Kapiti Coast Erosion Hazard Assessment

Part 1: Open Coast

A report prepared for the Kapiti Coast District Council

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EXECUTIVE SUMMARY

While the Kapiti Coast has been subject to open coast erosion assessments in the past, these have essentially been *regional assessments* in that they covered large areas at a relatively low level of detail. Given the extent of residential development along the coast and the potential for future development, together with the dire consequence of property loss associated with erosion plus the uncertainties associated with as climate change, the Kapiti Coast District Council (KCDC) commissioned a more detailed (*localized*) assessment. In particular the erosion hazard line methodology should be robust and defendable, use industry best practices, use a time-span of at least 50 yrs, and incorporate all available information.

In addition, where the coast is protected by structures or management practices, an erosion assessment for the simulated natural coast was also required. Calculating erosion hazard lines for the corresponding simulated natural coast/inlet enables the effect that management has had on coastal processes and morphological behaviour to be identified and the consequences of not committing to existing management for the next 50 to 100 years to be defined. While it is not anticipated that these structures will cease to be maintained, or that other management practices be discontinued, informed decisions will be able to be made on both the continuance of present structures and practices, and also on their future extension.

For practical reasons the ***Kapiti Coast Erosion Hazard Assessment*** was divided into three parts with Part 1 covering the open coast (*Open Coast Erosion Hazard Assessment*), Part 2 covering the inlets (*Inlet Erosion Hazard Assessment*) and Part 3 consisting of the data-base, (referred to as the *Coastal Erosion Hazard Data-Base*, or simply as the *Data-Base*), which includes all raw and processed data, along with computation details for the various hazard components used in the assessments.

The present report comprises *Part 1: Open Coast Erosion Hazard Assessment*, and assesses the erosion hazard from the southern end of Paekakariki Beach to the KCDC's northern boundary with Horowhenua District Council, a distance of approximately 38 km. Part 1, while originally completed in February 2007, was subsequently updated to incorporate a range of new data becoming available later in the 2007. In particular; high resolution colour vertical aerial photographs of the entire Kapiti coastline, and a district-wide beach profile survey. In addition, the latest information pertaining to climate change and sea-level rise from the International Panel on Climate Change (IPCC) was released in 2007. The *Kapiti Coast Erosion Hazard Assessment* now incorporates this information and is thus fully up-to-date.

The erosion hazard assessments use an *empirically-based* approach which quantifies the predicted cross-shore erosion hazard distance by summing several components. In particular, these components consist of:

- *longer-term historical shoreline change* which is derived by statistical analysis of up to 135 years of data (depending on location);

- *shorter –term shoreline change* which is also defined with respect to the historical shoreline record;
- *retreat associated with anticipated acceleration in sea-level rise from global warming,* which is derived via a shoreline adjustment model that utilized the substantial beach profile data-set held by the KCDC;
- *retreat of a dune scarp* (formed by undercut by storm waves) to achieve a stable slope, which is based on a slope stability model that utilized the KCDC's 3-dimensional LIDAR (Light Detecting and Ranging) data, and finally
- a *combined uncertainty* term which provides an acceptable safety margin. In addition to using the highest quality raw data that was available, the assessment utilized the most recent developments in image processing, data abstraction and statistical analysis, thereby ensuring robust and defendable output.

Along the southern coast, the erosion assessment was carried out for the following three seawall scenarios:

- *seawalls hold*, where the seawalls successfully maintain integrity and remain fully functional;
- *seawalls repair*, where the seawalls fail locally but are quickly repaired; and
- *seawall removal*, where widespread failure occurs and the remnants are then removed.

It is also noted that a more detailed assessment was carried out for south Paekakariki (Appendix A), because of its documented history of erosion, previous erosion hazard response (13 homes were removed in the early 1980s), and it contains a rare section of natural shoreline.

The final cross-shore erosion hazard distances (CEHDs) are depicted in Fig 9, and are summarized as follows:

- Along the southern coast (south of the Kapiti Boating Club at Paraparaumu Beach) the erosion hazard values differ quite dramatically for the three seawall scenarios. Under the *seawalls hold* scenario, the hazard distance equals zero next to the walls, while in non-seawalled areas some 49 – 120 m erosion may occur (depending on the site);

- Under the *seawall repair* scenario, the erosion hazard distances behind the failed sections of seawall at Paekakariki and Raumati range between 21 and 36 m (depending on the site). In the non-seawalled areas the hazard distances are the same as for the *seawalls hold* scenario;

- Under the *seawall removal* scenario, erosion hazard distances within the seawalled areas increase from 21 to 36 m up to 33 to 74 m, while in the non-seawalled areas they lower from 49 -120 m down to 36 - 61 m.

- North of the Kapiti Boating Club the seawall scenarios do not apply. The erosion hazard distance is greatest around the foreland (44 to 64 m) with values ranging between 26 to 44 m further north.

Based on these CEHDs, erosion hazard lines were derived along the entire open coast and high resolution images depicting these lines are available from the KCDC office. Three examples of these hazard lines overlying 2007 aerial photographs are given in Figs 10, 11 and 12. There is a choice of hazard line along the southern coast related to the future seawall scenario the council decides upon. In particular, there is the *hold, repair or remove scenarios* along the *official* seawalled areas at mid/north Paekakariki and south Raumati, plus a decision on how to handle the private seawalls which give partial shoreline protection at south Paekakariki and north Raumati (see Figs 10 and 11).

Finally it is noted that this erosion assessment has been carried out at the *local level* – this being the most detailed level usually undertaken by local government. Property owners still have the option of commissioning yet more detailed *site-specific* assessments and these may further refine the hazard lines defined in the present report.

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1 INTRODUCTION

1.1 Background and terms of reference

In June 2005, Coastal Systems Ltd was commissioned to re-assess the erosion hazard along the *open coast* administered by the Kapiti Coast District Council (KCDC), and this was later expanded to include the coastal inlets (see Fig 1). The ***Kapiti Coast Erosion Hazard Assessment*** comprises ***Part 1*** which covers erosion on the *open coast*, ***Part 2*** which covers erosion at *inlets*, and ***Part 3*** which contains the data-base. The *Coastal Erosion Hazard Data-Base* (referred to more simply as the *Data-Base*) contains the extensive sets of shoreline data used in the assessment, together with computation details of the various hazard components for each of the 68 *coastal measurement sites* used in the studies. The present report contains Part 1, the *Open Coast Erosion Hazard Assessment*. Note that while Part 1 was completed in February 2007, it was subsequently decided to update the assessment to incorporate a range of new data becoming available later in the 2007. In particular; high resolution colour vertical aerial photographs of the entire Kapiti coastline (this had not been done before), and a comprehensive district-wide beach profile survey. In addition, the latest information pertaining to climate change and sea-level rise from the International Panel on Climate Change (IPCC) was also expected in 2007. The *Kapiti Coast Erosion Hazard Assessment* now incorporates this information and is thus fully up-to-date.

The Kapiti Coast has been subject of several erosion assessments in the past; for example the generalized empirically-based assessment of Gibb (1978) and later the predominantly process-based, but still generalized, assessment of Lumsden (2003). Both these erosion assessments related to the open coast, and no previous assessment had been carried out for the 12 inlets. In addition, the previous assessments were *regional assessments* in that they covered large areas at a relatively low level of detail. However, given the extent of residential development along the coast and the potential for future development, the council required more *local* (detailed) assessments to be carried out. The brief for the present open coast erosion study consisted of the following:

i) Erosion hazard lines should be derived using a *robust and defendable* approach and use of industry *best practice*;

ii) The assessment should apply for at least a 50 yr time span or *planning horizon*[1];

iii) The assessment should be carried out at the *local level*[2] in urban areas and incorporate all available archival information. A lower level of assessment was acceptable for rural areas;

iv) Where coastal protections structures (seawalls and revetments) occur, an erosion hazard assessment for the *simulated natural coast*[3] should also be carried out.

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1. The *planning horizon* refers to the period of time for which the hazard zoning applies. While 50 or 100 yrs are often used by hazard assessors, there is no RMA requirement other than to require plan reviews every 10 yrs. This situation reflects the uncertainty involved in extrapolating rates of

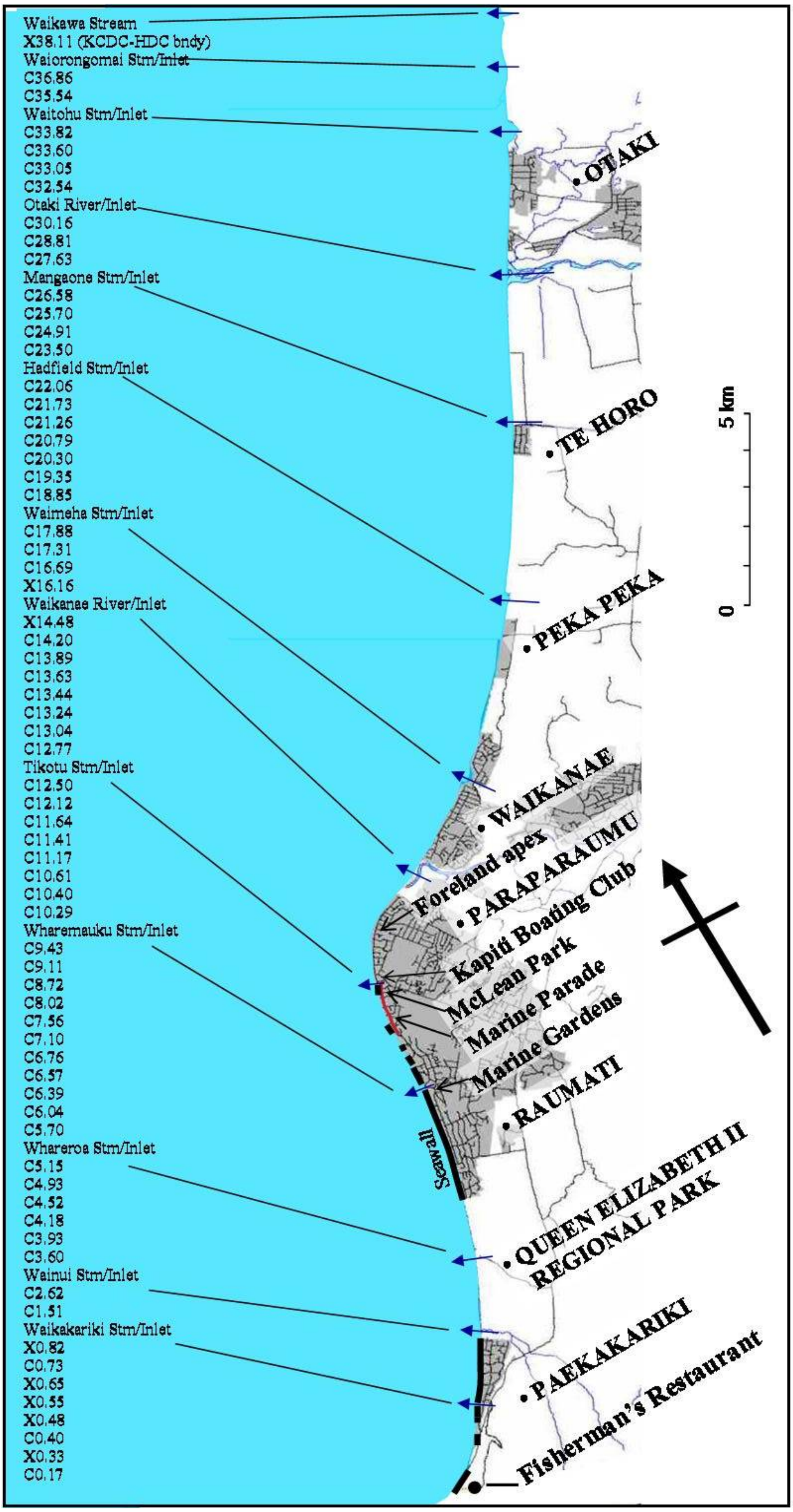


Figure 1 Map of the coastal area administered by the Kapiti Coast District Council which is referred to as the 'Kapiti Coast' in this report. Urban areas, water courses and stream mouths, seawalls and other locations referred to in the text have been marked. References across the top of map locate *coastal measurement sites* with the prefix **C** referring to sites used to provide data for determining erosion hazard **C**omponent values, references beginning with the prefix **X** referring to sites used to provide e**X**tra data for more detailed hazard assessment or for modelling the 2008 reference shoreline used for locating hazard lines, and the subsequent numbers refer to each site's longshore distance (km) from the datum at the southern end of Paekakariki Beach.

change into the future for an arbitrary period. Hazard zones should thus be viewed as indicating the degree and spatial extent of risk during the assigned period rather than providing certainty. While inordinate zone widths could be used to ensure hazard avoidance, such an approach is often not acceptable in developed areas. As a compromise, this hazard assessment uses a conservative approach when deriving the component values and these are then applied over a 50 year *prediction period*. The resulting hazard widths are thus expected to apply for well in excess 50 yrs.

2 It should be noted that while a *local erosion hazard assessment* is applicable to longshore reaches as small as a few hundred metres, this should not be confused with a *site-specific erosion hazard assessment* which contains the greatest level of detail and is carried out for individual properties usually at the property owners expense.

3 While *removal of these shoreline protection structures* is not an anticipated management strategy, it has been included to help quantify the effect the walls have on coastal processes and shoreline behaviour, thereby enabling informed decisions to be made on both their continuance and their future extension.

1.2 Environmental setting

Physical and cultural aspects of the study area have been described in earlier work (e.g. Gibb, 1978; Holland and Holland, 1985; Lumsden, 2003). Briefly, the northern section of coast (Waikanae to beyond Otaki) tends to consist of wide, accreting sandy beaches backed by dunes and isolated settlements. The exception being the mixed sand-gravel beaches and lack of foredune to the south of the Otaki River; The central region (Paraparaumu) consists of an accreting cuspate foreland with sandy beaches backed by dunes and concentrated settlement. The southern sections of coast (Raumati to Paekakariki) have narrower beaches which, in their natural state, have erosive tendencies, and they are backed by higher sand dunes. With the exception of Queen Elizabeth II Regional Park and a small area at south Paekakariki, this southern coast has been densely settled.

The coastal environment is also characterized by a range of engineering structures. These structures were established over the past 50 yrs to control shoreline erosion, and they continue to influence coastal processes. In particular, the structures consist of guidewalls and groynes to control river/stream mouths (e.g. Waikanae River, and the Wharemauku Stream), and seawalls along the Raumati and Paekakariki coasts to control shoreline erosion. Initial seawall construction followed a series of highly erosive storms in the mid 1950s (Donnelley, 1959). However, by the time of the infamous September 1976 storm, much of this initial seawall was in poor repair and widespread erosion occurred (Gibb and Wilshere, 1976; McHugh, 1981). More robust walls were then built between Marine Gardens and QEII, and along The Parade at Paekakariki. Subsequently, rock toe-protection was, and still is, being added. Lumsden (2003) estimated that the remaining life of these walls to be 10 to 15 yrs. Privately constructed walls of varying quality and longshore extent occur in Raumati, to the north of Marine Gardens, and also in south Paekakariki.

1.3 Approach

An empirically-based methodology was adopted as this approach is widely used in New Zealand for coastal erosion hazard assessment and is considered to be industry best-practice (Auckland Regional Council, 2000; Dahm and Monro, 2002). In addition, the assessment utilized the most recent developments in image processing, data abstraction and statistical analysis, thereby ensuring robust and defendable output.

The assessment uses the following formula to derive cross-shore erosion hazard distances (CEHD):

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

Where:

LT = *longer-term historic shoreline change.*

This component was derived for a 50 yr period using statistical analysis of shorelines derived from cadastral maps and aerial photographs;

ST = *Shorter-term shoreline fluctuation.*
This component was to be derived using statistical analysis of the historic shoreline data;

SLR = *Shoreline retreat associated with sea-level rise (SLR) induced by global warming.*
This component was derived for a 50 yr period based on the shoreline response model deemed to be most appropriate for the Kapiti Coast, and using the most recent SLR estimates;

DS = *Dune stability.*
This component accounts for scarp retreat to achieve a stable slope following storm erosion of the foredune;

CU = *Combined uncertainty*
This refers to the safety margin derived by combining the *measurement error* which is the combined errors (usually random) associated with the other four components, together with a range of *other factors* (precautionary measures used in post-component processing) which serve to increase the overall safety margin. These *other factors* which were quantifiable were included in the combined uncertainty (CU) value used in equation 1.

The open coast erosion hazard assessment incorporates the following three future scenarios for the existing seawalls:

(i) **Seawalls hold.** Walls maintain their integrity and successfully function for the duration of the prediction period;

(ii) **Seawalls are repaired.** Localized wall failures occur at some time during the prediction period but are quickly repaired, and

(iii) **Seawalls are removed.** Widespread wall failure occurs with remnants removed. Failure and removal are assumed to occur earlier in the prediction period.

Note that the associated seawall management programmes for these three scenarios could be:

(i) Optimum wall maintenance, strengthening and/or replacement as necessary[4];

(ii) Moderate wall maintenance with repair given ‘works priority’ where failure occurs, and

(iii) No wall maintenance with removal of remnants upon failure.

4. This assumes upgrading to adequate engineering standard (see Lumsden, 2003).

Note that each of the 68 coastal measurement sites (Fig 1) had its reference point coded with a distance-based name, with distance being relative to a datum at Fisherman's Restaurant. Furthermore, the code is prefixed with either C or X, with data from the former sites being used for determining **C**omponent values and the later to sites where e**X**tra data were collected for more detailed assessment. The precise survey co-ordinates for each coastal measurement site's reference point are given in the *Data-Base.*

In addition, for cross-referencing purposes, the location of any transects used in beach profile surveys which are in the vicinity of each coastal measurement site, are included in the *Data-Base* worksheet for that site. In the past, cross-shore beach profiles have been surveyed by several government agencies: the Kapiti Borough Council, the Manawatu Catchment Board, the Ministry of Works and Development, the Greater Wellington Regional Council and Horizons Regional Council.

Erosion hazard component values and resulting CEHDs are graphically depicted in Figs 5 to 9, with longshore distance on the horizontal axis such that 0 km corresponds to the Fisherman's Restaurant datum (given in section 2.3 of the *Data-Base*) at the Paekakariki Coast-SH1 intersection in the southern, and 38.1 km corresponds to the KCDC/Horowhenua District Council boundary in the north. The actual component values and CEHDs are tabulated in Appendix B and their derivation is detailed in the *Data-Base*.

1.4 South Paekakariki Study

The south Paekakariki coast has been subjected to significant episodes of erosion during the mid 1950s (Donnelley, 1959) and mid to late 1970s (Gibb and Wilshere, 1976; Gibb, 1978; Gibb and De Pledge, 1980) with 13 homes subsequently being removed from Ames Street in the early 1980s. The central and northern sections of the Paekakariki coast have continuous and substantial seawall protection. By contrast, the southernmost 1 km has a variety of protection with the central 300 to 600 m remaining in its natural state. Given the shoreline variation (natural and partially seawalled), the erosional history and the previous hazard response for this area, a detailed geomorphological study was carried out to provide additional information for use in the open coast erosion hazard assessment. The study, entitled *Shoreline Change at South Paekakariki: 1894 – 2007*, is included as Appendix A.

1.5 Reviews

This hazard assessment report was peer reviewed by Dr Mike Shepherd (coastal geomorphologist, Massey University) and Mr John Lumden (coastal engineering consultant). Written correspondence with these reviewers, including reconciliation of critical comment, is compiled in Coastal Systems Ltd (2007) which is available from the KCDC. The peer review compilation also contains comment relating to specific aspects of the hazard assessment was received from practitioners who have had direct involvement with coastal process or management investigations on the Kapiti Coast over the past 30 years: Dr Jeremy Gibb (coastal management consultant), Professor Bob Kirk and Dr Martin Single (coastal geomorphologists, University of Canterbury), and Mr Richard Reinen-Hamill, Senior Coastal Engineer with Tonkin and Taylor Ltd.

It is noted that these communications resulted in the inclusion of Appendices A and C which provide an in depth review and assessment of shoreline change along the southern Kapiti Coast. Professor Kirk and Dr Singles' comments on prediction periods and sea-level response modelling resulted in the inclusion of Footnote 1, and parts of Appendix D. Mr Reinen-Hamill, Senior Coastal Engineer with Tonkin and Taylor Ltd., provided useful comment on dune stability (Section 5), and this resulted in the inclusion of Appendix E. In addition, the statistical techniques used in the shoreline modelling were scrutinized by Dr S Ganesalingam from the Department of Mathematics and Statistics at Massey University.

1.6 Report outline

This report consists of separate Sections (2-5) describing the four hazard components (long-term change, short-term change, retreat from accelerated sea-level rise and dune stability) and derivation of their values under each of the three seawall scenarios. Relevant measurement errors and other uncertainties are considered within each of these 4 sections. The combined component values which give rise to the cross-shore erosion hazard distances (CEHDs) are described in Section 6. Section 7 describes the subsequent derivation of the coastal erosion hazard lines (or erosion set-back lines) and gives several illustrative examples (Figs 10 to 12). Finally, Section 8 discusses a range of other matters related to the assessment.

2 LONGER-TERM SHORELINE CHANGE

2.1 Introduction

Longer-term shoreline change refers to overall trends apparent in the 50 to 150 yrs of historical data available for the New Zealand coast. However, caution is required when trends are non-linear as prediction becomes less certain and a conservative modelling approach needs to be used. At Kapiti there are several instances of such behaviour, and in most cases they appear to correlate with human activity such as devegetation and revegetation, urban development, and coastal management.

2.2 Sources of longer-term shoreline data

The primary data source for both the longer-term and shorter-term shoreline analysis was vertical aerial photographs. For the Kapiti Coast, these photos date from the early 1940s and were sampled at approximately 5 to 10 yr intervals. Photographs were obtained from the KCDC archive or purchased from aerial surveyors. In addition, shoreline data already obtained from aerial photos and published in the *Coastal Resource Map Series* were used. These planimetric maps were produced by the Photogrammetric Branch of the Department of Lands and Survey in the 1980s for the National Water and Soil Conservation Organisation (NWASCO) using analogue stereographic techniques.

The vegetation-front was used as the shoreline indicator. This is common practice when using aerial photos because of the relatively clear demarcation. In addition, this vegetation line is a particularly suitable shoreline indicator for hazard assessment because it rapidly retreats under the elevated water levels and high waves of major erosive events but recovers much more slowly. The effects of storm erosion are thus preserved for a few years, thereby avoiding the need for more regular surveys. Ground inspection of dune morphology along with stereoscopic inspection of aerial photos to give 3D vision, were also used also used to help identify previous shorelines.

Prior to the advent of aerial photography, the main source of shoreline data is from cadastral maps which may depict a variety of shoreline indicators including the foredune-toe or more commonly, the high water mark at the time of the survey. However, high water marks are influenced by marine conditions, and these conditions can result in its location varying over several metres, thereby introducing a random error into the data. In addition, high tide lines are invariably several metres seaward of the dune vegetation line, and this introduces an unresolvable systematic error when combining cadastral and aerial-based shorelines. However, the seaward offset of the (earlier) cadastral data results in an over-estimation of shoreline erosion and this, fortuitously, provides a safety margin for any subsequently derived hazard distance. For the present exercise, cadastral shorelines were only obtained from the NWASCO Coastal Resource Maps.

Shoreline data contained in earlier reports such as Gibb (1978) and Holland and Holland (1985) were not used because of difficulty identifying reference measurement points. In addition, several errors were identified (noted in Section 2.4.2 and Appendix C); these were possibly related to manual techniques of data abstraction compared with the more accurate geo-rectification-based procedures (see below).

2.3 Processing and analysis of longer-term data

To compare shoreline locations from different years, NWASCO maps and aerial photographs were 'geo-rectified', i.e. transformed to a common spatial scale and standard map co-ordinate system – in this case the New Zealand Map Grid (NZMG). Cross-shore transects used in previous studies were then located as accurately as possible, and additional 'infill' reference points were assigned to provide more comprehensive coverage throughout the study area. In urban areas or along sections of coast with greater morphological change, transects were spaced only a few hundred metres apart, whereas in rural areas or along coastal reaches with little variation, the spacing increased and was often in excess of 1 km. In all, 68 sites were used for measuring various types of coastal information (see Fig 1), with the precise co-ordinates of the reference points (measurement origins) being recorded in Part 3 (Data-Base) to facilitate future updates. Note that for the partially seawalled sections of coast, assessments were made for several seawalled and non-seawalled locations to demonstrate differences. For example, north of Marine Gardens in Raumati, two locations without walls (C10.29, and C10.61) were used along with the intervening seawall located at Tainui Street (C10.40). This resulted in a marked fluctuation in the long-term output graph (Fig 5A), in the erosion hazard (cross-shore) distance output graph (Fig 9), along in the (longshore) erosion hazard line (Fig 10).

For each transect, the distance from the landward reference point to each shoreline was measured and recorded. This resulted in ~9 aerial-based data points and 1 or 2 earlier cadastral-based data points per transect, about 600 data points in total. These data were then loaded onto a spreadsheet for analysis. An example of a shoreline history (time-series) graph for north Waikanae Beach is depicted in Figure 2A. Note that the distance datum is the first measured shoreline, this being to simplify the shoreline modelling procedure described below.

In the past, longer-term shoreline trends have often been identified using the 'end-point' method in which the net change is divided by the overall time interval. Its appeal lies with its computational simplicity, and in situations where shoreline behaviour is linear, i.e. the rate of change is constant, and the end-points lie close on the trend, this approach provides a satisfactory means of defining the long-term trend – should one be present. However, in many situations the end points do not lie on the trend and shoreline behaviour is better described using 'regression-based linear modelling'. This technique fits a straight line to the data using a 'least squares' routine which incorporates the full set of data-points. Such regression-based modelling is increasingly being used in hazard assessment and will be used in the present analysis. The linear model is represented by equation 2 where Y is the dependent variable (shoreline location), X is the independent variable (time), *a* is the

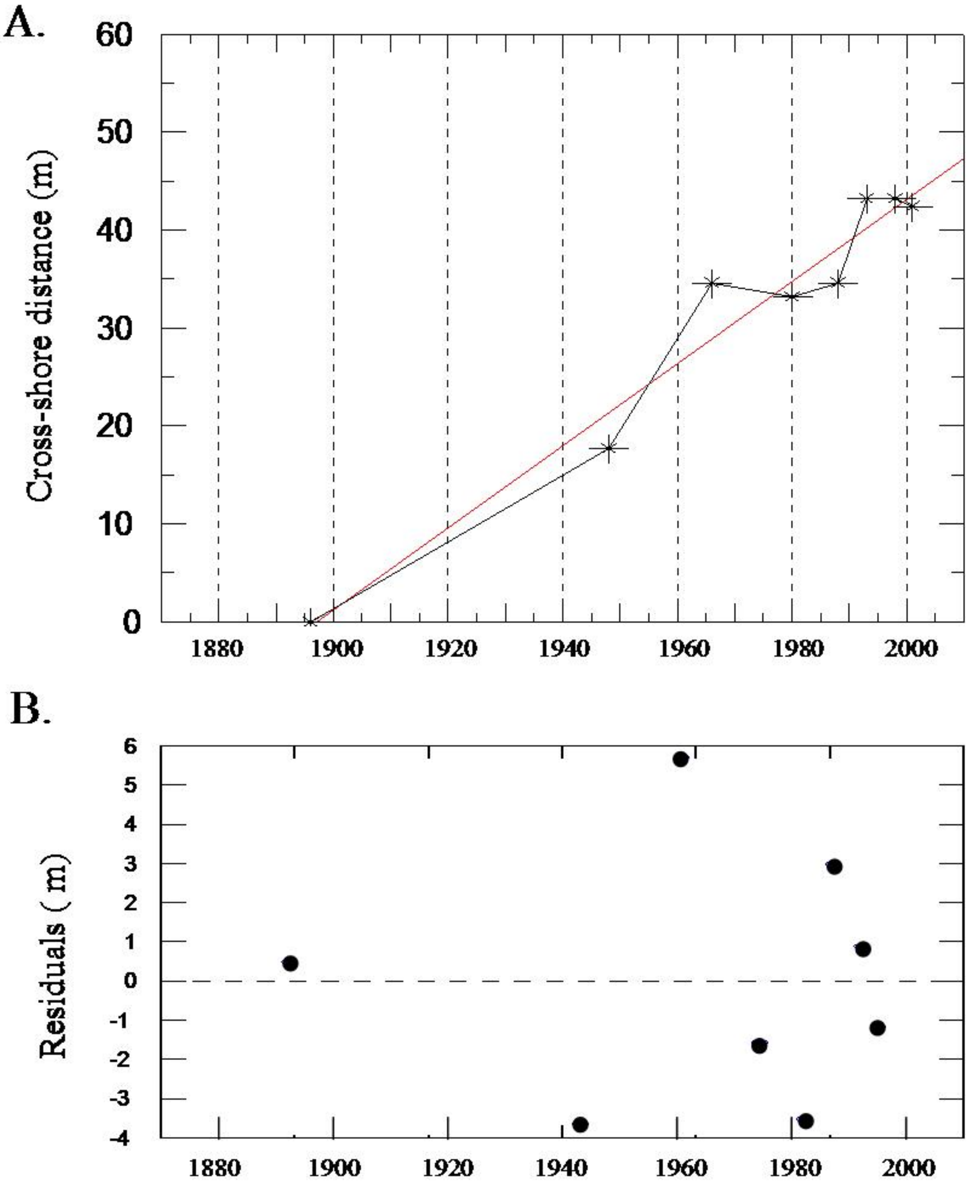


Figure 2 Example of shoreline change at North Waikanae (transect 18.85). A linear regression model (straight red line) has been fitted to the time-series in A to depict the longer-term trend of progradation (seaward advance). Differences between the modelled (straight line) and observed values (crosses) in A, are plotted in B. These differences (called ***residuals***) are used to determine the shorter-term shoreline fluctuation.

intercept on the Y-axis, *b* is the slope coefficient (rate of shoreline change) and *e* is the fitting error.

$$Y = a + bX + e \qquad (2)$$

The model output provides values for the rate of shoreline change and the fitting error which relates to the short-term change (Sections 3). In addition, statistics are available to provide a measure of the significance of the slope (F-ratio) and the reliability of the slope (the standard error of b) and these are considered later in the uncertainty Section (2.5).

Parameters are also available to describe the strength of the association (correlation coefficient), and the proportion of variance explained in the correlation of the two variables (coefficient of determination). These terms and concepts are described in statistical text books such as Shaw and Wheeler (1985), or manuals for statistical software such as Wilkinson, (1996). The correlation coefficient, together with the magnitude of the fitting error, indicate a changing trend, and non-linear regression procedures should be considered. Note, if the data-set contains only two points, then the output from linear regression will be the same as from end-point analysis.

A linear regression model has been fitted to the data-points in Fig 2A to define the long-term trend; in this case the shoreline is migrating seaward at an average rate of 0.42 m/yr. These data points clearly fluctuate about the fitted line. In this case, it can be seen that the end-point approach would yield a similar rate.

Linear modelling was carried out on data from each transect using the following time periods: the **entire record** (1870s to 2007); the **earlier period** (1870s to early 1950s); and the **later period** (1940s to 2007). Note that the earlier period was selected to precede coastal management, while the latter period was selected to include all available aerial photographs because of the accuracy and consistency of the associated shoreline data. There is a temporal overlap of about 10 years between the two data-sets.

Linear modelling was found to provide a relatively poor fit to data where medium-term change (10 to 50 yr patterns) were evident. In particular:

- Between the foreland apex and the Waikanae Rivermouth longer-term shoreline advance has been replaced with more stationary behaviour (see dashed line in Fig 3A);
- On the southeast side of the foreland a significant increase in the accretional rate has occurred (see dashed line in Fig 3B);
- Along the southern section of Marine Parade the accretional trend has changed to erosion (see dashed line in Fig 3C), and
- The erosional trend at QEII Park has increased (see dashed line in Fig 3D).

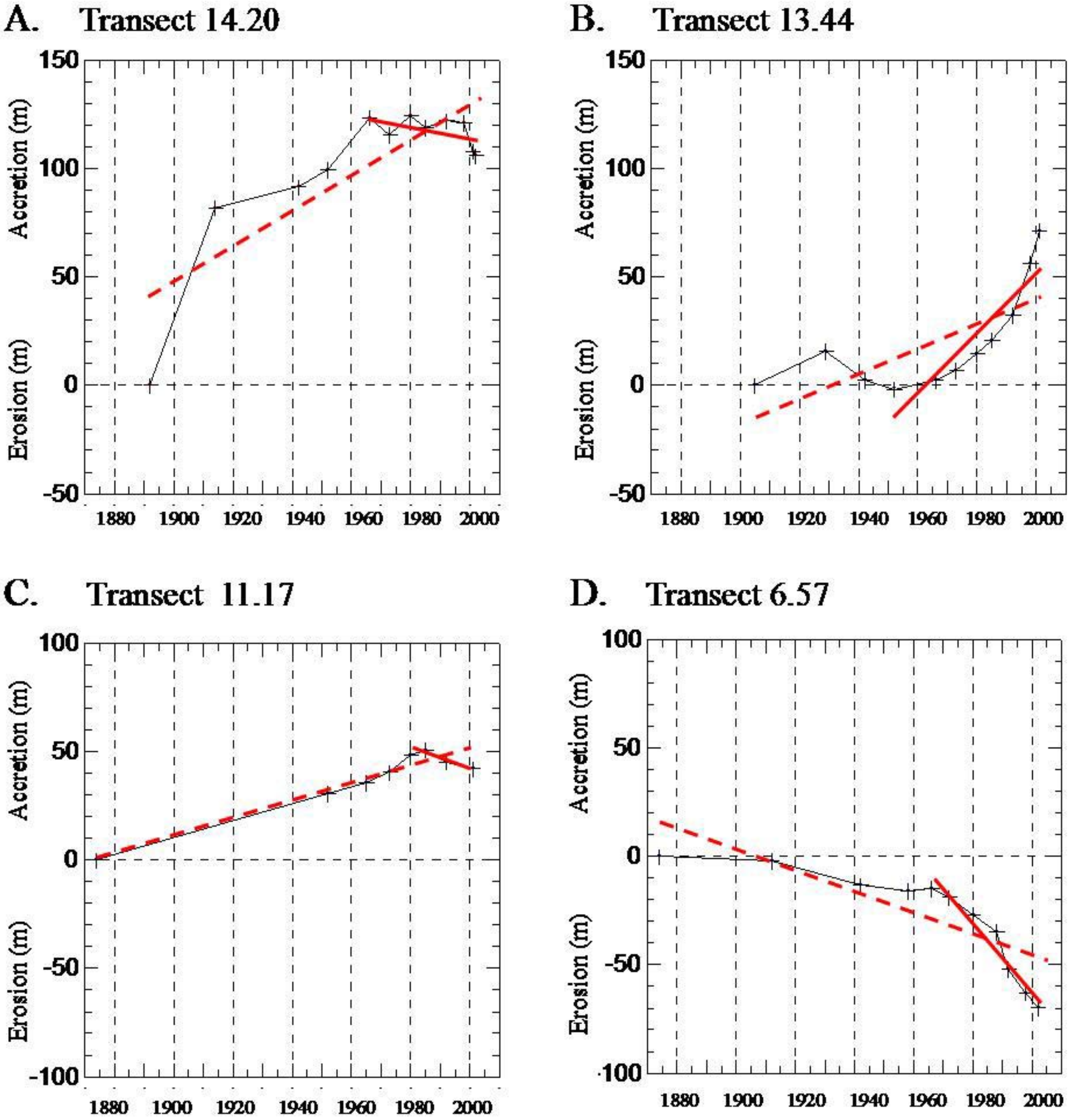


Figure 3 Examples of non-linear shoreline behaviour. A is at Paraparaumu between the foreland apex and Waikanae River, B is at Paraparaumu to the south of apex, C is at Raumati North to the south of Marine Parade and D is at the Raumati end of QEII.
The bold dashed lines depict linear models fitted to the entire record, while the shorter bold lines depict weighted linear models applied to more recent data (as explained in the text).

While non-linear models provide a better fit for such data, they may also lead to increased inaccuracy when used for predictive purposes. This situation occurs when the underlying processes responsible for the change in behaviour are uncertain, so future behaviour will also be uncertain and the non-linear pattern may change once again. In such circumstances, researchers (Fesnter et al., 1993) recommend non-linear models only be used to identify critical trend-change, and weighted linear models then be applied to post-change data. This approach has been adapted for use in the present study. Such *weighted* linear modelling techniques have been applied to the four examples in Fig 3 and are represented by the bold lines on these graphs. For completeness, in each case a linear model has also been fitted to the entire record (dashed line).

2.4 Longer-term results

2.4.1 Rates of change and discussion

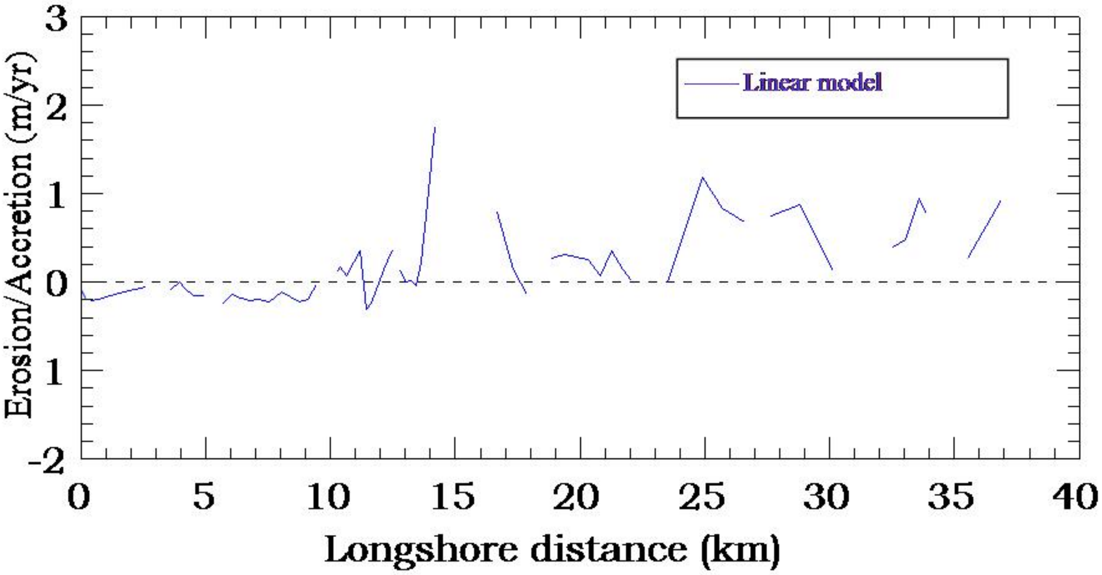
The longer-term rates of change for the *earlier period* (1870s to 1950s), and the *later period* (1940s to 2008), are depicted in Fig 4A and 4B respectively. Note that the later period results were derived using data from non-seawalled areas and interpolated across seawalled areas, while the southernmost values were derived from the South Paekakariki Study (Appendix A).

While the rates for the *entire record* were computed, they have not been included in the analysis as their trends were qualitatively similar to the *later data-sets*, with the exception of the areas represented by Figs 3A-D, and the later aerial-based data record provides for greater accuracy and predictive precision because of the single data source (vegetation line from aerial photos) and the larger number of data-points within each record.

The average rate of retreat along the Paekakariki-Raumati coast to Marine Gardens for the *earlier period* (Fig 4A) was -0.15 m/yr (-0.25 to -0.004 m/yr). Given that these rates may be exaggerated by the inclusion of tide-based shorelines from cadastral maps, and affected by lack of intermediate data-points, the pre-urban shoreline appears to have been relatively stable. Further north, from Marine Gardens to the south side of the foreland apex, the rate of shoreline change varied between -0.3 to +0.4 m/yr, before increasing up to +1.8 m/yr between the apex and the Waikanae River. With only one exception at Waikanae Beach (-0.16 m/yr) the shoreline north of Waikanae was accretional with rates as high as 1.2 m per yr (average 0.46 m/yr).

Results for the *later period* are depicted in Fig 4B. Rates derived from linear regression modelling are depicted by the green solid line and rates derived by weighted regression are depicted by the black dashed line. As noted earlier, the weighted regression technique was used for locations where a change in trend is evident.

A. Earlier record (1874 to 1950s)



B. Later record 1940s to 2007

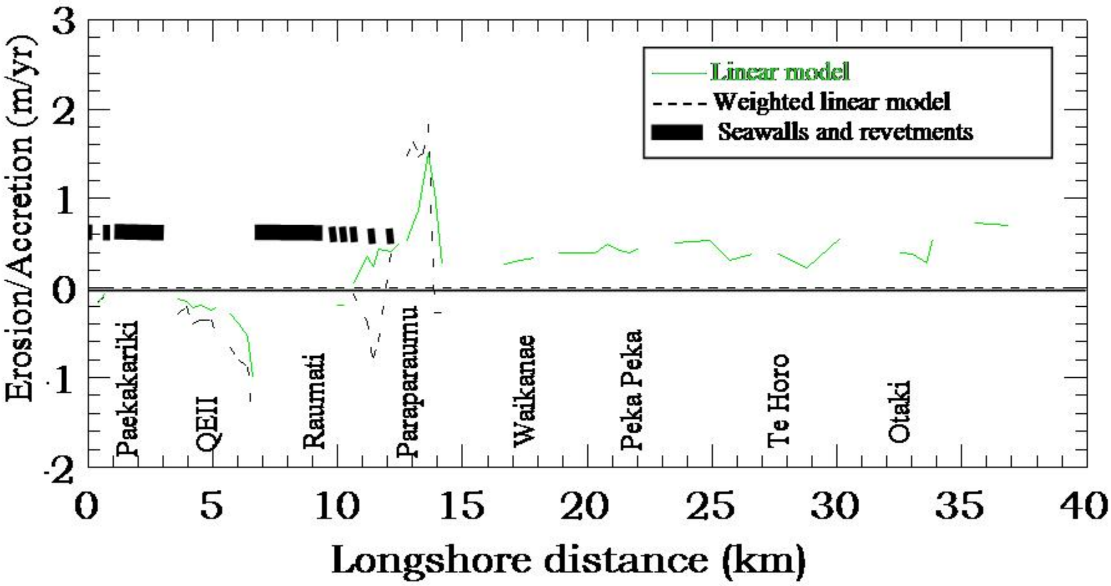


Figure 4 Longer-term rates of shoreline change for the *early (pre-seawall) period* (1870s to 1950s), are depicted in A. Rates for the *later (aerial photo) period* (1940s to 2007) are depicted in B, with the dashed line identifying those areas with more recent trend change. Details of the modelling procedures are given in the text. Discontinuities relate to areas affected by river and stream mouths (A and B), or seawalls (B). The longshore distances on the horizontal axis stretch from Paekakariki on the left to beyond Otaki on the right. While suburb and settlement names, along with horizontal bars representing seawalls or rock revetments, have been marked on the lower graph (B), they also apply to the upper graph (A).

The *later period* results (green solid line), show erosion south of C10-29 (approx Marine Gardens) with maximum erosion rates toward the northern end of QEII Park. Accretion occurs along the coast north of C10-29 with maximum value of 1.51 m/yr at the foreland apex. By contrast with the *earlier period* data (Fig 4A), the rate then decreases toward zero between the apex and the Waikanae Rivermouth. Possible reasons for this dramatic change in shoreline behaviour focus on inlet management and are discussed in *Part 2: Inlet Erosion Hazard Assessment*. Along the northern coast entirely positive rates occur with the average value being 0.42 m/yr, approximately the same as for the *earlier period* data. However, the longshore variability is less for the *later period* data and this is probably related to regressing over a greater number of data points.

The results in Fig 4B based on the *weighted linear model* (dashed line), identify locations where a more recent (medium-term) change in trend has occurred. NB time-series examples from these locations were depicted in Fig 3. The erosion rates have increased along the entire QEII coastline and this is likely to have been caused by seawall *end-effects*. Seawalls modify the hydrodynamic conditions and cause erosion both on the beach to seaward. Localized erosion also occurs at/beyond the ends of the wall, especially on the downdrift side if a coast is subject to significant longshore current. Erosion is also evident north of the Raumati seawalls and this extends at least as far as C11-64 (Rua Street) on Marine Parade. Such *medium-term* erosion may be related to *end effects* from the Raumati seawalls to the south. However, it is probably more likely to be associated with variation in sediment supply; this may be either a localized variation moving shore-normally, or the longshore propogation of a *sand wave*. Indeed, the weighted regression analysis (Fig 4B) emphasizes a more recent accretional trend south of the foreland apex, and this behaviour may be linked with the medium-term pattern of shoreline change north of the Raumati seawalls.

Between the foreland apex and the Waikanae River the weighted modelling shows the approximate stability (0.07 m/yr) from the general regression model being replaced by erosion (-0.28 m/yr). This change results from the substantial recession experienced between the late 1990s - early 2000 (see Fig 3A and relevant time-series in the *Data-Base*). Again, reasons from this change in shoreline behaviour are considered in the *Inlet Erosion Hazard Assessment.*

These atypical shoreline behaviours to each side of the foreland, may be related. Lumsden (1996) and Gibb (2002) have and speculated that eroded sediment from north of the apex is the source of sediment accumulating to the south. Sediment volume calculations by Gibb (2002) gave some support to such a hypothesis. However, it is likely that a portion of this eroded sediment was used to infill part of the Waikanae Estuary (see *Inlet Erosion Hazard Assessment*). In addition the time-series (see *Data-Base)* do not support a continuously migrating sand wave, the typical process by which sediment waves move along open coasts. The hypothesized transfer of sediment around the apex, and on toward the Kapiti Boating Club and Marine Parade, would therefore require an alternative sediment transport mechanism, possibly involving nearshore processes compared to (inter-tidal) beach processes. Further research would be required to explain the sediment dynamics in the vicinity of the foreland apex.

2.4.2 Comparison with earlier studies

Gibb (1978) and Holland and Holland (1985) have published broadly comparative long-term shoreline migration rates. The Gibb/Hollands identified 0.16 to 1.71 m/yr of longer-term accretion along the Waikanae to Otaki coast. This compares with 0.23 to 0.57 m/yr from the more comprehensive present study. Around the foreland, the Gibb/Hollands studies identified accretional rates of 0.09 to 2.54 m/yr. An updated long-term shoreline assessment by Gibb (2002) about the foreland apex area, found longer-term accretional rates had decreased to between 0.9 and 1.1 m/yr. These rates compare with -0.28 to 1.8 m/yr used for predictions in the present study, with the negative value reflecting the trend change from accretion toward erosional since the 1960s (Fig 3A) . Immediately to the west of the Raumati seawalls, the Gibb/Hollands studies found rates of approximately 0.5 m/yr. This compares with -0.78 to -0.06 m/yr in the present study, again reflecting the more recent erosional change. Rates for QEII ranged between -0.26 and 0.46 m/yr for the earlier studies c.f. -1.48 to -0.28 m/yr in the present study. Gibb (1978) reported rates of -0.72 to -0.03 m/yr at Paekakariki, compared with -0.26 to -0.15 m/yr for the *early period* and -0.16 to -0.05 m/yr for the *later period* as derived in the present assessment's South Paekakariki Study (Appendix A).

The differences in rates between the present study and the Gibb/Hollands studies, either reflect the more recent influence of seawall end effects and other forms of coastal management as noted above, or else to less sophisticated modelling procedures or measurement error in the Gibb/Hollands studies. For example, the substantially higher Paekakariki value in Gibb (1978) was a consequence of using an inappropriate shoreline indicator as explained in Appendix C.

2.4.3 Predicting longer-term change

The rates of change shown in Figs 3 and 4, provide the basis for predicting long-term shoreline change for the three seawall scenarios. Figure 5A depicts predicted long-term change under the *walls hold* and the *walls are repaired* scenarios for a 50 yr prediction period, while Fig 5B shows the predicted change under the *walls are removed* scenario. Note that the recently constructed rock revetment along southernmost (approx) 500 m of Marine Parade has been incorporated into this assessment.

Details of the computation procedures are provided in the *Data-Base*. Important considerations are briefly set out below.

Long-term shoreline change for *walls hold and walls repair* scenarios was based on the *later period* rates, while for the southern coast (south of C11-17), which is affected by seawalls, the *earlier period* rates were used.

Of particular note is that for all areas subject to a positive (seaward) shoreline trend, the rate was set to zero. This approach is common when assessing hazards for accreting coasts as it removes the assumption of continued accretion, provides an increased safety margin.

The maximum (95%) erosional rates of shoreline change over several transects with similar characteristics was selected to represent that reach. This approach helps to compensate for any bias introduced by possible under-sampling.

For the seawalled areas, the *wall removal* output included 50 yrs of *catch-up* erosion with this factor resulting in up to 12.5 additional metres of erosion. Also note that in areas with seawalls, the long-term shoreline change for *seawalls hold* = 0, as it is for *walls repair* scenario as in the latter case it is assumed that failed walls will be re-established in the same location.

Note that all predictions from about midway along Marine Parade to Otaki are the same regardless of seawall scenario.

It is possible that the substantial erosion predicted to occur under the *walls hold/repair* scenarios in areas adjacent to the present seawalls such as at QEII Park (up to 75 m), may be over-estimated because it is unclear whether or not the increased erosion rates due to *end-effects* will continue. It is possible that after initial adjustment to changes in wave, current and sediment transport patterns, recession rates may reduce as the system tends toward a new equilibrium. However, for hazard prediction purposes it is assumed that the higher existing rates will continue.

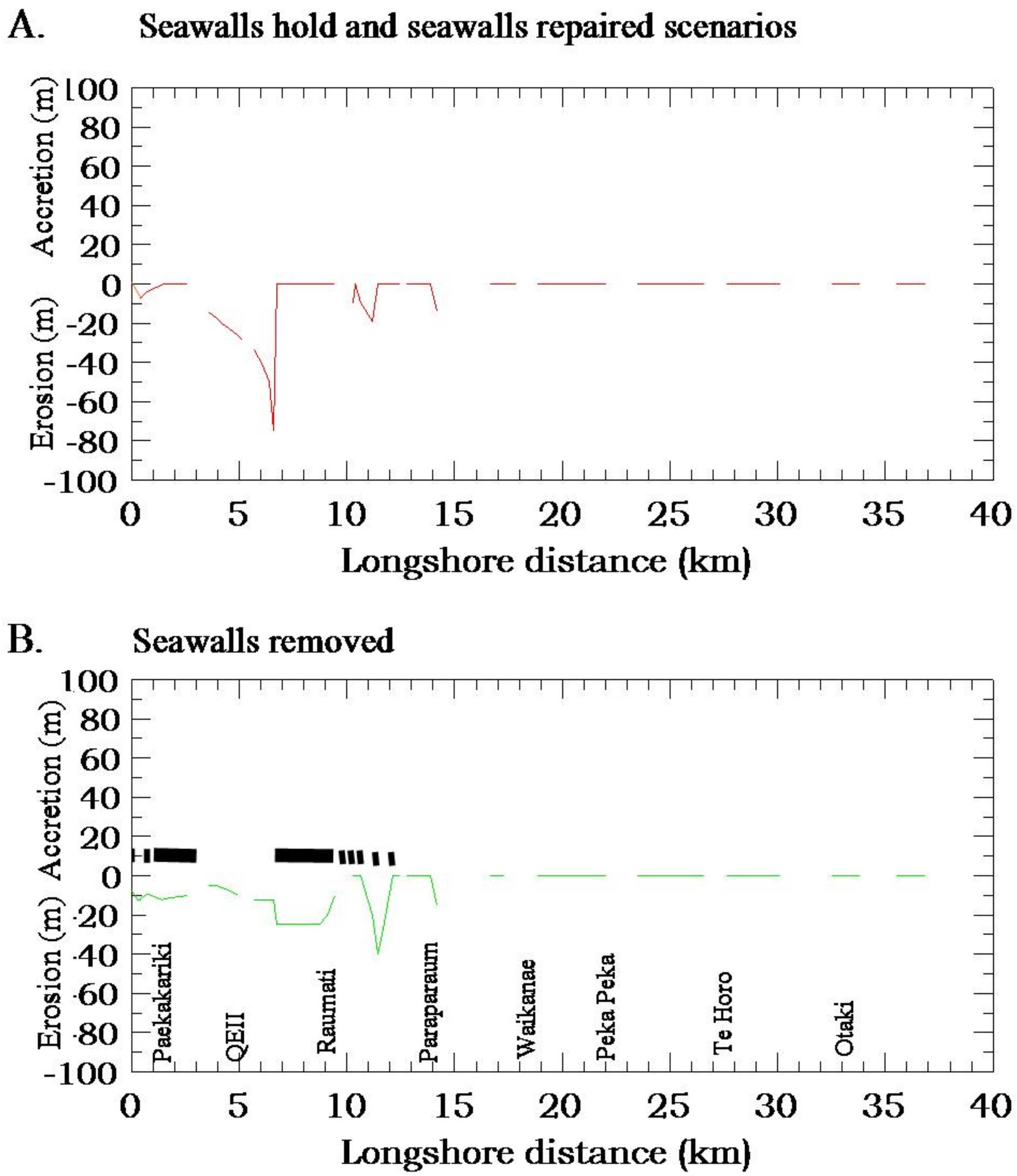


Figure 5 Longer-term shoreline change for a 50 yr prediction period under the seawalls ***hold*** or seawall ***repair*** scenarios are depicted in A, and under the wall ***removal*** scenario in B. Discontinuities relate to areas affected by river and stream mouths. The longshore distances on the horizontal axis stretch from Paekakariki on the left to beyond Otaki on the right. While suburb and settlement names, along with horizontal bars representing seawalls, have only been marked on the lower graph (B), they also apply to the upper graph (A).

2.5 Longer-term uncertainty

Measurement errors consisted of the shoreline location error (geo-rectification and shoreline detection errors), and the effect this had within the regression modelling process. Combining errors for geo-rectification (±3 m) and shoreline detection (±3 m), gave a value of ±4.2 m. Note that combining independent error terms was by the root sum of the squares (RSS) procedure (see Section 6.2). Furthermore, where longshore variation occurred in error value, an upper (approx 95%) value was selected to represent the entire coast.

The effect of the shoreline location error on the actual rates of change as determined by the regression procedure, was determined empirically to be ±3.7 m for the 50 yr prediction period. Note that the averaging process within regression procedures can reduce the error below that of the raw data for both rates of change and shorter-term variation (see Section 3.5).

Several other non-quantified uncertainty factors have been noted earlier in Section 2 and these act to increase the safety margin.
In particular:

- cadastral-based shorelines often have a seaward offset compared with aerial-based shorelines and this provides an over-estimate of erosion;

- use of a modelling technique that was weighted toward more recent erosion when that recent erosion may only be part of a (medium-term) temporary change, this includes areas undergoing seawall end-effects;

- setting positive rates of shoreline change to zero; and

- selecting a maximum erosional rate of change over several transects in the longshore direction, to represent that reach.

In Section 2.3 attention was drawn to statistics which address the statistical significance of the slope (F-ratio) and the reliability of the slope (the standard error of b). While some hazard assessments incorporate such statistics, this was not done in the present assessment as the weighting procedure, together with the variance reduction measures of setting positive rates to zero and the selection of the maximum longshore rate, were found to be adequate.

3 SHORTER-TERM SHORELINE CHANGE

3.1 Introduction

Shorter-term shoreline change refers to cross-shore fluctuations induced by major storms, climatic cycles or sediment variation. Such changes in the location of the vegetation line (the shoreline indicator used in this study), may occur at time intervals of several months to several years.

3.2 Sources of shorter-term data

The same aerial photos used for long-term trend determination were used to quantify shorter-term fluctuations. These data were chosen in preference to cross-shore profiling[1] and more recent LIDAR data because of uncertainties involved with locating benchmarks, spatial limitations, temporal limitations and uncertainties when correlating such elevation-based shorelines with vegetation-based shorelines derived from aerial photographs. Regarding the latter, if a shoreline indicator elevation is selected below the dune-toe, then the horizontal sweep of the shoreline may increase considerably due to marine processes and these processes may have minimal affect on the dune-base/vegetation.

3.3 Shorter-term data processing and analysis

In the past, shorter-term shoreline change has focused on the *maximum inter-survey difference* between consecutively sampled shoreline locations. However, if a long-term trend exists, then this can magnify the maximum difference and hence over-estimate shorter-term change, a practice referred to as *double dipping.* Hazard analysists have been required to apply *professional judgment* in separating the short-term change from the longer-term trend. By comparison, the regression techniques introduced in Section 2, provide an objective means of determining the short-term shoreline fluctuation independent of any long-term effect by utilizing the *fitting errors or residuals*. For example, residuals associated with the regression modelling in Fig 2A are depicted in Fig 2B.

The *standard error of estimate (SEE)* is the statistic used to estimate population variability based on the residuals. In particular, the SEE equals the square root of the residual mean square as determined by an *analysis of variance* routine. Note that the *population* refers to all shoreline locations rather than the sample of shorelines used for analysis. It can be shown, e.g. see Shaw and Wheeler (1985), that 2 x SEE on each side of the regression line, i.e. ± (2 x SEE), will encompasses 95% of population values. In other words, we can be 95%

1. Since the 1970s, cross-shore profiles have been surveyed on the Kapiti Coast by the Ministry of Works and Development, the Department of Lands and Survey, the Kapiti Borough Council, the Manawatu Catchment Board, the Kapiti Coast District Council, Greater Wellington Regional Council and Horizons Regional Council. Despite an extensive search, the only pre-1990s profiles located are those in the Horizons Regional Council archive for Te Horo and Otaki. By contrast, district wide profile surveys are available from the KCDC since 2000 at one to two yearly intervals. In addition, over 100 profiles are available for the Paraparaumu coast, these having been surveyed as part of the KCDC's beach nourishment monitoring programme (Lumsden, 1996) and the GWRC's Waikanae River management programme (Westlake, 2003).

certain that this interval will encompass the range of possible shorelines. Alternatively, ± 3 x SEE will encompasses 99% of population values. As the shorter-term fluctuation is a particularly significant component in erosion hazard analysis, the 3 x SEE option will be adopted in this study to minimize uncertainty.

To illustrate the effect of ± 3 x SEE, this value for data depicted in Fig 2 is ±10.4 m. This is substantially greater than the largest observed negative residual (landward fluctuation) of 3.8 m. This difference between the largest residual and the 99% confidence limit helps compensate for the fact that irregular sampling intervals within aerial photo records will quite likely lead to missed erosion extremities. The maximum inter-survey difference approach has no such safeguard and once again safety factors based on professional judgment must be applied when using this method.

It should be noted that the regression-based SEE approach assumes that the residuals are *normally distributed*, i.e. they fit a *bell-shaped (normal)* frequency distribution. To test this requirement, residuals were plotted on a normal probability scale prior to undertaking regression analysis. In all cases they fell approximately on a straight line which is a test requirement for normality.

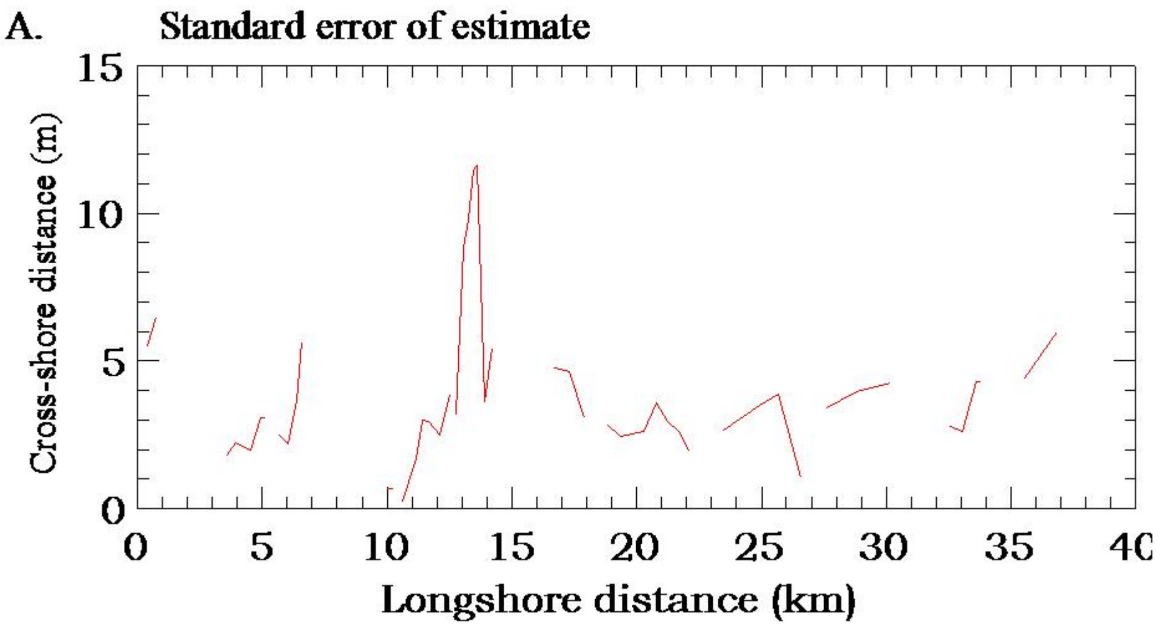
While the short-term fluctuation is defined by the interval ± (3 x SEE) about the regression line, and as the final hazard distance is referenced to this *average* shoreline location, only the landward or negative variation is relevant. So, unless otherwise noted, in this hazard assessment the short-term fluctuation will refer only to the negative portion.

3.4 Shorter-term results

3.4.1 This study

Figure 6A depicts the 3 x SEE values along the Kapiti Coast based on *later period* data. Note that *earlier period* data were considered to be too sparse for use in a variability analysis. The maximum (95%) value over several transects with similar characteristics was selected to represent that reach and these values then given negative signs to signify erosion (Fig 6B). This *maximizing adjustment* is important as it increases the likelihood of detecting larger shoreline recessions as beach response to storm erosion can vary substantially in the longshore direction. In addition, as data were unavailable for seawalled areas, the SEE-based values from adjacent sites were interpolated across these areas. Further details on the derivation of the short-term component values and their application to the three seawall scenarios are given the *Data-Base*.

The results in Fig 6B show most of the north coast has a value of 12 m with this increasing up to 18 m towards the boundary with Horowhenua District Council, and up to 36 m at the Paraparaumu foreland. North Raumati and QEII have values of 10 m while South Raumati



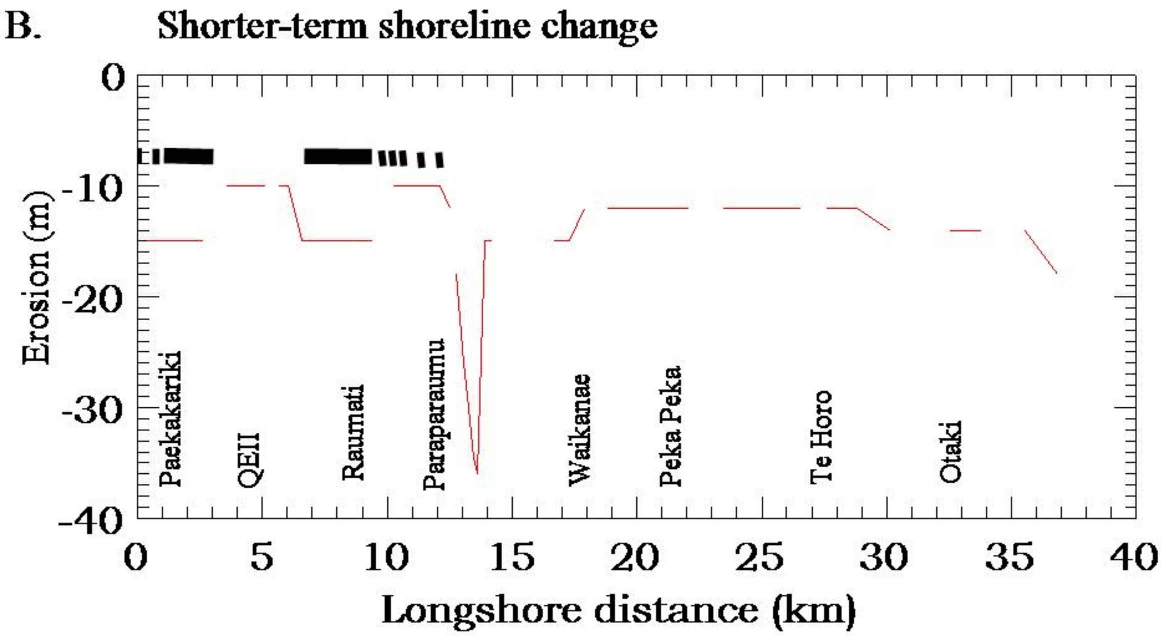


Figure 6 Standard error of estimate (A) used to derive short-term shoreline change or fluctuation (B) as explained in text. Discontinuities relate to areas affected by river and stream mouths. Part of the discontinuities in A also relate to lack of data for seawalled areas, with values for such areas in B being based on interpolation from adjacent sites. The longshore distances on the horizontal axis stretch from Paekakariki on the left to beyond Otaki on the right. While suburb and settlement names, along with horizontal bars representing seawalls and rock revetments, have only been marked on the lower graph (B), they also apply to the upper graph (A).

and Paekakariki have 15 m. Note that the extremely high values at, and immediately south of, the foreland are to some extent an artifact of the methodology of fitting a straight line to curved data. The SEE values are thus overly high and the resulting hazard distances (Section 6) conservative. However, as the associated hazard zone (Section 7) does not affect private property no additional refinement of the methodology for this area was undertaken.

The same values were applied to all seawall scenarios with the exception of the seawalls hold option for which ST = 0.

3.4.2 Comparison with earlier studies

Maximum shorter-term shoreline fluctuations along the south coast were estimated by Gibb (1978) to range between 40 and 50 m based on shoreline data he obtained from cadastral maps. This compares with the ±(10 to 15 m) interval used for the present hazard assessment. This difference is substantial and is addressed in Appendix C. That comparison concluded that the erosional shorelines reported in Gibb (1978) were incorrect, possibly due to the use of atypical shoreline indicators by the original surveyors (NB also see Section 2.4.2).

A sequence of five profiles surveyed by the Ministry of Works and Development between 1974 and 1979, appeared as Fig 3 in Gibb and DePledge (1980). These surveys spanned the particularly severe erosional episode of the late 1970s at a site approximately 750 m north of the Fishermans Restaurant. The landward recession of the dune-toe was reported as 12 m which is within the ±(10 to 15 m) short-term fluctuation used in the present assessment. While such retreat is dramatic and caused considerable consternation at the time and 13 homes were removed, the shoreline subsequently underwent recovery during the 1980s that was in keeping with expected dune erosion-recovery behaviour detailed in Appendix A.

3.5 Shorter-term uncertainty

The shorter-term measurement error was determined by empirically assessing the effect the shoreline location error (geo-rectification and shoreline detection errors ±4.2 m) had on 3 x SEE. This resulted in a value of ±2.6 m.

An additional 5 m uncertainty factor was included for the seawall locations under the *walls are repaired* scenario to account for increasing scour potential through the prediction period. During this time, the bed level fronting the seawalls is expected to lower under the influence of long-term processes and SLR. While retreat associated with these factors amounts to approximately 15 m under natural conditions, positive feedback processes would only enable a portion of this to occur during a single, or cluster, of extreme events.

A significant non-quantified uncertainty factor results from the selection a maximum (95%) fluctuation over several transects in the longshore direction to represent that reach.

4 SEA-LEVEL RISE

4.1 Introduction

Sea-level rise associated with global warming is expected to result in shoreline recession for coasts comprising weakly consolidated sediment such as the sandy, dune-backed beaches which characterize much of the Kapiti region. Different shoreline response mechanisms are expected to apply to different types of coastal environment, and several models have been developed. This section will consider official sea-level rise estimates, assess the shoreline response models, and then apply the one considered to be most appropriate for the Kapiti Coast.

Global warming may also alter wind patterns as well as the wave and current climate along the Kapiti Coast. However, at the present time the nature of such change, and hence the shoreline response, is not quantifiable and therefore not directly included in the present erosion hazard assessment.

4.2 Sea-level rise estimates

Sea-level rise predictions by the International Panel on Climate Change (IPCC) have been published on four occasions: 1990, 1995, 2001 and 2007. The 2008 draft NIWA/MFE recommendations relating to the most recent IPCC predictions are for a 50 to 60 yr *most likely value* of 0.31 m, and an *extreme value* to 0.42 m.

Before selecting a sea-level rise value for the present erosion hazard assessment, consideration must be given to several other factors. While the extreme NIWA/MFE values broadly account for *possible high emissions and ice sheet contribution uncertainties, and possible differences in the New Zealand region*, they do not directly compensate for the New Zealand average regional historical SLR of 1.7 mm/yr, nor do they take into account the relative vertical movement resulting from local tectonic adjustment which is estimated to be average 0.4 to 0.5 mm/yr of uplift in the Kapiti area. Both these factors are, to some extent, likely to already be accommodated within the empirically-based long-term shoreline change modelling used in this assessment; so without compensation this results in an element of double counting (or *double dipping*) for this component.

Given the non-compensation for regional and local relative sea-level rise contributions, the most likely value (0.3 m) was used in the present assessment. Further assurance in the appropriateness of this value is provided by the observation that locations along the Kapiti Coast with the higher sea-level rise retreat values correspond with, and are thus compensated by, long-term progradation, but this is not recognized in the assessment as positive long-term values were set to zero (Section 2.4.3).

4.3 Shoreline Response Model

Different models and applicability considerations are detailed in Appendix D. Briefly, the most widely applied shoreline response model, the Bruun Model (Bruun, 1983), argues that *an elevated sea-level enables wave action to erode the upper beach while maintaining the form of the profile, and that this eroded sediment is transported offshore and deposited such that the quantity of eroded material balances the quantity of deposited material*. However, the model has come under increasing criticism in recent years regarding its underlying assumptions. While conditions on parts of the east coast of New Zealand are more suited to meeting these assumptions, its application to the New Zealand west coast is more questionable because of the existence of reefs and longshore sediment transfer (littoral drift), neither of which are allowed for in the model's assumptions.

The most plausible alternative model for use at Kapiti is the Komar Model (Komar et al., 1999) which is based on the concept of *conservation of form of the inter-tidal beach as sea-level changes.* Calculation of this shoreward, and upward, shift in the profile is defined by equation 3 (equation D2 in Appendix D).

$$R = S/\tan \beta \qquad (3)$$

where R is the profile shift (retreat) in the landward direction, S is the predicted rise in sea-level and tan β is the average inter-tidal slope. Note that the *average* inter-tidal slope is used as it is the predominant slope that will control the profile response in the longer-term.

4.4 Results

Reliable estimates of the average inter-tidal slope for those areas not fronted by seawalls were derived from the KCDC and Horizons Regional Council data-bases of available district-wide beach profiles (see section on Sea-Level Rise in the *Data-Base*). Note that a tidal range of 2 m was used to determine average slope as this value approximates the average spring tide variation. Average slopes (tan β) were negatively rounded to the nearest 0.001 thereby maximizing shoreline retreat values. The 22 profile measurement sites did not always correspond with the coastal sites used for shoreline measurements (Fig 1), so average inter-tidal slopes were interpolated and slopes for the coastal measurement sites were thus identified. Further details on these data, derivation of average slopes per coastal measurement site and shoreline retreat under the three seawall scenarios, are provided in the *Data-Base*.

The average inter-tidal slopes are depicted in Fig 7A. Beach slopes for most locations were in the 1 to 2 degree range. However, steeper slopes occur at south Paekakariki (3 degree) and south of the Otaki River (3 to 6 degrees). Both these areas are close to sources of coarser sediment and
experience higher wave energy. Flattest slopes (0.8 deg) occur about the foreland apex, the region with the finest sediment and lowest wave energy.

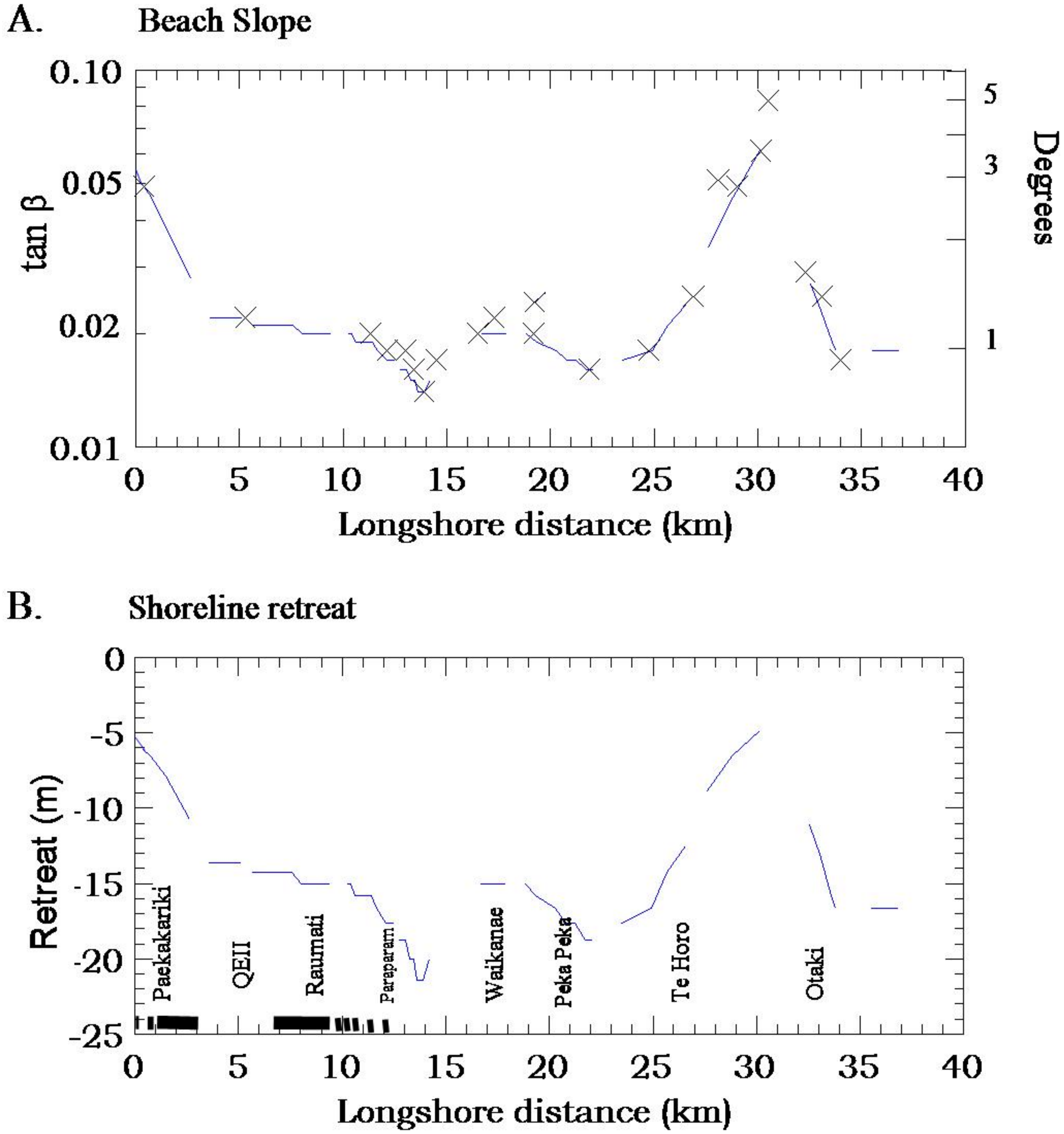


Figure 7 Average inter-tidal slopes are depicted in A with **X** marking average slopes at the 21 profile measurement sites, and the intervening interpolation lines, from which values for the coastal measurement site were obtained, are also shown. The associated shoreline retreat distances are shown in B. Discontinuities relate to areas affected by river and stream mouths. The longshore distances on the horizontal axis stretch from Paekakariki on the left to beyond Otaki on the right. While suburb and settlement names, along with horizontal bars representing seawalls, have only been marked on the lower graph (B), they also apply to the upper graph (A).

Applying the beach slope values to equation 3, together with a sea-level rise projection of 0.3 m, yields the shoreline retreat values depicted in Fig 7B. In most locations, shoreline recession is in the range of 10 to 17 m. This increases to 21.4 m at the foreland apex and decreases to 5.4 m at the southern end of Paekakariki and 4.8 m at the southern side of the Otaki Rivermouth.

Note that under the *seawalls hold*, and the *seawalls repair* scenarios, the sea-level rise erosion hazard component is zero.

4.5 Uncertainties

Accuracy of shoreline retreat associated with sea-level rise depends on the errors associated with inter-tidal slope measurements which were derived from high resolution beach profiles. The resulting slope error is estimated to be within ±0.05 degrees (or $\tan\beta = \pm 0.001$). As lower slopes produce greater shoreline retreat, this value was applied to the minimum slope that occurred within the study area of 0.8 degrees (or $\tan\beta = 0.014$) and this produced additional shoreline retreat of 1.6 m. Such an error value was thus adopted for the entire study area, thereby providing an increased margin of error for much of the coast.

As explained in Section 4.2, non-compensation for regional and local relative sea-level rise contributions make 0.3 m conservative for the selected prediction period, thereby increasing the safety margin.

5.0 DUNE STABILITY

5.1 Introduction

Episodes of shoreline erosion occur when storm waves are able to reach the upper beach. Such erosion can extend back into the foredune and leave a near vertical *scarp or cliff-like* feature. As subsequent scarp-top adjustment (retreat) can affect landward property this phenomenon needs to be incorporated within the erosion hazard assessment.

Following marine undercutting and slumping (dune failure processes), a set of dune recovery processes occur (see Appendix A, Section 6). Briefly, over subsequent months to years the top of the escarpment retreats toward a stable angle and a debris slope develops at the base. The shoreline thus *recovers* to a more seaward location while the escarpment top retreats further to attain stability. Even on coasts undergoing longer-term erosion, some post-storm shoreline recovery occurs. This is facilitated by the beach rebuilding under the action of smaller post-storm waves, thereby preventing ongoing wave removal of the debris as it accumulates at the base of the excarpment.

The stable slope-angle for dry dune sand is ~34 degrees and this is used in the present hazard assessment to predict slope evolution. However, remnant vegetation (roots), and subsequent growth, allow for a higher stability angle, and along the south Paekakariki study area, for example, these angles range up to 41 degrees.

5.2 Method

The model used to determine retreat of the scarp top (equation 4) is based on the *slope replacement theory* for cohesiveless materials (Clark and Small, 1982).

$$STR = h/2(\tan \propto) \qquad (4)$$

Where STR is the landward distance the scarp-top must retreat to achieve dune stability (DS in equation 1), h is the height of the escarpment and $\propto$ is stable slope angle (34 degrees). The mathematical derivation of equation 4 is given in Appendix E.

Note that this equation assumes 50% recovery of the foredune toe erosion, i.e. the recovery-erosion ratio is 1:2 or the recovery proportion is 0.5. If greater recovery occurs, then the model over-estimates cliff-top recession which is still an acceptable situation for hazard assessment. But if recovery is less that 50% then the model under-estimates scarp-top retreat which is unacceptable. Fifty percent recovery is typically used for erosion hazard assessment in coastal environments and the appropriateness of this value at Kapiti is evaluated in Appendix A (Section 4).

Additional model assumptions consist of no removal of debris by wave action, no vegetation establishment on the slope, the ground is horizontal landward of the scarp top, and there is no addition to the debris slope from seaward (wind-blown sand). These assumptions are unlikely to be met in this coastal environment so the implications will now be considered.

Both input of wind-blown sand and establishment of vegetation (roots) act to increase the recovery distance so the model will over-estimate scarp-top recession recession. By contrast, wave-induced debris removal will reduce the recovery distance so the model will under-estimate the cliff-top retreat. However, adequate toe-extension is observed to follow episodes of erosion along the south Paekakariki Coast (Appendix A, Section 4), so model adjustment was not considered necessary. Finally, while the requirement for horizontal topography landward of the cliff is met in some instances there are many locations where this is not the case. This limitation, however, was overcome by the selection of the most elevated location to represent each sector and this is now considered further.

Selection of a scarp height to represent each transect was determined using the following approach. The other hazard components plus their associated errors were first added together to provide the landwardmost erosion distance for the prediction period. A 3D inspection of the coastal topography using the council's LIDAR data was then carried out to locate the highest point within each sector and this value was used to represent the sector. As the LIDAR data only extends to Otaki Beach, the maximum dune height for sites further north was based on the maximum value along the entire northern Kapiti Coast.

Note that data acquisition, analysis and application to the differing seawall scenarios are listed in the Dune Stability section of the *Data-Base*.

5.3 Results

The maximum dune height in the vicinity of each coastal measurement site is depicted in Fig 8A. While the heights show considerable local variation, there is a distinct lowering in dune height from the southern end of the Paekakriki Coast at 20 to 25 m, to QEII (10 to 20 m), to the Raumati Coast (5 to 10 m) and to the northern coast at 1 to 5 m.

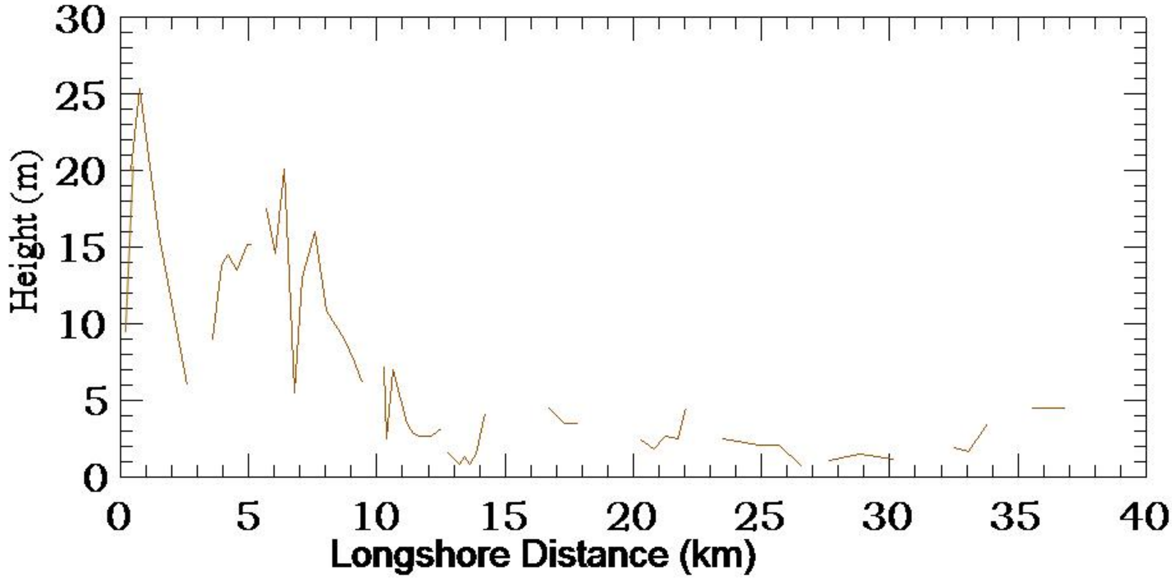
The modelled scarp-top retreat values are depicted in Fig 8B with negative sign representing landward distance. These values follow the dune height variation and range from 15 to 20 m of recession in the south, down to 1 to 3 m in the north.

5.4 Uncertainties

Measurement errors consist of the LIDAR accuracy (±0.55 m), cross-shore location of the dune-toe (± 2 m) and cross-shore location of the maximum dune height per sector (±1 m). The combined RSS value of these terms is ±2.3 m.

The selection of the maximum dune height per sector, together with the minimum stability angle will over-estimate scarp-top retreat in many locations.

A. Dune height



B. Scarp-top retreat

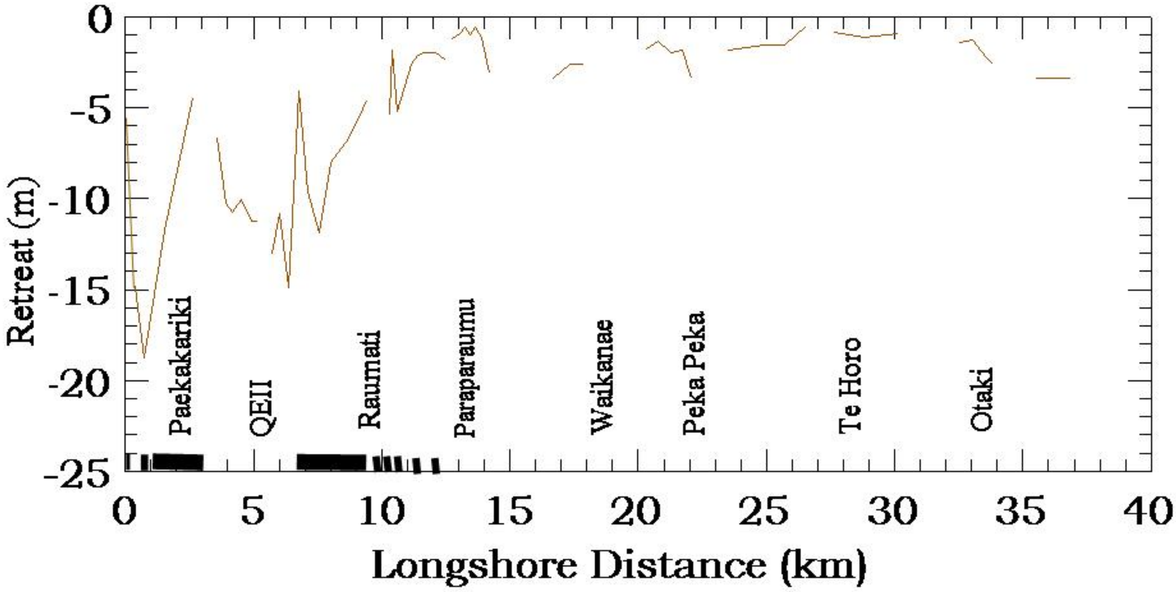


Figure 8 Height of dunes (A) in relation to shoreline retreat caused by other hazard components, and associated retreat of scarp top (B) necessary to attain dune stability. Discontinuities relate to areas affected by river and stream mouths. The longshore distances on the horizontal axis stretch from Paekakariki on the left to beyond Otaki on the right. While suburb and settlement names, along with horizontal bars representing seawalls, have only been marked on the lower graph (B), they also apply to the upper graph (A).

6 COASTAL EROSION HAZARD DISTANCES

6.1 Introduction

As defined by equation 1, the cross-shore erosion hazard distance (CEHD) values were derived by summing the longer-term (LT), shorter-term (ST), sea-level rise (SLR) and dune stability (DS) component values as described in Sections 2 to 5 above, together with the combined uncertainty (CU) values. This section will firstly address the matter of combined uncertainty before deriving the hazard distances for the three seawall scenarios.

6.2 Combined Uncertainty

There are several types of uncertainty involved in the present hazard assessment and these have been described in the preceding sections. In particular there are measurement errors (usually random) pertaining to each component with LT = ±3.7 m; ST = ±2.6 m, SLR = ±1.6 m, and DS = ±2.3 m. Note that only the negative (shoreward) value need be taken into account in an erosion hazard assessment. In addition, there were several other uncertainty factors noted in the preceding sections. Those which are quantifiable have been included within the combined uncertainty value for use in equation 1. However, several non-quantifiable factors were also described, some of which significantly increase the overall safety margin.

In the past, there is been a tendency to combine error terms by addition. However, such terms are often derived from variables which are independent of each other, and to assume that they are likely to occur at the same time 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 5.

$$CE = \sqrt{(E_1^{\,2} + \dots\dots\dots + En^2)} \qquad (5)$$

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, DS and CU (which are independent) to equation 5 gives 5.3 m, so this was rounded up to 6 m for use in equation 1.

The CU value can vary for the different seawall scenarios and this is described in the Combined Uncertainty section (3.2) of the *Data-Base*. Of particular note is the use of CU = 0 for seawalled sections of coast under the *seawalls hold* scenario. Under the *seawalls repair* scenario, an additional 5 m was added to account for increasing scour potential through the prediction period (NB Section 3.5). In addition, there are no LT or SLR error terms in the *seawalls repair* scenario as their component values = 0, so the combined components in this case = 3.5 m and this value was rounded to up 4 m as an added precaution.

6.3 Coastal erosion hazard distances

The combined component distances for the three seawall scenarios are depicted graphically in Fig 9, with the tabulated component values for each scenario being given in Appendix B and also in the relevant sections of the *Data-Base*.

South of the Kapiti Boating Club at Paraparaumu Beach the hazard distances can be seen to differ quite dramatically under the different scenarios (see Fig 9D). Under the *seawalls hold* scenario (Fig 9A), the hazard distance equals zero next to the walls, while in non-seawall areas the hazard distance is 49 to 120 m. Along the partially seawalled south Paekakariki and the coast north of Marine Gardens, the predicted hazard distances are between 46 and 53 m. At south Paekakariki, this would result in between 11 to 23 m of cliff-top recession along the Ames Street reserve. This is well in excess of the 0.5 to 7.4 m of retreat observed over the past 64 yrs (Appendix A), and illustrates the conservativeness of the hazard assessment model and assumptions used in this *Open Coast Erosion Hazard Assessment.*

Under the *seawalls repair* scenario (Fig 9B), the same hazard distances apply in the non-seawalled areas as occur under the *walls hold* scenario described above. Behind the failed seawalls, the hazard distance was determined using short-term fluctuation, dune stability and the relevant uncertainty values, and this amounts to some 21 to 36 m. Field evidence to support the conservativeness of this range at seawall locations comes from the fact that less than half this amount of retreat was observed to occur during the September 1976 event (Gibb and Wilshere, 1976) which, together with events in July 1954 and October 1957, is one of the 3 most erosive events on record (NIWA, 2000).

Under the *seawall removal* scenario, CEHDs increase significantly in areas presently with seawalls (33 to 74 m) compared with the *walls repair* scenarios (21 to 36 m). But under this (*seawalls removed)* scenario, CEHDs are lower within the non-seawalled areas (36 to 61 m c.f. 49 to 120 m) with the exception of south Paekakariki and just to the south of Marine Parade where the values are slightly higher.

From the Kapiti Boating Club at Paraparaumu Beach to the northern extent of KCDC territory, the coastal erosion hazard distances are the same for all seawall scenarios. These distances are greatest around the foreland (44 to 64 m) with values ranging between 26 to 44 m along the northern coast.

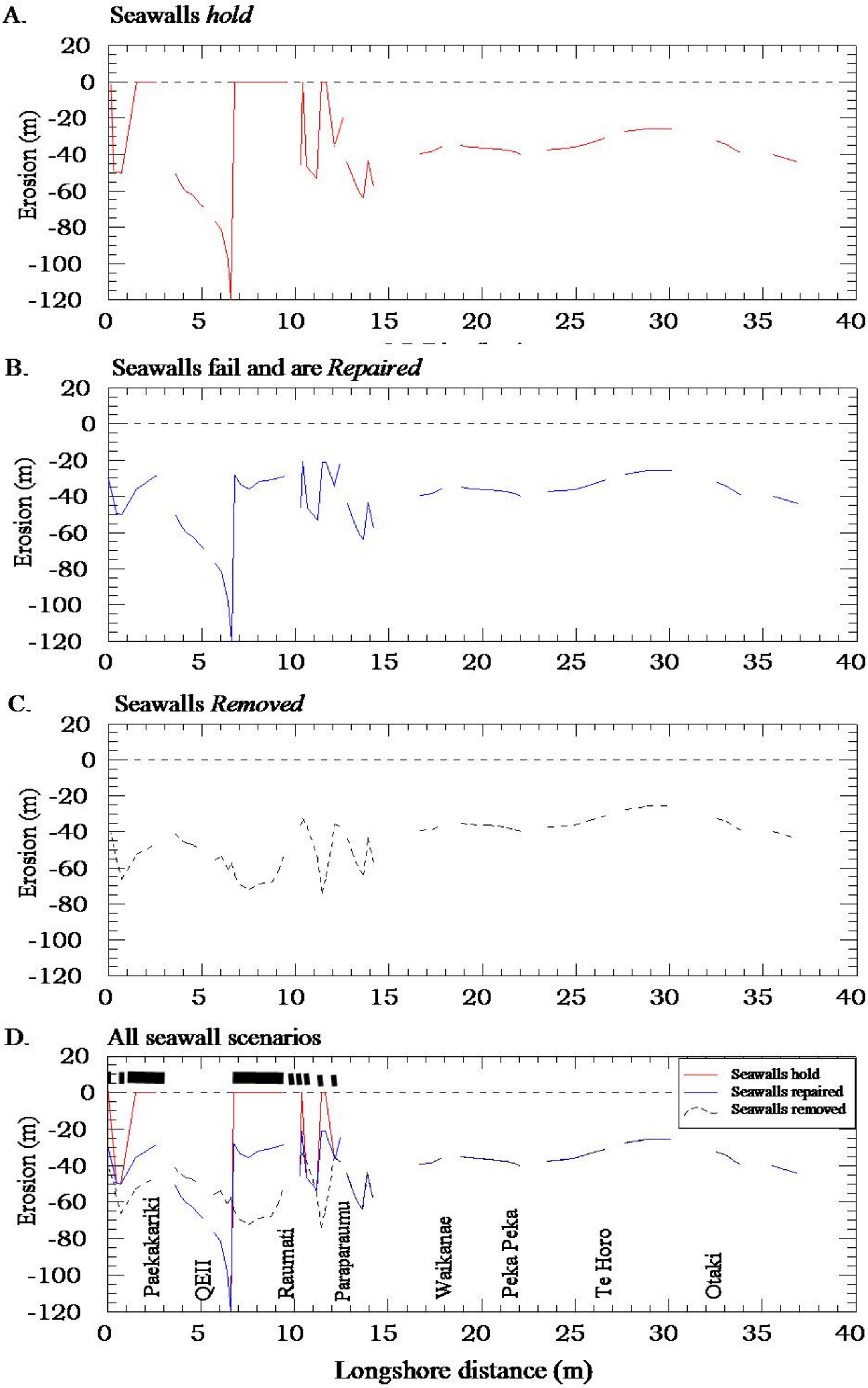


Figure 9 Final erosion hazard distances for each seawall scenario (A-C) and superimposed (D), for a 50 yr prediction period. Discontinuities relate to areas affected by river and stream mouths. The longshore distances on the horizontal axis stretch from Paekakariki on the left to beyond Otaki on the right.

7 COASTAL EROSION HAZARD LINES

7.1 Introduction

The shoreline from which the cross-shore erosion hazard distances (CEHDs in Section 6), are referenced to locate the *open coast erosion hazard lines* (which may also be referred to as erosion *set-back* lines) is referred to as the *measurement origin* or *reference shoreline*. This section will review reference shorelines typically used in erosion hazard assessment, develop a robust method of locating the measurement shoreline, describe the method used to locate the erosion hazard line for each coastal measurement site, and finally, illustrate the output using three examples (Figs 10-12). Note that the full derivation of the hazard line for each coastal measurement site is given in the *Data-Base.*

Note that erosion hazard lines have not been produced for the *seawalls hold* scenario as it is unlikely that this option will be adopted (see Section 8.1). However, the hazard line location for this scenario can easily be visualized on overlay maps, such as those shown in Figs 10 – 12, as being either along the actual seawall in seawalled areas, or as following the *seawall repair* hazard line in non-seawalled areas (see Fig 9).

7.2 Previous measurement origin

Erosion hazard assessment practitioners have tended to use the most recently surveyed shoreline as the reference shoreline along sandy coasts (e.g. Gibb, 1998; Healy and Dean, 2000; Dahm and Munro 2002). However, this approach can be problematic as this shoreline may not be representative, i.e. it does not coincide with the average shoreline location. So if the most recent shoreline is seaward of the average shoreline, then the resulting location of the erosion hazard line will have a seaward bias. By comparison, if the most recent shoreline is landward of the average shoreline location, then the resulting hazard line location will have a landward bias as a portion of the calculated hazard distance will have essentially been double counted. Unless the practitioner can determine where the most recent shoreline is relative to the underlying fluctuation, this potentially large error can neither be quantified nor removed.

7.3 Model-based measurement origin

The regression-based shoreline modelling used in the present study (Section 2) provides a robust method of determining a valid measurement origin. In particular, the shoreline model (equation 2) describes the average shoreline location throughout the shoreline record and thus gives a suitable hazard measurement origin for any particular year. Note that for the present erosion hazard assessment, the modelled 2008 shoreline will be used as the measurement origin.

For convenience, and to simplify future updates, the measurement origin is calculated relative to the *reference point* for each coastal measurement site. NB the reference point is the location from which all shoreline cross-shore distances were measured and the point from which future shoreline measurements will be made when the *Data-Base* is updated. Precise co-ordinates are known for each reference point and these are recorded in the *Data-Base*.

The measurement origin relative to the reference point is the modelled distance plus the *offset* distance of the first shoreline to the reference point. It will be recalled from Section 2.3 that while all shoreline measurements were made relative to the reference point, the first shoreline was subsequently used as the distance datum to simplify the shoreline modelling procedure. The derivation for the measurement origin at each coastal measurement site is detailed in the *Data-Base.*

7.4 Location of erosion hazard lines

The location of the erosion hazard line is identified by simply relating the coastal erosion hazard distance (CEHD values in Appendix B) to the measurement origin. Again, the derivation is fully described for each coastal measurement site in the *Data-Base*.

In situations where the coastline between adjacent coastal measurement sites was not straight, linear interpolation between erosion hazard set-back locations could lead to an error of several metres. In such situations, intermediate shoreline off-sets were determined based on the 2007 aerial photographs and these offsets were then applied to the erosion hazard line so as to replicate the plan shape of the coast.

Note that the *Data-Base* is supplied in both hard copy and electronic format, and included with the electronic version are vector files of the managed and natural shoreline erosion hazard lines for both the open coast and inlets.

7.5 Examples of open coast erosion hazard lines

While high resolution images depicting the erosion hazard lines along the entire Kapiti Coast are available from the KCDC office, 3 examples of hazard lines overlaying 2007 aerial photos are provided in Figures 10-12. Two examples (Figs 10 and 11) relate to the seawalled coastline at south Paekakariki and Raumati Beach north of Marine Gardens, and the remaining example (Fig 12) is for part of the natural coast at Waikanae Beach.

The seawalled examples were selected as they depict areas of *official* seawall, i.e. seawall/revetment that was professionally designed and constructed and which is maintained by the KCDC, together with *private* seawalls that were established in a piecemeal fashion by property owners and give only partial protection to these sections of coast. In addition, south Paekakariki and north Raumati have contrasting coastal processes with the former having an erosional trend, while the latter has, in the past, tended to be relatively stable, although it is now being affected by an episode of medium-term erosion (see Section 2.4.1). Note that some of the sections of seawall depicted in Figs 10 and 11 are included to illustrate the difference in hazard line location between protected and unprotected areas rather that exactly represent seawalls locations.

Fig 10 Example of erosion hazard lines for a partially seawalled stretch of coast at Paekakariki. The hazard lines relate to the *seawalls repaired* and *seawalls removed* scenarios (see text). The northern-most seawall was professionally designed and is maintained by the KCDC. The remaining partially seawalled coast contains a range of privately constructed and maintained structures. The depicted sections of seawall are approximate and used here to illustrate variation in the erosion hazard.

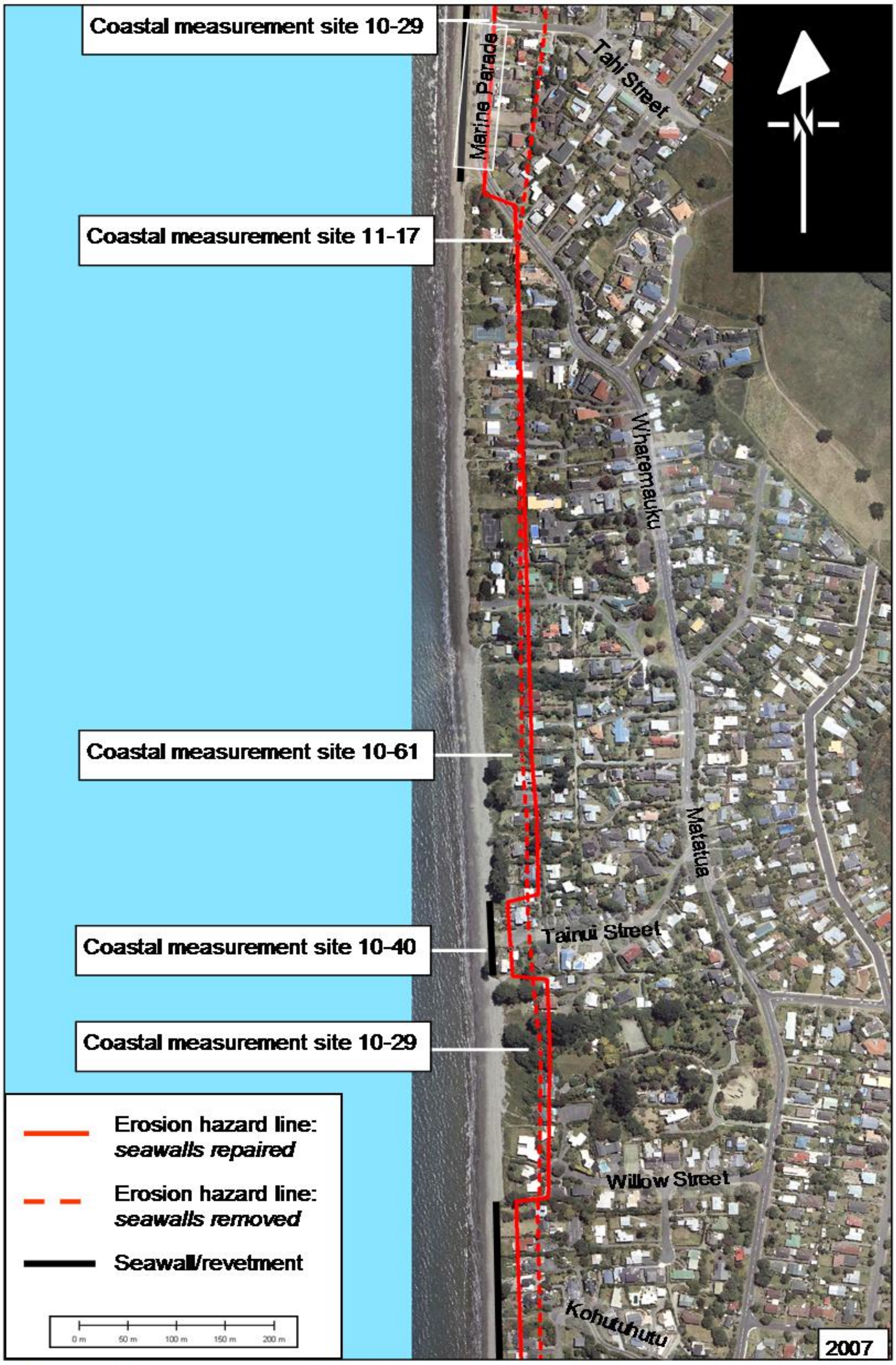


Fig 11 Example of erosion hazard lines for a partially seawalled stretch of coast at Raumati Beach between Marine Gardens (just off base of photo) and Tahi St off Marine Parade (top of photo). The hazard lines relate to the *seawalls repaired* and *seawalls removed* scenarios (see text). Northernmost *rock revetment* was designed and established by he KCDC in 2006. The central seawall is an example of an official *road-end* protection structure. The lowermost seawall is as example of privately constructed and maintained seawall. While other road-end and private sections of seawall occur along this stretch of coast, the depicted examples are used here to illustrate variation in the erosion hazard.

Fig 12 Example of an erosion hazard line along a natural stretch of open coast at Waikanae Beach. While sand conservation fencing has recently been constructed along part of the fore-dune, this does not affect the present erosion hazard assessment.

8.0 FURTHER CONSIDERATIONS

8.1 Erosion hazard line options

In this assessment, the erosion hazard has been carried out for 3 seawall scenarios: *seawalls hold, seawalls are repaired and seawalls are removed*, so the council will need to decide which alternative to adopt**.** While general *seawall removal* is not an anticipated management strategy, it has been included to help quantify the effect the walls have on coastal processes and shoreline behaviour. When deciding upon the preferred seawall scenario, the need for long-term functionality of the walls or revetments must be recognized and policy/resource commitment made to strengthening, maintaining and repairing them throughout the forthcoming 50 to 100 yrs. The *seawalls hold* scenario is therefore probably unrealistic in terms of the strengthening and cost required to ensure the walls never fail.

Issues relating to *official* and *private* seawalls, and also *partial* and *continuous* seawalls, should also be considered. When deciding upon long-term commitment of resources for strengthening, maintaining and repairing official seawalls fronting private residences such as at South Raumati, council may consider entering into formal arrangements with these beneficiaries. In other areas where discontinuous private protection works predominate, e.g. south Paekakariki (Fig 10) and north Raumati (Fig 11), the council and residents will need to address a range of issues including long-term structural integrity, longshore effects and other requirements of the New Zealand Coastal Policy Statement (NZCPS) if the *seawalls repair* scenario were to ever apply in these areas. The variation in erosion hazard lines in Figs 10 and 11 illustrate the impact protection works can have on erosion hazard lines.

8.2 Site-specific assessments

The council should recognize that privately commissioned *site-specific* erosion hazard assessments may further refine the hazard lines defined in the present report.

In Section 1.1 the concept of different levels of erosion hazard assessment was raised. In particular these consist of *regional, local and site-specific assessment* with the spatial application decreasing and analysis detail increasing accordingly. Regional assessments therefore tend to be undertaken for rural areas and local assessments for urban areas. The present Kapiti Coast erosion assessments were undertaken at the local level within, and on the margins of, settled areas, while somewhat less detail was applied in the rural areas. Nonetheless, even with data points spaced at only a few hundred metres (local assessment level) significant variation within sectors (as defined by adjacent coastal measurement sites) can still occur. For example, large spatial variation in dune height, and thus in dune stability values, occurred within some sectors and the largest observed value was applied throughout that sector. A site-specific assessment can take such variation into account.

In addition, the approach used in the present assessment of applying the upper 95% value for longer-term rates and shorter-term variation derived from several adjacent sectors to all those sectors, may have resulted in an overly large component value being applied to some locations.

Approaches such as these help to minimize uncertainty and increasing the safety margin; however, they may also have resulted in some hazard distances derived in this report being greater than those that would be derived by a site-specific hazard assessment.

8.3 Other management issues

While *hard protection* now characterizes the southern Kapiti Coast, the present erosion hazard assessment has increased our understanding of longer-term coastal behaviour, and this may enable the future application of *soft* options in some situations. Note that hard protection consists of engineering structures which tend to have the environmental disadvantage of exacerbating the loss of beach sand. By contrast, soft options include beach/shoreface nourishment or beach drainage, which tend to promote beach restoration. Intermediate options such as submerged breakwaters can provide both shoreline protection and beach enhancement.

The council should recognize the need for dune stabilization works where significant dune-toe erosion occurs and subsequent blowout development is likely. This action is necessary as if left unchecked such dune erosion leads to serious wind-blown sand, sand-drifts and sand-burial, hazards which were not included within the present assessment.

8.4 Monitoring and future re-assessment

The council must ensure that an adequate long-term monitoring programme is implemented which will provide information and data suitable for updating the erosion hazard assessment

This present erosion hazard assessment should apply for at least 10 yrs, after which it should be reviewed to incorporate additional monitoring data, climate change information, hazard assessment technique refinement and relevant output from any site-specific erosion hazard assessments.

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REFERENCES

Auckland Regional Council, 2000. Coastal Erosion Management Manual: Coastal Hazard Strategy. *Technical Publication No. 130, 110p*

Bruun, P., 1983. Review of conditions for uses of the Bruun Rule of erosion. *Coastal Engineering*, 7, 77-89.

Carter, R.W.G.; Hesp, P.A.; Nordstrom, K.F., 1990. Erosional landforms in coastal dunes. In Nordstrom, K.F.; Psuty, N.P; Carter, R.W.G (Eds.), *Coastal Dunes: Form and Process*, pp 217-250.

Clark, R.J., and Small, M.J., 1982. *Slopes and Weathering.* Cambridge University Press, London, 112p

Coastal Systems Ltd., 2007. *Summary of peer reviewer comments on the KCDC Open Coast Erosion Hazard Assessment report.* Prepared for the Kapiti Coast District Council by Coastal Systems Ltd., CSL Document No 2007-01, 18p.

Crowell, M., Douglas, B.C., and Leatherman, S.P., 1997. On forecasting future U.S. shoreline positions: A test of algorithms. *Journal of Coastal Research*, 13(4), 1245-1255.

Dahm, J. and Munro, A., 2002. *Coromandel Beaches: Coastal Hazards and Development Setbacks Recommendations*. Report prepared for Environment Waikato, 180p

Davidson-Arnott, R.G.D., 2003. Modelling the response of sandy coasts to sea-level rise. *Proceedings of the the Canadian Coastal Conference*.

Dean, R.G., 1990. Beach response to sea-level change. In Mehaute, B.L., and Hanes, D.M., (eds) *The Sea, Ocean Engineering Science*, (9) 869-887. John Wiley and Sons, New York.

De Lange, W.P., 2000, Inter-decadal pacific oscillation (IPO): a mechanism forf forcing decadal scale coastal coastal change on the northeast coast of New Zealand. *Journal of Coastal Research, Special Issue 34*, 657-664.

Donnelley, L.S., 1959. Coastal Erosion – Paekakariki to Waikanae. New Zealand Engineering, 48-52.

Fenster, M.S.; Dolan, R., and Elder, J.E., 1993. A new method for predicting shoreline positions from historical data. *Journal of Coastal Research.* 9(1), 147-171.

Gibb, J.G., and Wilshere, D.S., 1976. Coastal Erosion – Kapiti Coastline; notes on the storm of Saturday 11th to Monday 13th September, 1976. Internal report to the Commmisioner of Works, Ministry of Works and Development, Wellington, New Zealand, 10p.

Gibb, J.G., 1978. The problem of coastal erosion along the 'Golden Coast' western Wellington, New Zealand. *Water and Soil Technical Publication No 10*. Ministry of Works and Development, Wellington. 19p.

Gibb, J.G., and De Pledge, D.R., 1980. Coastal Erosion at Paekakariki, Wellington's West Coast. An internal Report, Ministry of Works and Development, Wellington, 22p.

Gibb, J.G., 2002. *Potential effects on the coast of proposed gravel extraction from the Waikanae River, Wellington Region*. A Report prepared for the Wellington Regional Council, New Zealand. 24p.

Gibbard, R.G., 1972. Beach morphology and sediments of the west Wellington Coast – Wanganui to Paekakariki. Unpublished M.Sc.Thesis. Geography Department, Massey University , New Zealand. 100p.

Goldberg, E., and Frisby, R.B. 1981. *Kapiti Coast volunteer surf observation programme, April 1974 – June 1975, analysis of observations*. Water and Soil Division, Ministry of Works and Development, Wellington, New Zealand. 59p.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering*, 4, 253-277.

Healy, T. R. and Dean, R. G., 1999. Methodology for delineation of coastal hazard zones and development setback for open coasts. In Herbich, J B. (ed), *Handbook of Coastal Engineering*, MrGraw-Hill, New York.

Hicks, M.D.; Green, M.O.; Smith, R.K.; Swales, A.; Ovenden, R., and Walsh, J., 2002. Sand volume change and cross-shore sand transfer, Mangawhai Beach, New Zealand. *Journal of Coastal Research*, 18(4), 760-775.

Holland, M.K., and Holland, L.D., 1985. Processes of Coastal Change Manawatu – Horowhenua. *Report No. 66. Manawatu Catchment Board and Regional Water Board, New Zealand*. 192p.

IPCC, 2007. *Climate change 2007: The Physical Science Basis – Summary for Policymakers*. Intergovernmental Panel on Climate Change, 18p.

Kirk, R.M; Kench, P.S. and Single, M., 1999. *Assessing and Managing Coastal Hazards – An Integrated Approach*. Report prepared for the Auckland Regional Council. 47p.

Komar, P.D.; McDougal, W.G.; Marra, J.J, and Ruggiero, P., 1999. The rational analysis of setback distances: applications to the Oregon Coast. *Shore and Beach*, 67 (1), 41-49.

Lumsden, J., 1996. Beach nourishment Trial at Marine Parade Paraparaumu: Final Report March 1996. *A report prepared for the Kapiti Coast District Council*. 20p.

Lumsden, J., 1999. Coastal Erosion at Waters Edge Subdivision,175 Manly St., Paraparaumu, May 1999. *A report prepared for the Kapiti Coast District Council*. 20p.

Lumsden, J., 2003. Strategies for Managing Coastal Erosion on the Kapiti Coast. *A draft report prepared for the Kapiti Coast District Council*. 2 vol., 362p.

McHugh, L. R., 1981. *The Response to Coastal Erosion along the Raumati, Paekakariki Coastline*. Unpublished BA Hons Dissertation, Victoria University, Wellington. 81p.

Morris, R.W., and Associates. 1984. *Kapiti Borough Council Coastal Investigations Report No 3A.* A report for the Kapiti Borough Council. 31p.

Nicholls, R.J.; Birkemeier, W.A., and Lee, G-h., 1998. Evaluation of depth of closure using data from Duck, NC, USA. *Marine Geology*, 148, 179-201.

NIWA, 2000. Kapiti Coast Erosion Hazard Investigation: Waves, Tides, Storm Surge and Sea-level Rise. *NIWA Client Report LUM01301/1*.

Pickrill, R.A., and Mitchell, J.S., 1979. Ocean wave characteristics around *NZ. New Zealand Journal of Marine and Freshwater Research*. 13 (6), 501-520.

Pilkey, O.H.; Young, R.S.; Riggs, S.R.; Smith, A.W.S.; Wu, H., and Pilkey, W.D. 1993. The concept of shoreface profile of equilibrium: a critical Review. *Journal of Coastal Research*, 9(1), 255-278.

SCOR Working Group 89. 1991. The response of Beaches to Sea-level Changes: a review of predictive models. *Journal of Coastal Research*, 7(3), 895-921.

Shand, R.D.; Bailey, D.G., and Shepherd, M.J., 2000. Morphological investigations along the Wanganui Coast: 1990 – 1998. *Miscellaneous Publication 2000/1, School of Global Studies, Massey University*. 141p.

Shaw, G., and Wheeler, D., 1985. *Statistical Techniques in Geographical Analysis*, John Wiley and Sons, New York, 364p.

Westlake, S.J., 2003. Evaluation of coastal monitoring surveys around the Waikanae Rivermouth. *Report WGN_DOCS#169182*, *Greater Wellington Regional Council*, New Zealand. 18p.

Wilkinson, L., 1996. Systat 8. http://www.spss.com

APPENDIX A

Shoreline change at south Paekakariki: 1894 – 2007

1 Background

The Paekakariki coast was subjected to significant episodes of erosion during the mid 1950s (Donnelley, 1959) and mid-late 1970s (Gibb and Wilshere, 1976; Gibb, 1978). The perception of significant ongoing erosion, together with concern that the slope fronting residences was in “imminent danger of collapsing onto the beach” (Gibb and De Pledge, 1980), resulted in 13 homes being removed from Ames Street in the early 1980s.

The central and northern sections of the Paekakariki coast have continuous and substantial seawall protection. By contrast, the southernmost 1 km has a variety of protection with the central 300 to 600 m remaining in its natural state. Note that all longshore distances relate to the datum near Fisherman’s Restaurant which is used throughout the hazard assessment. From 0 to 0.3 km, rock revetment protects the Fisherman’s Restaurant and several adjacent condominiums on its northern side. From 0.6 to 0.9 km, some shoreline protection appears to be provided by remnants of a seawall constructed following the erosive events of the 1950s. Further north, more substantial and effective private protection works continue to just south of The Parade, after which a timber seawall and rock revetment provide protection for this waterfront road. Note that wave dissipation over a subtidal reef provides some shoreline protection over the initial 300 to 400 m of coast.

Given the erosional history and the previous hazard response for this area, the present geomorphological study, was carried out to provide information for the open coast erosion hazard assessment being undertaken by the Kapiti Coast District Council. The general location of the study area is depicted in Fig 1, and a more detailed view of the study site shoreline is shown in Fig 2.

As indicated above, the study area has seawall remnants along the northern 200 m but no protection along the southern 300 m. A sand-dominated, inter-tidal beach characterizes this part of the coast although gravels are evident at times. The aerial photo analysis showed the mean inter-tidal beach width was approximately 20 m (10 m to 30 m), with both cusped and uniform morphologies occurring. The mean subtidal surfzone width was approximately 50 m (10 to 200 m) with both shore parallel bar and trough, and transverse bar and rips being present at different times. The average width of the *back-beach* (that area between the upper foreshore and dune-toe) was approximately 7 m (0 to 12 m). The seawall remnants are usually located within the back-beach and are presently 4 to 8m seaward of the vegetation-front.

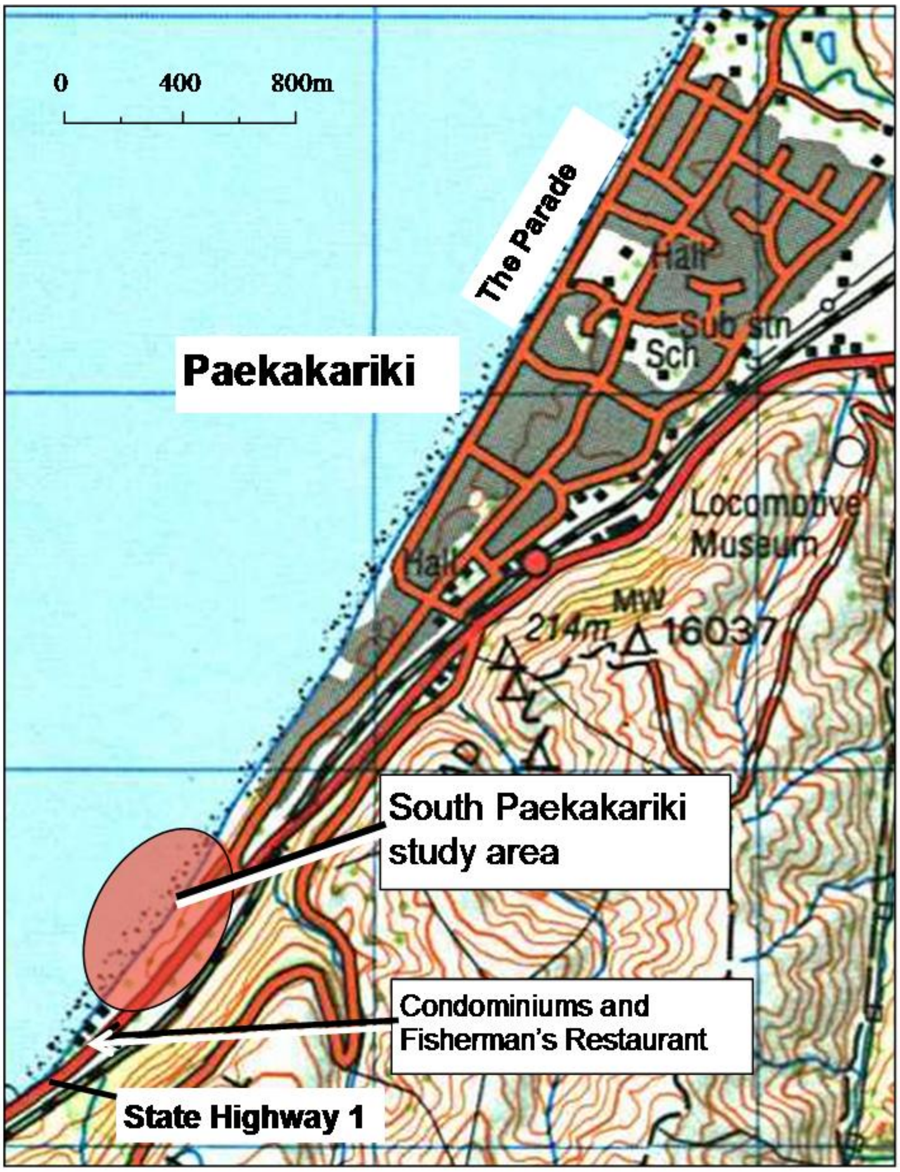


Figure 1 Location map of the south Paekakariki study area.

A dune approximately 10 to 30 m high runs the length of the study area. While this dune is referred to as a *foredune* given its frontal location, it may not have formed from wind-blown sand accumulating at the landward margin of the beach, this being the usual mode of foredune development. Gibbard (1972), suggested this dune to be the remnant of a *parabolic dune* similar to those more clearly evident in QEII. Such dunes would have migrated across the Kapiti foreland, including the area in question, in the general direction of the prevailing wind perhaps several thousand years ago at a time when the shoreline was well seaward of its present location. These dunes were subsequently truncated due to shoreline erosion over several centuries. The erosion and recovery processes the south Paekakariki dune is subjected to, gives the dune a scarped or cliff-like appearance.

2 Methods

Historical shorelines were obtained from both cadastral plans and aerial photos. Cadastral-based shorelines available from the NWASCO *Coastal Resource Map Series,* in particular the 1:5000 district-wide version, were used. Stereo pairs of the following air photos were obtained: Aug 1942, Jan 1954, Nov 1956, Nov 1966, Oct 1973, Nov 1979, Oct 1980, Apr 1986, Feb 1993, Mar 1998, July 2000, Dec 2001, Oct 2002, Apr 2004 and Jan 2007. Electronic, geo-rectified images for 1998, 2001, 2002, 2004 and 2007 were available from the KDCD data-base. The other photos were either digitized by scanning contact prints, or, for smaller scale photographs, negative scans were obtained from the aerial surveyors. These electronic files were then geo-rectified and continuous shorelines abstracted.

These shoreline data are recorded in the *Coastal Erosion Hazard Data-Base* and depicted in Fig 2. Note that the shoreline indicator was the vegetation-front which approximates the foredune-toe. Data-points from 7 transects based on reference points at 0.33 km, 0.4 km, 0.48 km, 0.55 km, 0.65 km, 0.73 km and 0.83 km (see Fig 2) were analysed using statistical techniques described in the *Open Coast Erosion Hazard Assessment Report*.

While errors were assumed to be the same as those detailed in the Hazard Report, in many cases the 3D image obtained using stereoscopic inspection enabled more accurate detection of the vegetation-front. Furthermore, vegetation remnants and paleosoil outcrops could be clearly identified and used to locate the landwardmost extent of erosion prior to photography. In this way maximum possible retreat distances were determined for the 1954-57 and 1976-78 erosion events.

The scarp top along the Ames Street reserve could be detected on higher quality images with the aid of stereoscopic vision. In this manner, the edge was located on the 1942, 1966, 1979, and 2004 aerials, with the 2004 scarp edge location being updated by field inspections in 2006 (see Fig 2A). Data from 14 transects spaced at 15 to 20 m in the longshore direction, were analysed. These results provided an invaluable field test for the actual hazard distances derived in the assessment, and they were also used to assess the 0.5 recovery-erosion ratio requirement for the dune-stability model.

Beach width is a useful indicator as to the capacity of the inter-tidal beach to dissipate incoming wave energy prior to it reaching, and subsequently eroding, the upper beach-dune area. While elevation-based data (ground surveys or LIDAR) are preferred when undertaking such assessment, an approximation of the seaward limit of the beach can be made using vertical aerial photos. In particular, wave breaking tends to concentrate on the *low tide step* which is a (usually) well-defined *drop-off* near the low tide line. The low tide step was located on each photo along that section of coast fronting the Ames Street reserve (see Fig 2A) and compared with corresponding shoreline behaviour.

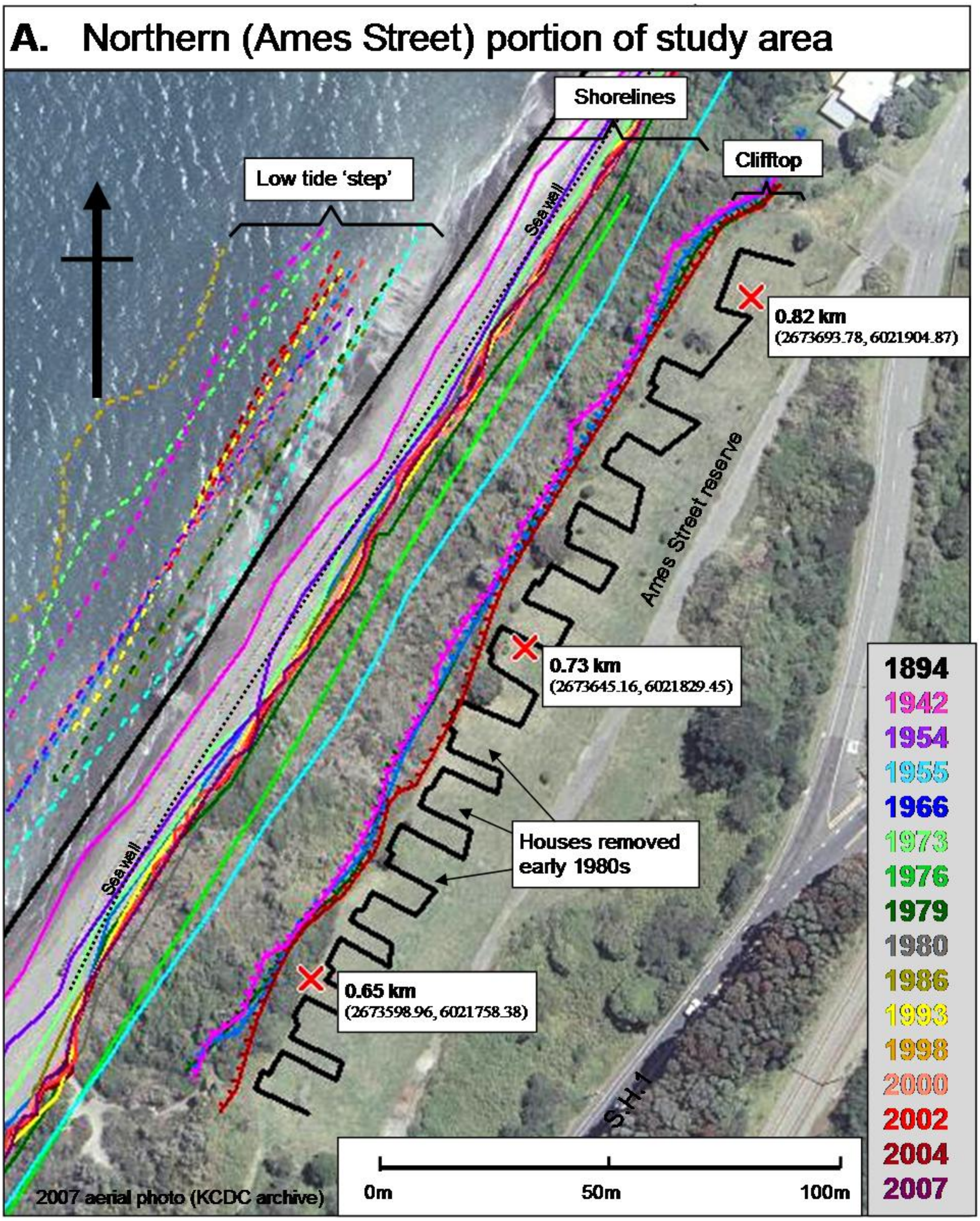
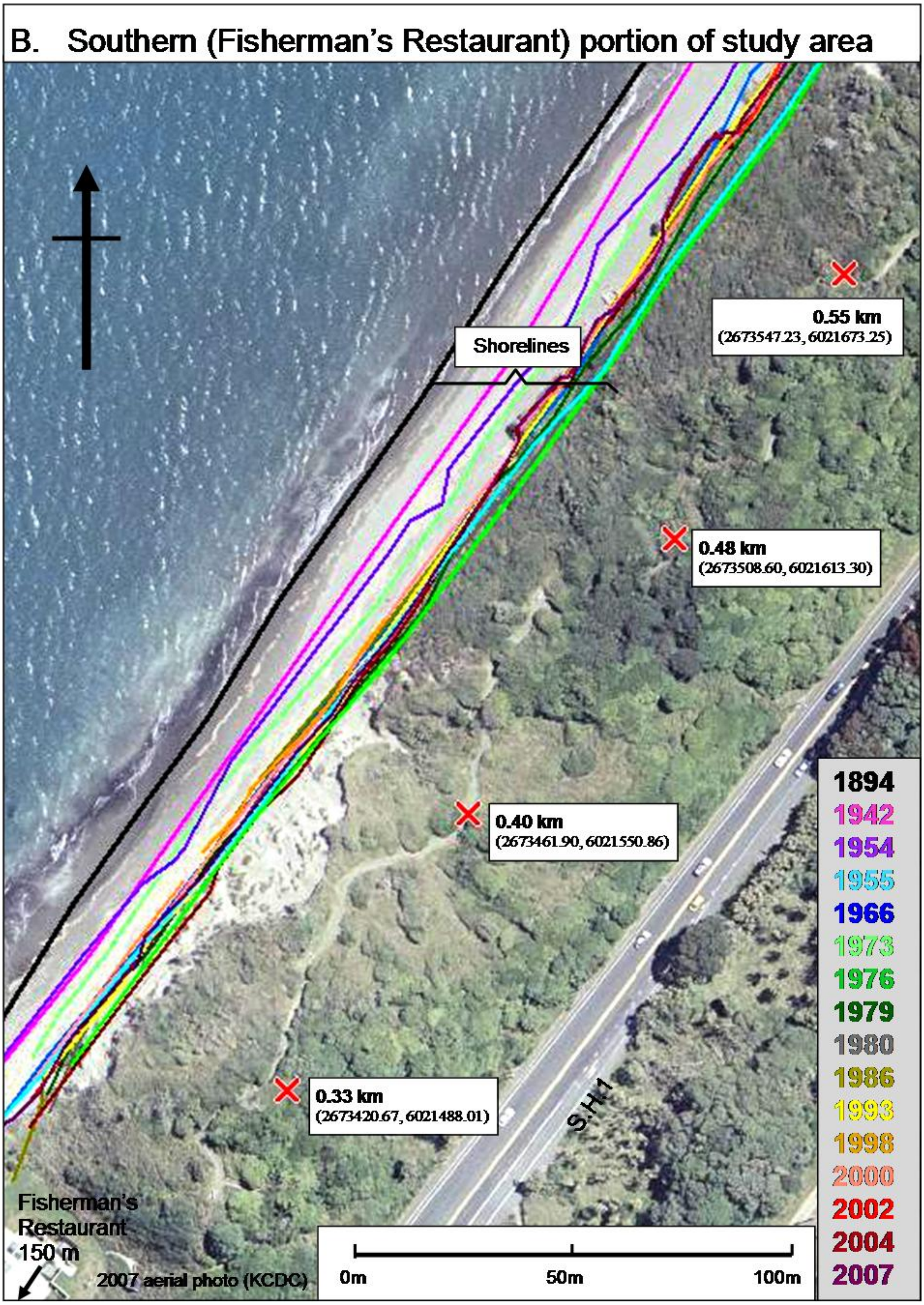


Figure 2 Shorelines, edge of cliff (clifftop) , and seaward margin of beach (low tide 'step') for the northern portion of the South Paekakariki Shoreline Study area (A) and the southern portion (B). The northern section has some protection from seawall remnants (dotted line). The outline of 13 homes removed from Ames Street in the early 1980s is marked in A. Crosses locate reference points off the 7 cross-shore transects used for the shoreline analysis together with their NZMG (NZGD49) ground co-ordinates. The distance datum is located near the Fisherman's Restaurant; its co-ordinates are: 2673201.67, 6021248.27


B. Southern (Fisherman's Restaurant) portion of study area
Shorelines
0.55 km
(2673547.23, 6021673.25)
0.48 km
(2673508.60, 6021613.30)
0.40 km
(2673461.90, 6021550.86)
0.33 km
(2673420.67, 6021488.01)
S.H.1
Fisherman's Restaurant 150 m
2007 aerial photo (KCDC)
0m
50m
100m
1894
1942
1954
1955
1966
1973
1976
1979
1980
1986
1993
1998
2000
2002
2004
2007

Slope profiles were obtained from the recently surveyed LIDAR data held by the KCDC, and several field inspections were also carried out. Such results and observations, together with interpreting archival profile data, enabled the slope processes characterizing the study area to be defined, and the suitability of the slope stability model used in the Open Coast Erosion Hazard Assessment Report to be further assessed.

3 Shoreline behaviour

General description

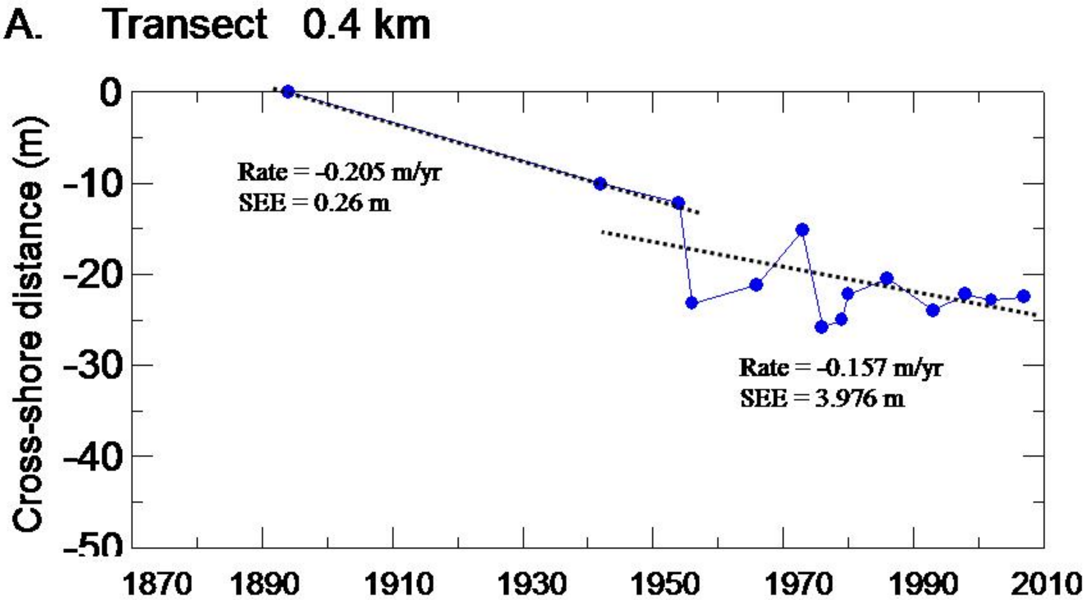
Time-series graphs for the locations 0.4 km and 0.73 km from The Fisherman's Restaurant datum are shown in Figs 3A and 3B respectively. Note that these locations correspond with Coastal Measurement Sites 0-4 and 0-73 as used in the *Open Coast Hazard Assessment Report* (Section 2.3). These data show an overall landward directed trend in shoreline position, with clearly defined fluctuations which represent periods of erosion and subsequent recovery. Such shorter-term behaviour occurred during the 1950s, 1970s and 1990s and these episodes correspond with the more energetic periods of the IPO, i.e. the Inter-decadal Pacific Oscillation (de Lange, 2000). However, the results in Fig 3 also show that the magnitude of erosion-recovery episodes has been decreasing through time and several explanations may apply including reduced sediment supply from the south (Gibb and De Pledge, 1980), changes in the runoff regime (Holland and Holland, 1985), and differences in beach width during times of erosive storms event (see Section 5 below). The longshore similarity in shoreline behaviour suggests that the same processes occur along both sections of this beach, but the difference in pattern indicates process magnitudes can vary.

3.2 Rates of change

Regression models have been fitted to the *earlier* (*pre-seawall) period* (1894-1954) and to the *later* (*aerial photo) record* (1942-2007) subsets, in keeping with the approach used in the *Open Coast Erosion Hazard Report*. These results are depicted in Fig 3 and show the long-terms rates of change for the *earlier period* were approx -0.2 m/yr at both sites. By contrast, the *later data record* had a reduced rates at both sites: -0.16 m/yr at 0.4 km, and -0.05 at 0.73 km.

These results suggest that there has been a lessening of the erosion rate over time. However, the distinct change at the northern site (0.73 km) appears to be related to the significant erosion-recovery episode which occurred during the 1950s, together with the more recent increase in shoreline stability.

The rates of shoreline change for all seven sites are included in Fig 4A where a distinction is evident between rates from the non-seawalled southern sector (<0.6 km) and the remnant seawalled northern sector (>0.6 km). The horizontal bars in Fig 4A identify the minimum values (maximum erosive trends) used to represent these sectors in the open coast erosion hazard assessment. In particular, the southern sector's earlier rate is -0.25m/yr and its later rate is -0.15m/yr, while the northern sector's earlier rate is -0.2 /yr and its later rate is -0.075 m/yr.



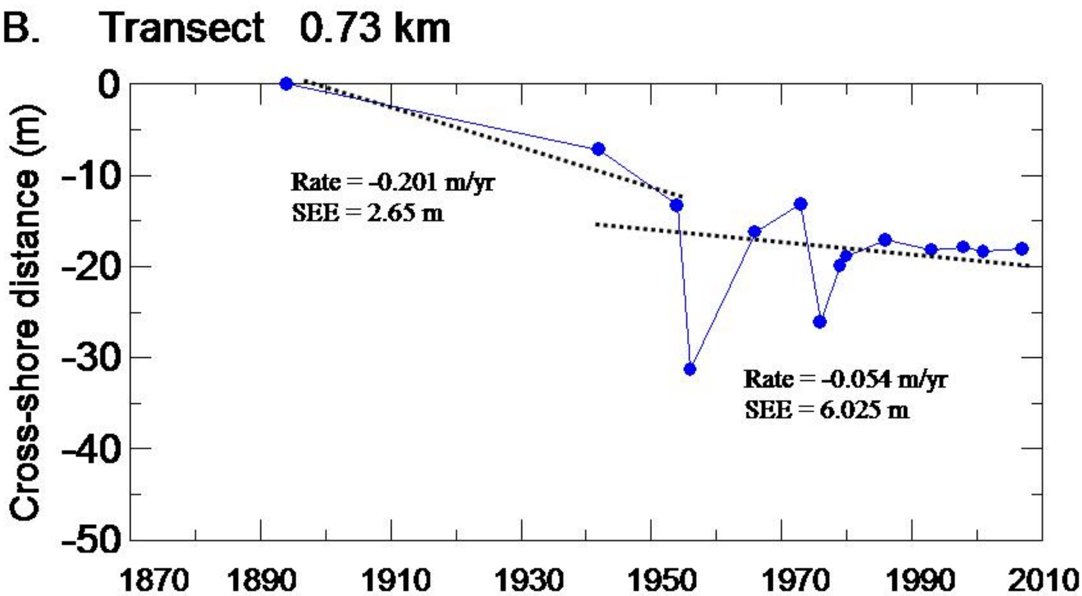


Figure 3 Shoreline time-series for transects sites 0.4 km (A) and 0.73 km (B). Cross-shore distances have been measured relative to the initial 1894 cadastral shoreline, with negative values relating to landward directed change (erosion). Linear regression models have been fitted (dashed lines) to these data for the early period (1894 to 1954) and the later aerial photo period (1942 to 2007) in keeping with the approach used in the Open Coast Erosion Hazard Assessment. The SEE is a measure of spread about the regression lines that is used to define the short-term fluctuation (see text)

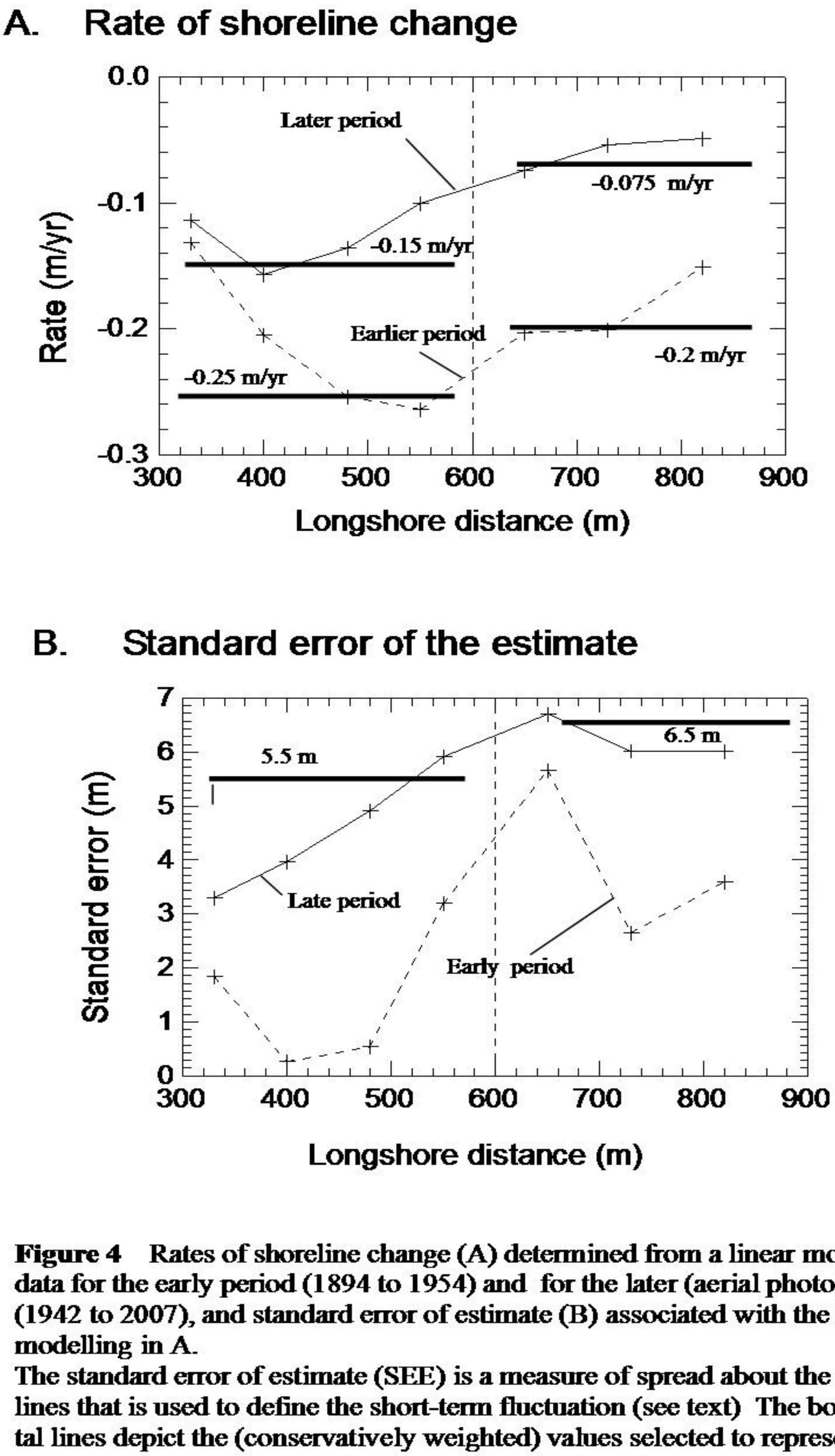


Figure 4 Rates of shoreline change (A) determined from a linear model fitted to data for the early period (1894 to 1954) and for the later (aerial photo) period (1942 to 2007), and standard error of estimate (B) associated with the regression modelling in A.
The standard error of estimate (SEE) is a measure of spread about the regression lines that is used to define the short-term fluctuation (see text) The bold horizontal lines depict the (conservatively weighted) values selected to represent the non-seawalled (<600 m) and partially seawalled (>600 m) sections of the study area.

3.3 Shorter-term fluctuation

The maximum negative fluctuation (or maximum residual distance between observation and regression line) for the southern sites is 6.1 m and 14.3 m for the northern sites. However, as described in Section 3.3 of the *Open Coast Erosion Hazard Assessment Report*, the estimate for the population's range of shoreline locations is provided via the *standard error of estimate* (SEE).

The short-term fluctuation determined via the SEE helps account for shoreline locations outside the envelope of sampled positions. In particular, it can be shown that ±3 x SEE provides an interval about the average shoreline position (as defined by the regression line) within which, based on the provided sample, we can be 99% confident that the all shorelines positions are located. The interval is thus 6 x SEE units wide. In hazard assessment, it is the negative, or landward, portion of the interval that is of relevance, so we refer to the short-term fluctuation as being 3 x SEE units wide.

The SEEs for all 7 sites have been plotted in Fig 4B. The residuals from the early data (1894-1954) are, in most cases, considerably lower than those from the later period of aerial record (1942-2007). This relates more to the number of data points (approximately 3 c.f. 13) than to greater shoreline fluctuation occurring during the latter period. The representative (conservatively weighted) SEE value for the southern sector (<0.6 km) is 5.5 m and 6.5 for the northern sector (>0.6 km). Multiplying these values by 3 to get the negative (landward) fluctuation values used in the *Open Coast Erosion Hazard Assessment Report*, although it is noted that these values were subsequently relaxed slightly for site-specific reasons as explained in the *Coastal Erosion Hazard Data-Base*.

4 Scarp-top behaviour

Scarp-top retreat over the past 64 yrs (1942-2006) at 14 sampling locations along the Ames Street reserve are depicted in Fig 5. Retreat distances during this period ranged between 0.5 m and 7.4 m with a mean of 3.62 m. It is noted that the largest inter-survey retreat was 5.4 m and this occurred at site 0.73 km between 1979 and 2006 (see Fig 2A). Maximum inter-survey retreat at the other 13 sites during the 1942 to 2006 period varied between 0.5 and 5.1 m.

The scarp-top retreat data provides a means of validating the requirement of the slope stability model (equation 4 in the *Open Coast Hazard Assessment Report*) that the recovery-erosion ratio is 1:2 (proportion = 0.5 so recovery is 50%). Separate determinations of this ratio were made for the three transect sites along the Ames Street reserve, i.e. at 0.65 km, 0.73 km and 0.82 km. The approach assumes no long-term trend in shoreline position during the measurement period and given the results in Section 3, this assumption seems reasonable. The maximum erosion at each site during the 64 yr period is taken to be the maximum residual; this give values of 16.2 m, 14.3 m and 14.1 m respectively. The corresponding scarp-top retreat is

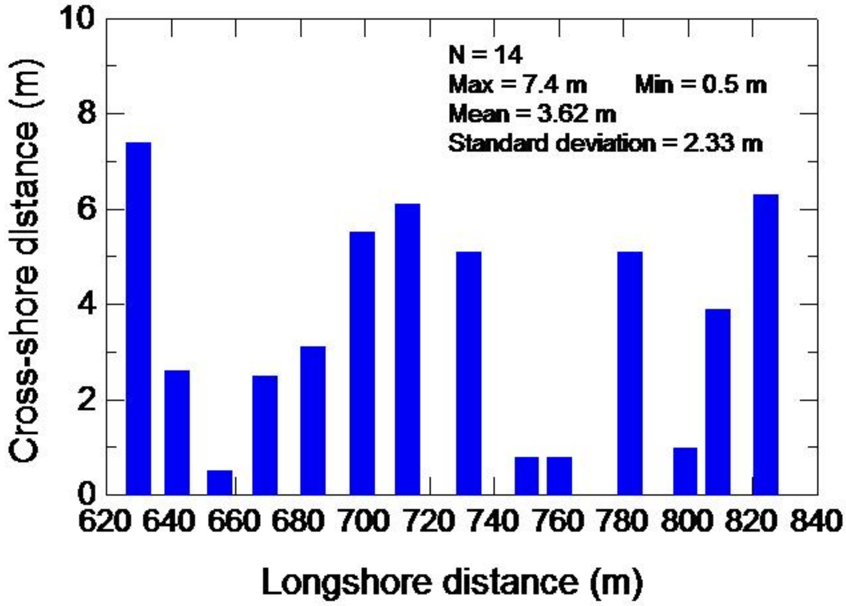


Figure 5 Retreat of scarp-top along Ames Street reserve for period 1942 to 2006. Longshore distances relate to the Fisherman's Restaurant datum. Sampling locations were spaced 15 to 20 m apart.

used as proxy for net change at the shoreline; these values are 2.6 m, 5.1 m and 6.3 m respectively.

Subtracting the net change from the erosion values gives inferred shoreline recovery distances of 13.6 m, 9.2 m and 7.8m. Recovery proportions are thus 0.84, 0.64 and 0.55. As all proportions exceed the 0.5 requirement, the model will over-estimate scarp-top retreat and is thus acceptable for use in the hazard assessment.

5 Changes in beach width

The relative width of a beach is a useful indicator as to its erosional vulnerability with increased width providing greater opportunity for waves to break and dissipate their energy before reaching the upper beach and foredune. By contrast, when a beach is narrower, substantial erosion can occur even when waves and sea level are not extreme.

The width of a beach can vary over a range of time-scales which relate to seasonality and lower frequency forcing, as well as episodic variation in sediment supply. Time-series comparing the beach width and shoreline change at the 0.73 km transect are depicted in Fig 6. These data show how the beach was in a narrowed state during the mid 1950s erosion episode. A significant reduction in width is also evident between the two data-points (1974 and 1979) bracketing the mid-late 1970s episode of erosion.

The driving events for these two major episodes of erosion were the July 1954 and September 1976 storms. In each case neither the level of the high tide nor the barometric

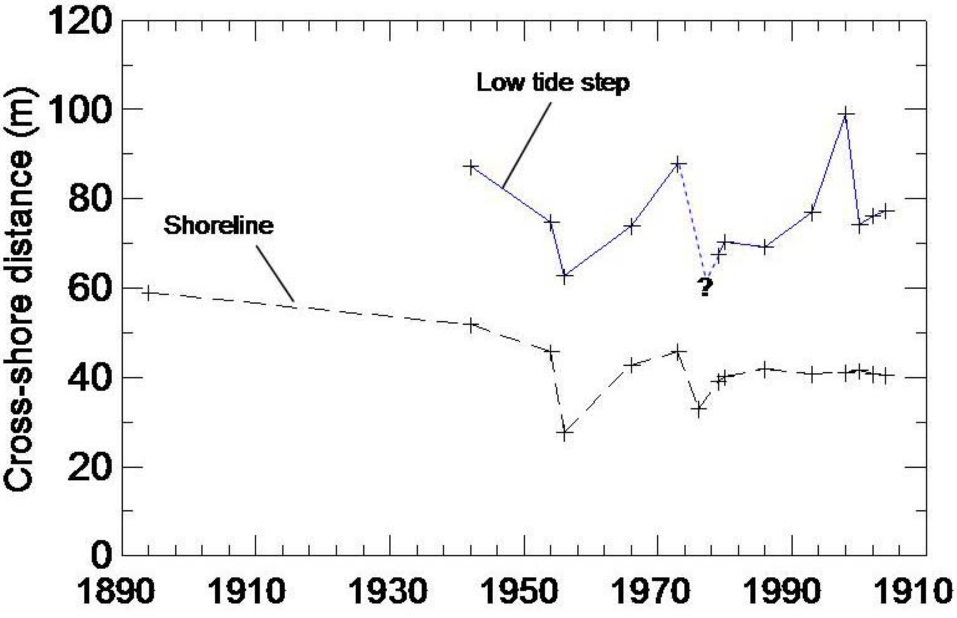


Figure 6 Comparison of shoreline (represented by the vegetation-based foredune-toe) and beach width (represented by the low tide 'step') behaviour at transect 0.73 km. No location was available for the beach in 1976, but a value lower than the 1979 local minimum is likely—hence the question mark. The upward spikes on the low tide step relate to periods of beach widening from landward welding of the off-shore bar.

pressure was particularly low. The erosion has therefore been attributed to storm surge and high waves (NIWA, 2000). However, coincidence with a depleted beach also appears to have played a significant role in enabling waves to reach and erode the foredune.

6 Slope processes

As indicated in the preceding section, significant episodes of shoreline erosion occur when storm waves are able to reach the upper beach. Such erosion can extend back into the foredune and leave a near vertical scarp or cliff that may be several metres high. Coastal dunes in temperate climates undergo a well recognized geomorphological failure-recovery sequence (e.g. Carter et al., 1990). This section will briefly describe the sequence and use illustrations from the south Kapiti coast to demonstrate its applicability in this area.

Substantial slope failure is usually initiated by marine undercutting with rotational slumping and tabular slides resulting in a steep slip-face (see Fig 7A). With subsequent drying out of the slope, avalanching occurs, initially via chutes controlled by vegetation remnants, along with small falls, slumps and slides of blocks which are often held together by vegetation: the debris slope thus forms (see Fig 7B). Over subsequent months-years the top of the escarpment retreats landward and upward (Fig 7B) until a continuous ramp forms and eventually a stable slope is achieved. If no vegetation is present, the slope will lower to 34

A. **Initial marine-driven slope failure**

B. **Post-failure slope processes**

C. **Post-failure marine and wind-based processes**

Figure 7 Examples of inferred slope processes along the south Paekakariki coast. Marine undercutting, large-scale slumping and wave-driven debris removal (A). Avalanching, together with small vegetation-bound block falls and slides (B) reduce the slope angle and assist the lower debris slope to development. Marine-borne debris and wind-blown sand (evident by driftwood and embryo dune development respectively) contribute to growth of the debris slope (C) and seaward-directed shoreline recovery.

degrees, the angle of repose of dry dune sand. However, vegetation usually re-establishes and root binding allows for a steeper stable slope.

The ongoing accumulation of debris at the base of the escarpment results in seaward extension of the shoreline. While more energetic wave conditions will truncate such extension, the volume and width of beaches usually increase following storms as sediment is returned landward under gentler (constructive) wave conditions. Debris slopes thus tend to survive and extend seaward until the next major episode of erosion. This process of shoreline recovery is further enhanced by beach sediment being blown onto, and up, the debris slope. If conditions allow, dune vegetation will extend seaward and enhance the entrapment of sand. These latter processes are inferred in Fig 7C.

It is the development of the debris slope under both slope processes and marine-aeolian processes that increase basal support and thus limit the extent of landward recession at the scarp-top. *So, the greater the shoreline recovery, the less the scarp-top retreat.*

A set of profiles surveyed by the Ministry of Works and Development between 1974 and 1983 near site at 0.73 km, are reproduced as Fig 8. These profiles bracket the mid-late 1970s erosion episode and are consistent with the processes described above. The October 1976 profile was surveyed following the September erosion event and shows the expected steep scarp-face associated with initial slope failure. The August 1979 profile also depicts a steep face which relates to subsequent erosion events and post-event slumping. By contrast, the February 1983 profile shows the slope having adjusted back to the pre-event geometry by recession of the upper face and debris accumulation on the mid-lower slope. Minimal recession of the upper slope suggests input of wind-blown sand to the debris slope.

The shoreline (dune-toe) recession and recovery denoted by the arrows in Fig 8, provide an alternative means of estimating the recovery-erosion ratio. By 1983, the distances were 6.5m of recovery c.f. 10 m of erosion. This gives a proportion of 0.65 which exceeds the requirement of the dune stability model used in Section 5 of *the Coastal Erosion Hazard Assessment Report.* Any further recovery would act to increase this proportion.

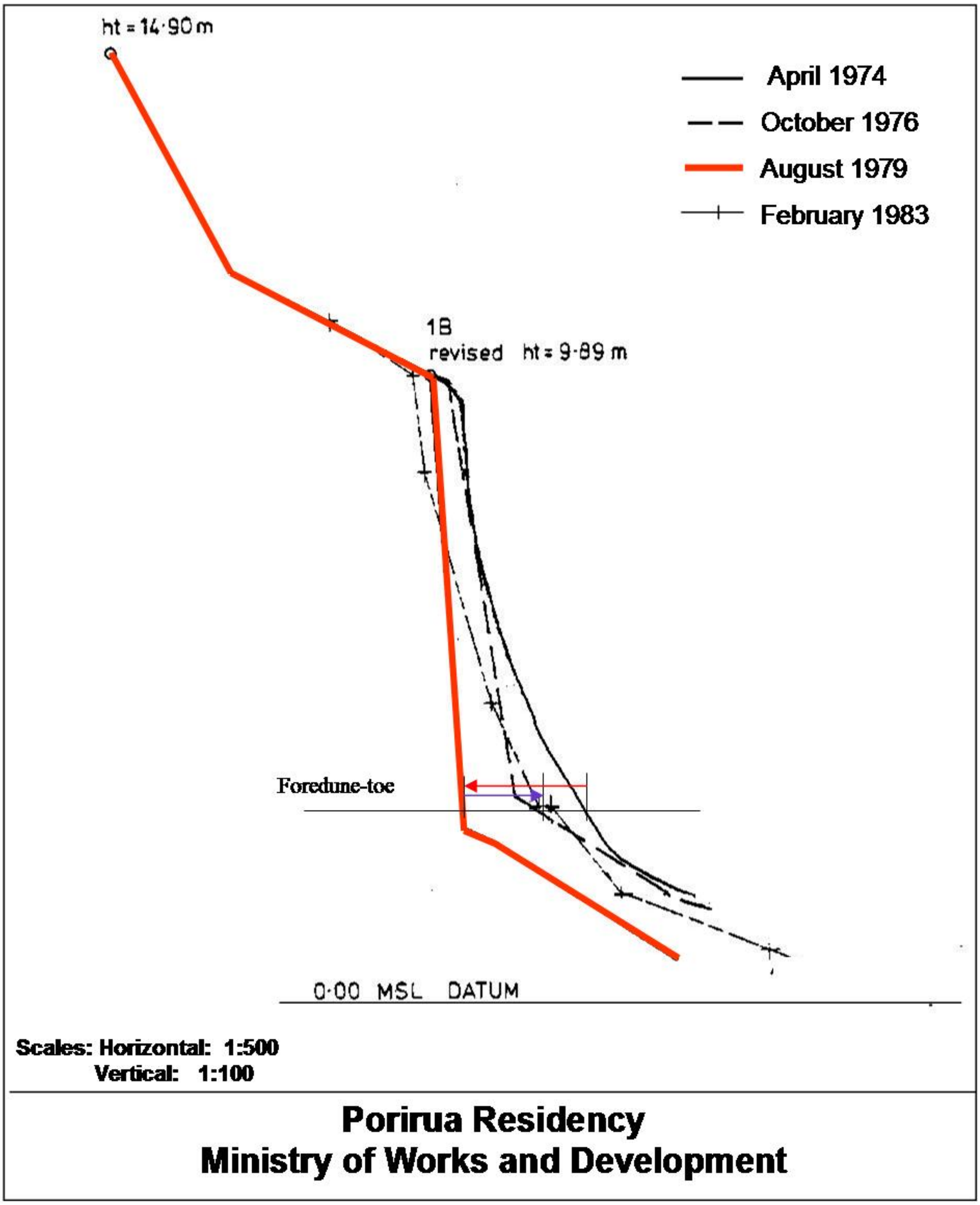


Figure 8 Beach and dune profiles for MW&D transect 1B which is ~ 0.73 km north of Fisherman's Restaurant. This set of profiles illustrate pre-erosion configuration (April, 1974), slope failure associated with the September erosion event (October, 1976), subsequent slope failure associated with erosion events in the late 1970s (August, 1979), and slope adjustment during the early 1980s to pre-event geometry (February, 1983). Inferred processes are discussed in text. Arrows denote recession (1974 to 1979) and subsequent recovery (1979 to 1983) at MSL +3 m which equates to the present day dune-toe .

7 Conclusions

This geomorphological study of the south Paekakariki coast has identified several system characteristics relevant to hazard assessment. In particular:

- There has been a reduction in the long-term erosion trend from -0.2 to -0.075 m/yr in the northern sector (in front of the Ames Street reserve), and from -0.25 to -0.15 m/yr in the southern sector;

- The short-term fluctuation value derived to represent the southern sector was 16.5 m and 19.5 m for the northern sector;

- The scarp-top has retreated on average 3.6 m (0.5 to 7.4 m) since 1942, and in only one instance has it reached the location of a house removed in the early 1980s;

- The major episodes of erosion coincided with a relatively narrow beach;

- Dune failure and subsequent adjustment process at south Paekakariki are consistent with the generally recognized geomorphological sequence in temperate climates;

- The dune erosion-recovery process acts as a filter which reduces scarp-top recession such that the greater the shoreline recovery, the less will be the scarp-top retreat;

- The recovery-erosion ratios identified in this study provide support for the dune stability model used in the open coast erosion hazard assessment.

Finally it is noted that given the high levels of natural character and amenity value for the unmodified section of coast at south Paekakariki, consideration could be given to a sand harvesting technique which should provide some protection, or at least retard the underlying pattern of erosion, to this area. During periods of relatively high beach volume, sand is mechanically harvested (scraped) from the foreshore and deposited at the base of the scarp. Dune vegetation quickly establishes on this artificial dune which continues to grow by trapping wind-blow sand. During periods of low beach sand volume when the scarp would normally be vulnerable to storm wave attack, the stored sand is eroded instead and released back into the littoral system. This method requires ongoing monitoring to determine when and how much sand can be harvested. It has been applied successfully elsewhere.

Appendix B Hazard component values

B-1 Seawalls Hold

Key (Terms as used in equation 1 of *Open Coast Erosion Hazard Report*)

Dist: Longshore distance (km)
LT: Long-term retreat (m)
ST: Short-term (landward) fluctuation (m)
SLR: Sea-level rise induced retreat (m)
DS: Dune stability by scarp-top retreat (m)
CU: Combined uncertainly (m)
CEHD: Cross-shore erosion hazard distance (m)

Distance	LT_Hold	ST_Hold	SLR_Hold	DS_Hold	CU_Hold	CEHD
0.17	0.0	0.0	0.0	0.0	0.0	**0.0**
0.40	-7.5	-15.0	-6.1	-14.8	-6.0	**-49.4**
0.73	-3.8	-15.0	-6.5	-18.8	-6.0	**-50.0**
1.51	0.0	0.0	0.0	0.0	0.0	**0.0**
2.62	0.0	0.0	0.0	0.0	0.0	**0.0**
3.30	.	.	.	.	.	**.**
3.60	-14.5	-10.0	-13.6	-6.7	-6.0	**-50.8**
3.93	-17.5	-10.0	-13.6	-10.2	-6.0	**-57.4**
4.18	-20.0	-10.0	-13.6	-10.7	-6.0	**-60.4**
4.52	-22.5	-10.0	-13.6	-10.0	-6.0	**-62.1**
4.93	-26.5	-10.0	-13.6	-11.3	-6.0	**-67.4**
5.15	-28.5	-10.0	-13.6	-11.3	-6.0	**-69.4**
5.40	.	.	.	.	.	**.**
5.70	-33.5	-10.0	-14.3	-13.0	-6.0	**-76.8**
6.04	-40.5	-10.0	-14.3	-10.8	-6.0	**-81.6**
6.39	-50.0	-13.0	-14.3	-14.9	-6.0	**-98.2**
6.57	-75.0	-15.0	-14.3	-9.6	-6.0	**-119.9**
6.76	0.0	0.0	0.0	0.0	0.0	**0.0**
7.10	0.0	0.0	0.0	0.0	0.0	**0.0**
7.56	0.0	0.0	0.0	0.0	0.0	**0.0**
8.02	0.0	0.0	0.0	0.0	0.0	**0.0**
8.72	0.0	0.0	0.0	0.0	0.0	**0.0**
9.11	0.0	0.0	0.0	0.0	0.0	**0.0**
9.43	0.0	0.0	0.0	0.0	0.0	**0.0**
10.00	.	.	.	.	.	**.**
10.29	-9.5	-10.0	-15.0	-5.3	-6.0	**-45.8**
10.40	0.0	0.0	0.0	0.0	0.0	**0.0**
10.61	-9.5	-10.0	-15.8	-5.2	-6.0	**-46.5**
11.17	-19.0	-10.0	-15.8	-2.6	-6.0	**-53.4**
11.41	0.0	0.0	0.0	0.0	0.0	**0.0**
11.64	0.0	0.0	0.0	0.0	0.0	**0.0**
12.12	0.0	-10.0	-17.6	-2.0	-6.0	**-35.6**
12.50	0.0	-12.0	0.0	-2.4	-6.0	**-20.4**
12.60	.	.	.	.	.	**.**

12.77	0.0	-18.0	-18.8	-1.2	-6.0	**-43.9**
13.04	0.0	-26.0	-18.8	-0.9	-6.0	**-51.6**
13.24	0.0	-30.0	-20.0	-0.6	-6.0	**-56.6**
13.44	0.0	-34.5	-20.0	-1.0	-6.0	**-61.5**
13.63	0.0	-36.0	-21.4	-0.6	-6.0	**-64.0**
13.89	0.0	-15.0	-21.4	-1.1	-6.0	**-43.5**
14.20	-15.0	-15.0	-20.0	-3.1	-6.0	**-59.1**
14.60	.	.	.	.	.	**.**
16.69	0.0	-15.0	-15.0	-3.3	-6.0	**-39.3**
17.31	0.0	-15.0	-15.0	-2.6	-6.0	**-38.6**
17.88	0.0	-12.0	-15.0	-2.6	-6.0	**-35.6**
18.30	.	.	.	.	.	**.**
18.85	0.0	-12.0	-15.0	-2.0	-6.0	**-35.0**
19.35	0.0	-12.0	-15.8	-2.0	-6.0	**-35.8**
20.30	0.0	-12.0	-16.7	-1.8	-6.0	**-36.4**
20.79	0.0	-12.0	-17.6	-1.3	-6.0	**-37.0**
21.26	0.0	-12.0	-17.6	-2.0	-6.0	**-37.6**
21.73	0.0	-12.0	-18.8	-1.9	-6.0	**-38.6**
22.06	0.0	-12.0	-18.8	-3.3	-6.0	**-40.1**
22.60	.	.	.	.	.	**.**
23.50	0.0	-12.0	-17.6	-1.9	-6.0	**-37.5**
24.91	0.0	-12.0	-16.7	-1.6	-6.0	**-36.2**
25.70	0.0	-12.0	-14.3	-1.6	-6.0	**-33.8**
26.58	0.0	-12.0	-12.5	-0.5	-6.0	**-31.0**
27.30	.	.	.	.	.	**.**
27.63	0.0	-12.0	-8.8	-0.8	-6.0	**-27.6**
28.81	0.0	-12.0	-6.5	-1.1	-6.0	**-25.6**
30.16	0.0	-14.0	-4.8	-0.9	-6.0	**-25.7**
31.00	.	.	.	.	.	**.**
32.54	0.0	-14.0	-11.1	-1.4	-6.0	**-32.5**
33.05	0.0	-14.0	-13.0	-1.3	-6.0	**-34.3**
33.60	0.0	-14.0	-15.8	-2.2	-6.0	**-38.0**
33.82	0.0	-14.0	-16.7	-2.6	-6.0	**-39.3**
34.50	.	.	.	.	.	**.**
35.54	0.0	-14.0	-16.7	-3.3	-6.0	**-40.0**
36.89	0.0	-18.0	-16.7	-3.3	-6.0	**-44.0**

Appendix B Hazard component values
B-2 Seawalls Repaired

Key (Terms as used in equation 1 of *Open Coast Erosion Hazard Report*)

Dist:	Longshore distance (km)
LT:	Long-term retreat (m)
ST:	Short-term (landward) fluctuation (m)
SLR:	Sea-level rise induced retreat (m)
DS:	Dune stability by scarp-top retreat (m)
CU:	Combined uncertainly (m)
CEHD:	Cross-shore erosion hazard distance (m)

Distance	LT_Repair	ST_Repair	SLR_Repair	DS_Repair	CU_Repair	CEHD
0.2	0.0	-15.0	0.0	-6.7	-9.0	**-30.7**
0.4	-7.5	-15.0	-6.1	-14.8	-6.0	**-49.4**
0.7	-3.8	-15.0	-6.5	-18.8	-6.0	**-50.0**
1.5	0.0	-15.0	0.0	-11.7	-9.0	**-35.7**
2.6	0.0	-15.0	0.0	-4.4	-9.0	**-28.4**
3.3	.		.			**.**
3.6	-14.5	-10.0	-13.6	-6.7	-6.0	**-50.8**
3.9	-17.5	-10.0	-13.6	-10.2	-6.0	**-57.4**
4.2	-20.0	-10.0	-13.6	-10.7	-6.0	**-60.4**
4.5	-22.5	-10.0	-13.6	-10.0	-6.0	**-62.1**
4.9	-26.5	-10.0	-13.6	-11.3	-6.0	**-67.4**
5.2	-28.5	-10.0	-13.6	-11.3	-6.0	**-69.4**
5.4	.		.			**.**
5.7	-33.5	-10.0	-14.3	-13.0	-6.0	**-76.8**
6.0	-40.5	-10.0	-14.3	-10.8	-6.0	**-81.6**
6.4	-50.0	-13.0	-14.3	-14.9	-6.0	**-98.2**
6.6	-75.0	-15.0	-14.3	-9.6	-6.0	**-119.9**
6.8	0.0	-15.0	0.0	-4.1	-9.0	**-28.1**
7.1	0.0	-15.0	0.0	-9.6	-9.0	**-33.6**
7.6	0.0	-15.0	0.0	-11.9	-9.0	**-35.9**
8.0	0.0	-15.0	0.0	-8.0	-9.0	**-32.0**
8.7	0.0	-15.0	0.0	-6.7	-9.0	**-30.7**
9.1	0.0	-15.0	0.0	-5.6	-9.0	**-29.6**
9.4	0.0	-15.0	0.0	-4.6	-9.0	**-28.6**
10.0	.		.			**.**
10.3	-9.5	-10.0	-15.0	-5.3	-6.0	**-45.8**
10.4	0.0	-10.0	0.0	-1.9	-9.0	**-20.9**
10.6	-9.5	-10.0	-15.8	-5.2	-6.0	**-46.5**
11.2	-19.0	-10.0	-15.8	-2.6	-6.0	**-53.4**
11.4	0.0	-10.0	0.0	-2.1	-9.0	**-21.1**
11.6	0.0	-10.0	0.0	-2.0	-9.0	**-21.0**
12.1	0.0	-10.0	-17.6	-2.0	-6.0	**-35.6**
12.5	0.0	-12.0	0.0	-2.4	-6.0	**-20.4**
12.6	.		.			**.**
12.8	0.0	-18.0	-18.8	-1.2	-6.0	**-43.9**

13.0	0.0	-26.0	-18.8	-0.9	-6.0	**-51.6**
13.2	0.0	-30.0	-20.0	-0.6	-6.0	**-56.6**
13.4	0.0	-34.5	-20.0	-1.0	-6.0	**-61.5**
13.6	0.0	-36.0	-21.4	-0.6	-6.0	**-64.0**
13.9	0.0	-15.0	-21.4	-1.1	-6.0	**-43.5**
14.2	-15.0	-15.0	-20.0	-3.1	-6.0	**-59.1**
14.6	.		.			**.**
16.7	0.0	-15.0	-15.0	-3.3	-6.0	**-39.3**
17.3	0.0	-15.0	-15.0	-2.6	-6.0	**-38.6**
17.9	0.0	-12.0	-15.0	-2.6	-6.0	**-35.6**
18.3	.		.			**.**
18.9	0.0	-12.0	-15.0	-2.0	-6.0	**-35.0**
19.4	0.0	-12.0	-15.8	-2.0	-6.0	**-35.8**
20.3	0.0	-12.0	-16.7	-1.8	-6.0	**-36.4**
20.8	0.0	-12.0	-17.6	-1.3	-6.0	**-37.0**
21.3	0.0	-12.0	-17.6	-2.0	-6.0	**-37.6**
21.7	0.0	-12.0	-18.8	-1.9	-6.0	**-38.6**
22.1	0.0	-12.0	-18.8	-3.3	-6.0	**-40.1**
22.6	.		.			**.**
23.5	0.0	-12.0	-17.6	-1.9	-6.0	**-37.5**
24.9	0.0	-12.0	-16.7	-1.6	-6.0	**-36.2**
25.7	0.0	-12.0	-14.3	-1.6	-6.0	**-33.8**
26.6	0.0	-12.0	-12.5	-0.5	-6.0	**-31.0**
27.3	.		.			**.**
27.6	0.0	-12.0	-8.8	-0.8	-6.0	**-27.6**
28.8	0.0	-12.0	-6.5	-1.1	-6.0	**-25.6**
30.2	0.0	-14.0	-4.8	-0.9	-6.0	**-25.7**
31.0	.		.			**.**
32.5	0.0	-14.0	-11.1	-1.4	-6.0	**-32.5**
33.1	0.0	-14.0	-13.0	-1.3	-6.0	**-34.3**
33.6	0.0	-14.0	-15.8	-2.2	-6.0	**-38.0**
33.8	0.0	-14.0	-16.7	-2.6	-6.0	**-39.3**
34.5	.		.			**.**
35.5	0.0	-14.0	-16.7	-3.3	-6.0	**-40.0**
36.9	0.0	-18.0	-16.7	-3.3	-6.0	**-44.0**

Appendix B Hazard component values

B-3 Seawalls Removed

Key (Terms as used in equation 1 of *Open Coast Erosion Hazard Report*)

Dist: Longshore distance (km)
LT: Long-term retreat (m)
ST: Short-term (landward) fluctuation (m)
SLR: Sea-level rise induced retreat (m)
DS: Dune stability by scarp-top retreat (m)
CU: Combined uncertainly (m)
CHED: Coastal erosion hazard distance (m)

Distance	LT_Remove	ST_Remove	SLR_Remove	DS_Remove	CU_Remove	CEHD
0.2	-8.0	-15.0	-5.4	-6.7	-6.0	**-41.1**
0.4	-12.5	-15.0	-6.1	-14.8	-6.0	**-54.4**
0.7	-10.0	-15.0	-6.5	-18.8	-6.0	**-56.3**
1.5	-12.0	-15.0	-7.9	-11.7	-6.0	**-52.6**
2.6	-10.0	-15.0	-10.7	-4.4	-6.0	**-46.2**
3.3	.		.		.	**.**
3.6	-5.0	-10.0	-13.6	-6.7	-6.0	**-41.3**
3.9	-5.0	-10.0	-13.6	-10.2	-6.0	**-44.9**
4.2	-6.3	-10.0	-13.6	-10.7	-6.0	**-46.6**
4.5	-7.5	-10.0	-13.6	-10.0	-6.0	**-47.1**
4.9	-10.0	-10.0	-13.6	-11.3	-6.0	**-50.9**
5.2	.	-10.0	-13.6	-11.3	-6.0	**.**
5.4	.		.		.	**.**
5.7	-12.5	-10.0	-14.3	-13.0	-6.0	**-55.8**
6.0	-12.5	-10.0	-14.3	-10.8	-6.0	**-53.6**
6.4	-12.5	-13.0	-14.3	-14.9	-6.0	**-60.7**
6.6	-12.5	-15.0	-14.3	-9.6	-6.0	**-57.4**
6.8	-25.0	-15.0	-14.3	-4.1	-6.0	**-64.4**
7.1	-25.0	-15.0	-14.3	-9.6	-6.0	**-69.9**
7.6	-25.0	-15.0	-14.3	-11.9	-6.0	**-72.1**
8.0	-25.0	-15.0	-15.0	-8.0	-6.0	**-69.0**
8.7	-25.0	-15.0	-15.0	-6.7	-6.0	**-67.7**
9.1	-20.0	-15.0	-15.0	-5.6	-6.0	**-61.6**
9.4	-10.0	-15.0	-15.0	-4.6	-6.0	**-50.6**
10.0	.		.		.	**.**
10.3	0.0	-10.0	-15.0	-5.3	-6.0	**-36.3**
10.4	0.0	-10.0	-15.0	-1.9	-6.0	**-32.9**
10.6	0.0	-10.0	-15.8	-5.2	-6.0	**-37.0**
11.2	-20.0	-10.0	-15.8	-2.6	-6.0	**-54.4**
11.4	-40.0	-10.0	-15.8	-2.1	-6.0	**-73.9**
11.6	-30.0	-10.0	-16.7	-2.0	-6.0	**-64.7**
12.1	0.0	-10.0	-17.6	-2.0	-6.0	**-35.6**
12.5	0.0	-12.0	-17.6	-2.4	-6.0	**-38.0**
12.6	.		.		.	**.**

12.8	0.0	-18.0	-18.8	-1.2	-6.0	**-43.9**
13.0	0.0	-26.0	-18.8	-0.9	-6.0	**-51.6**
13.2	0.0	-30.0	-20.0	-0.6	-6.0	**-56.6**
13.4	0.0	-34.5	-20.0	-1.0	-6.0	**-61.5**
13.6	0.0	-36.0	-21.4	-0.6	-6.0	**-64.0**
13.9	0.0	-15.0	-21.4	-1.1	-6.0	**-43.5**
14.2	-15.0	-15.0	-20.0	-3.1	-6.0	**-59.1**
14.6	.		.		.	**.**
16.7	0.0	-15.0	-15.0	-3.3	-6.0	**-39.3**
17.3	0.0	-15.0	-15.0	-2.6	-6.0	**-38.6**
17.9	.	-12.0	-15.0	-2.6	-6.0	**-35.6**
18.3	.		.		.	**.**
18.9	0.0	-12.0	-15.0	-2.0	-6.0	**-35.0**
19.4	0.0	-12.0	-15.8	-2.0	-6.0	**-35.8**
20.3	0.0	-12.0	-16.7	-1.8	-6.0	**-36.4**
20.8	0.0	-12.0	-17.6	-1.3	-6.0	**-37.0**
21.3	0.0	-12.0	-17.6	-2.0	-6.0	**-37.6**
21.7	0.0	-12.0	-18.8	-1.9	-6.0	**-38.6**
22.1	0.0	-12.0	-18.8	-3.3	-6.0	**-40.1**
22.6	.		.		.	**.**
23.5	0.0	-12.0	-17.6	-1.9	-6.0	**-37.5**
24.9	0.0	-12.0	-16.7	-1.6	-6.0	**-36.2**
25.7	0.0	-12.0	-14.3	-1.6	-6.0	**-33.8**
26.6	0.0	-12.0	-12.5	-0.5	-6.0	**-31.0**
27.3	.		.		.	**.**
27.6	0.0	-12.0	-8.8	-0.8	-6.0	**-27.6**
28.8	0.0	-12.0	-6.5	-1.1	-6.0	**-25.6**
30.2	0.0	-14.0	-4.8	-0.9	-6.0	**-25.7**
31.0	.		.		.	**.**
32.5	0.0	-14.0	-11.1	-1.4	-6.0	**-32.5**
33.1	0.0	-14.0	-13.0	-1.3	-6.0	**-34.3**
33.6	0.0	-14.0	-15.8	-2.2	-6.0	**-38.0**
33.8	0.0	-14.0	-16.7	-2.6	-6.0	**-39.3**
34.5	.		.		.	**.**
35.5	0.0	-14.0	-16.7	-3.3	-6.0	**-40.0**
36.9	0.0	-18.0	-16.7	-3.3	-6.0	**-44.0**

APPENDIX C

Assessing previously reported extreme shoreline erosion distances on the south Kapiti Coast using geomorphic evidence

Gibb (1978) listed several periods of substantial erosion (40-50 m over 6 to 18 yr intervals) along the south Kapiti Coast. In particular at, or near, the transect 0.74 km in south Paekakariki, and at transects 8.02 and 9.10 km in South Raumati. These inter-survey erosion distances are much greater than any identified in the present Kapiti Erosion Hazard Study, and greater than the associated short-term fluctuation component value proposed in the hazard assessment (±15m). Gibb identified these periods of erosion by comparing shorelines shown on cadastral maps. While such shoreline comparison can result in large differences due to differing indicators being used in subsequent surveys, or from higher frequency beach processes affecting the location of tide-based shoreline indicators (c.f. the vegetation-front indicator used in the predominantly aerial photo-based present study), any possible significant episodes of erosion from sources not used in the present study must be investigated.

While the cadastral maps containing the erosional shorelines identified by Gibb (years 1880 and 1958) were not available, the NWASCO maps use in the present hazard study accurately define the pre-erosional shorelines used by Gibb (years 1874 and 1940). By applying Gibb's shoreline retreat distances to the NWASCO shorelines, the location of the Gibb's erosional shorelines were identified. When comparing these two shorelines with the others used in the present study, they were further landward and located within relatively high (15 to 27 m) sand dunes (see A-C below). This result casts doubt as to the accuracy of these two erosional shorelines as dune recovery from such erosion would not be possible within the available time and under the operating environmental conditions.

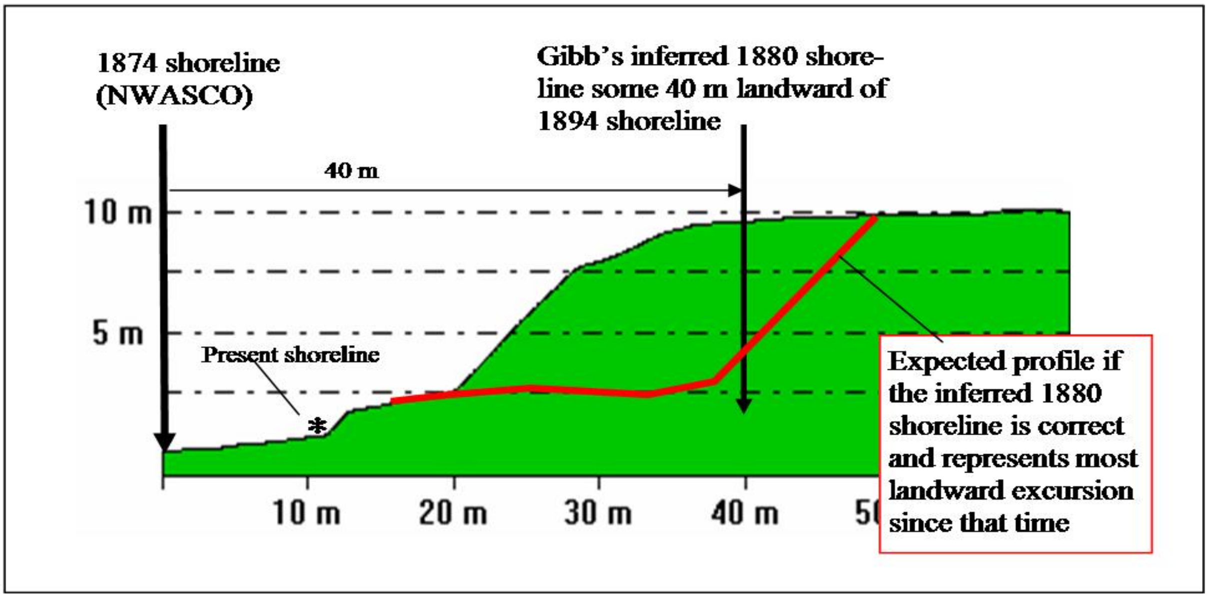
The expected profile associated with these alleged erosional shorelines have been marked in A-C. Modelling assumptions include a relatively steep erosion scarp existing at the time of survey, the shoreline was located close to the scarp-base and the slope subsequently lowered to 34 degrees (stable for dry dune-sand) with the ramp comprising dune debris and wind-blown sand (as described in Section 5 and Appendix A). Backbeach sand accumulations were accounted for, but limited sand availability and long-term shoreline recession make incipient foredune development unlikely at such locations. The modelled profiles are 15 to 25 m landward of the present day profile, indicating the alleged erosional shorelines must be in error by at least these amounts.

In addition, the 1956 (November) shoreline identified from high resolution geo-rectified aerial photography (negative scans), coupled with stereograph analysis, is also marked on C. This shoreline captures the extensive erosion associated with the July 1954 event. An outcropping paleo-soil evident on aerial photos is marked as well; this feature is close to the 1956 shoreline and locates the landwardmost extent of historical erosion. While an erosive event also happened in October 1957, the soil marker implies that the effect of this event was not as widespread.

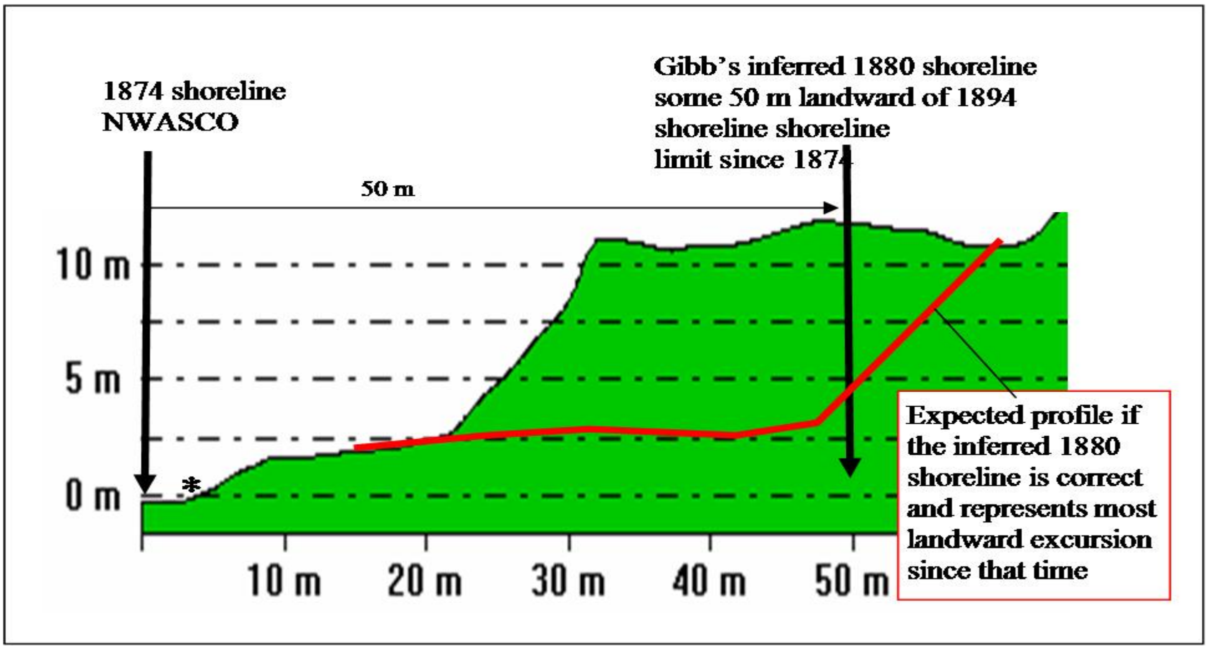
This geomorphic evidence shows the 1880 and 1958 shoreline locations used by Gibb (1978) to identify significant episodes of erosion cannot be correct. The 20 to 25 m of erosion indicated here as having occurred during that time interval is about half the 40 to 50 m distance used by Gibb, and sits within the ±15 m interval used for the present hazard assessment.

It may be that the original surveyors mapped the local dune crest or upper limit of an erosion scarp as the shoreline indicator. This does seem to have been the case at south Paekakariki (C below). An inspection of the original surveyor's field books may resolve this matter; however, given the geomorphic evidence it was not necessary to pursue this as part of the present study.

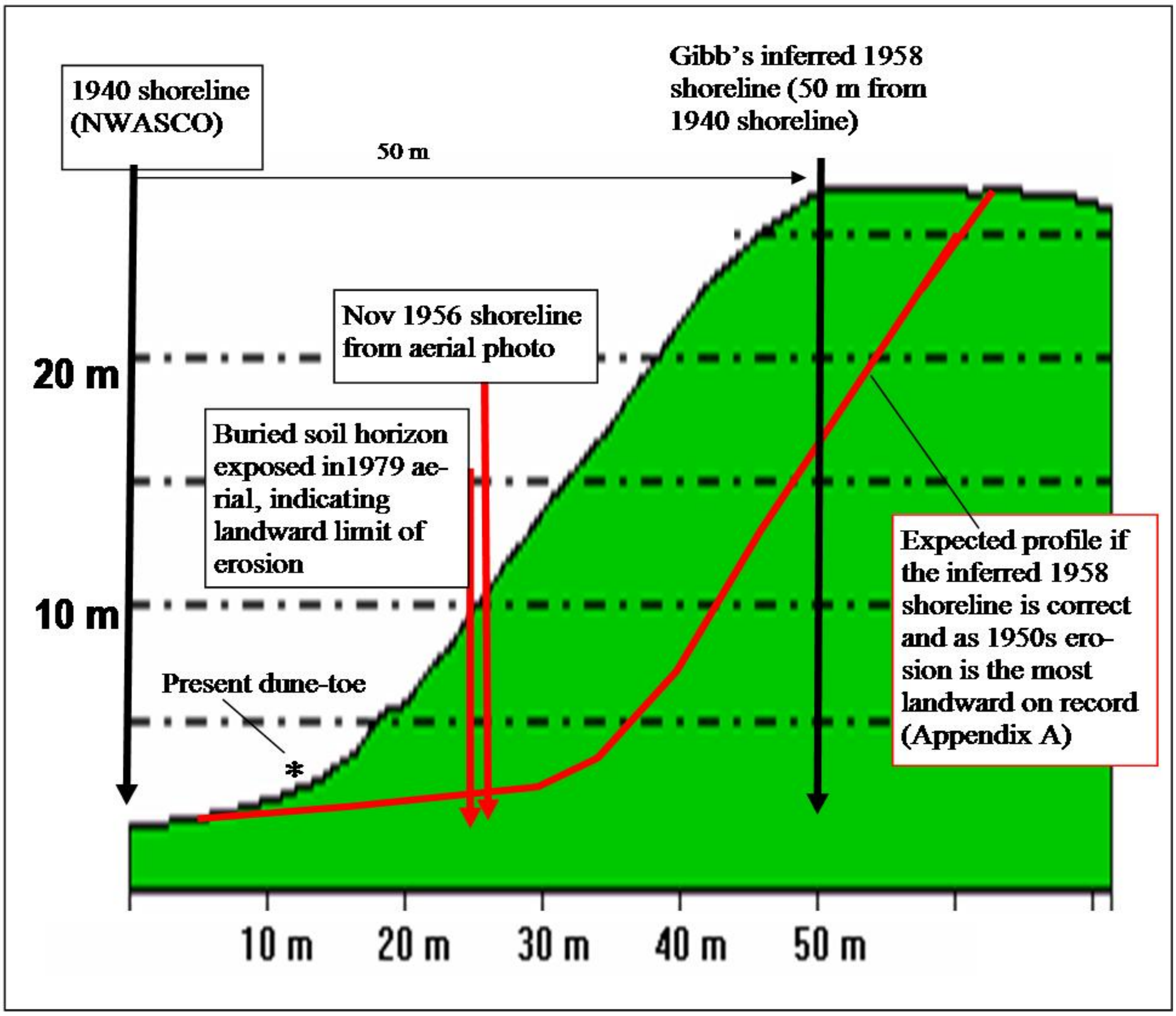
A. LIDAR-based profile 20m to north of transect 9.1km (MWD 7, Gibb 085)



B. LIDAR-based profile 20m north of transect 8.02 km (MWD 6, Gibb 084)



C. LIDAR-based profile at transect 0.74 km (~Gibb 076)



APPENDIX D

Assessment of shoreline response models to sea-level rise

The most commonly used shoreface response model to a rise in sea level on coasts of unconsolidated sediment, is that proposed by Bruun (1983) which is based on the thesis 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 model does not incorporate variation in sediment supply, assumes no lithological controls and also assumes conservation in terms of longshore transport volume. While debate exists as to the validity of the assumptions, the general upward and landward translation of at least the beach profile is generally accepted (Kirk et al., 1999; SCOR Working Group 89, 1991). However, the rate at which profile adjustment occurs remains unclear.

The model translates the entire beach and nearshore profile upward and landward in relation to the programmed sea-level rise. Bruun calculated the shoreline retreat using the following equation:

$$R = (L/[B + d])S \qquad \text{(D1)}$$

where R is the profile shift in the landward direction, S is the predicted rise in sea-level, L is the cross-shore length of the profile, B is the height of the beach-berm or dune above initial MSL, and d is the depth below initial MSL beyond which significant sediment exchange is not considered to occur (*closure depth*). Locating this seaward end point is particularly contentious with some researchers doubting the existence of such a point (Pilkey et al., 1993), and others arguing that the phenomenon may not apply to coasts which do not meet the Bruun assumptions – in particular those coasts characterized by open systems dominated by longshore sediment transport (SCOR Working Group 89, 1991).

Closure depth can be estimated using several methods including wave statistics, change in profile slope, onset of constant variance in the profile bundle, and changes in sediment characteristics. While relatively consistent depths have been obtained using these different methods on the east coast of the North Island (Hicks et al., 2002), wider variation was found in a comparative study at Wanganui, 100 km northwest of the Kapiti Coast. While Wanganui has a somewhat more energetic coast than at Kapiti, the two locations demonstrate similar general west coast characteristics of sandy beaches with offshore bars and backed by sand dunes, regular storms with shorter period waves, and wind or tide-driven longshore currents. Generalisations from the Wanganui closure study are therefore likely to also apply to Kapiti.

Table 1 Comparison between different closure indicators and associated dune recession from a sea-level rise of 0.45 m/yr, using data from the Wanganui Coast[1]

Closure indicator	Depth (m) (below MSL)	Recession[2] (m)	Notes
di[3]	37.7	173	Hallermeier (1981) Unreliable if depth >20m
dl[3]	10.5	26.3	Hallermeier (1981)
Adjusted dl	7.5	21.6	Nicholls et al. (1998)
Profile bundle	6.4	22.4	Constant standard deviation.
Slope change	14.5	30.8	Break in slope
Sediment characteristics	16-17.5	36.7-51.6	Change in size and skewness

Notes:
1. Shand et al. (2000).
2. Dune recession determined using the Bruun (1983) Rule.
3. di: depth at seaward limit of 'shoal zone', and dl: depth at landward limit of 'shoal zone', determined using wave statistics.

.

Results from the Wanganui study are given in Table 1 and show a wide range of values for both closure depth (6.4 to 17.5 m if the unreliable di value of 37.7 m is discarded), and corresponding shoreline recession (21.6 to 51.6 m) based on equation 1. This outcome adds further doubt as to whether a definable closure depth exists for open systems on the New Zealand west coast where conservation of longshore drift (driven by wind, wave and tide-based currents) is unlikely.

At the other extreme of shoreline response to SLR is the theory that there is no need for nearshore deposition at all. Davidson-Arnott (2003) recently argued that sediment eroded from the upper beach-dune system could be completely absorbed within the landward dunes. However, the concept has yet to gain acceptance by the scientific community

Another approach is that of Komar et al. (1999) which is based on conservation of the inter-tidal beach form during a rise in sea level. Justification for this approach is based on the argument that this is the area most likely to be affected by processes associated with a rise in sea-level, and that the effect will be an upward and landward translation of the inter-tidal beach. Calculation of this profile shift is carried out using the following equation.

$$R = S/\tan \beta \qquad \text{(D2)}$$

where R is the profile shift in the landward direction, S is the predicted rise in sea-level, and tan β is the average inter-tidal slope.

The Komar Model was considered most applicable and defendable for use on the Kapiti Coast.

APPENDIX E

Derivation of dune stability model (equation 4) and additional comment

1 Background

Mr Richard Rienen-Hamell of Tonkin and Taylor Ltd (see Section 1.5) made several comments in relation to the dune stability Section (6) in the *Open Coast Erosion Hazard Assessment* report. These matters related primarily to clarifying equation 4, and also to the possibility of settlement cracks attributing to loss of toe support for a building located at the limit of scarp retreat. Appendix E addresses these matters.

2 Derivation of equation 4

With regard to Figure 1 below, it is evident that as the cross-section area of deposition (A_{dep}) approximates the eroded area of deposition (A_{eroded}), and as the scarp face is approx perpendicular,

$h/(DTR + STR) = \tan \propto$

but $DTR \sim STR$

therefore $h/2*STR = \tan \propto$

so $STR = h/2*\tan \propto$ (equation 4, hazard assessment report).

3 Final settlement

The model was applied using $\propto = 34^0$, the angle of repose for dry dune sand so no further adjustment is required to attain stability. Given that field measurements at south Paekakariki (Appendix A) showed that the actual slope angles range between 34 and 41degrees (with the higher angles being associated with root binding), the modelled output, in general, has an inherent safety margin.

Finally, it is noted that in the unlikely event that this safety margin did not apply and the dune stability adjustment finished adjacent to a building, that structure should not place occupants at risk as the latter part of the adjustment process takes several months to complete. The building itself should also not be at risk as slope processes (wind-driven) will generally result in some seaward recovery of the crest and this can minimize surface cracks developing.

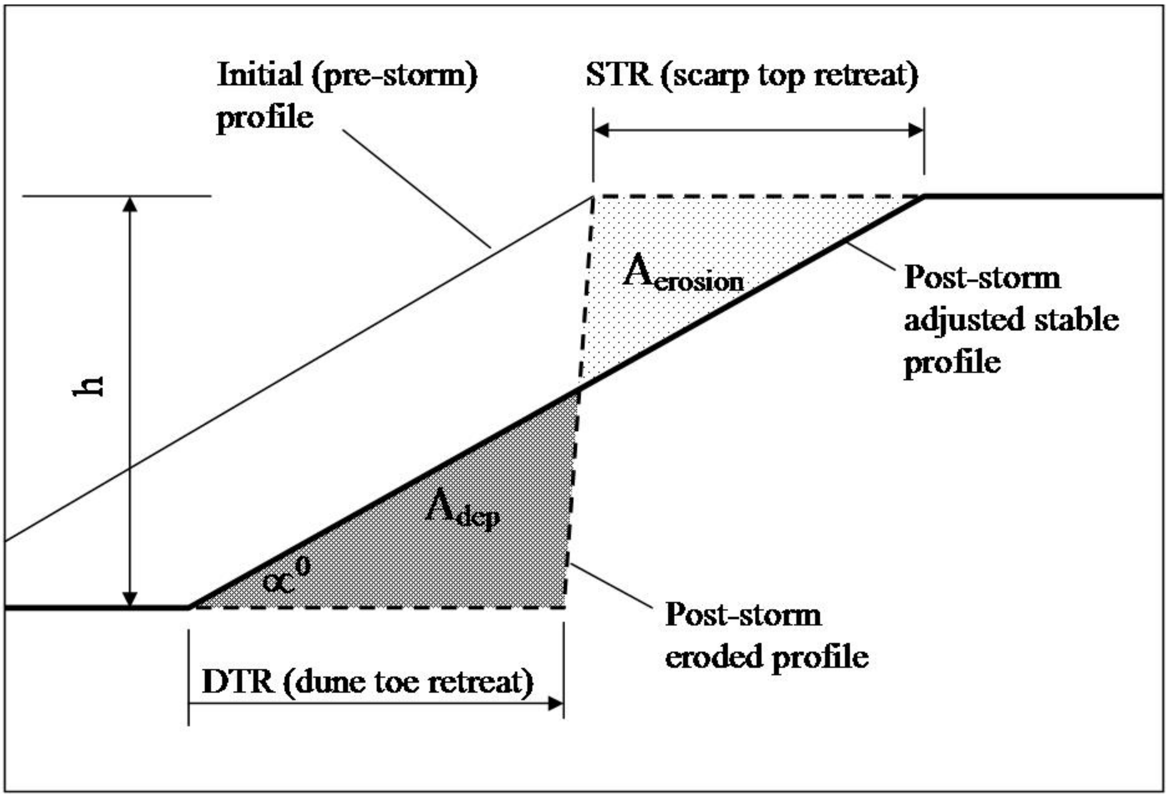


Figure 1 Diagram illustrating the terms used in developing the slope stability model in Section 2 above.