to give the coastal erosion hazard distance (CEHD):

- Longer-term shoreline erosion over 100^+ yrs (LT) = 0
- Shorter-term shoreline fluctuation (ST) = 7.8 m
- Retreat from 100^+ yrs of climate change induced sea-level rise (RSLR) = 14.3^+ m
- Slope stability (SS) = 1m
- Combined uncertainties (CU) = 11.5 m

Combining these values as in equation 1 gives a CEHD value of = 34.6^+ m.

Because the regression analysis for CEN (Figure 2B) showed no statistically significant trend, the reference shoreline the CEHD is measured from will be the time-averaged aerial-based shoreline location which was 44.7 m from the CEN datum (the initial 1877 shoreline). The erosion hazard distance is thus 34.6 + 44.7 = 79.3 m from datum. However, the perimeter of the building site is 86.1 m from datum (41 m from perimeter to 2007 shoreline + 45.1 m from the 2007 shoreline to datum). The 100^+ yr erosion hazard location is thus less than 86.1 – 79.3 = 6.8 m from the perimeter.

When evaluating this inequality, however, the reader should be mindful of the several non-quantified safety margin contributions noted in Section 7.

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