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Regional Assessment of Areas Susceptible to Coastal Erosion

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Regional Assessment of Areas Susceptible to Coastal Erosion

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1 Executive Summary

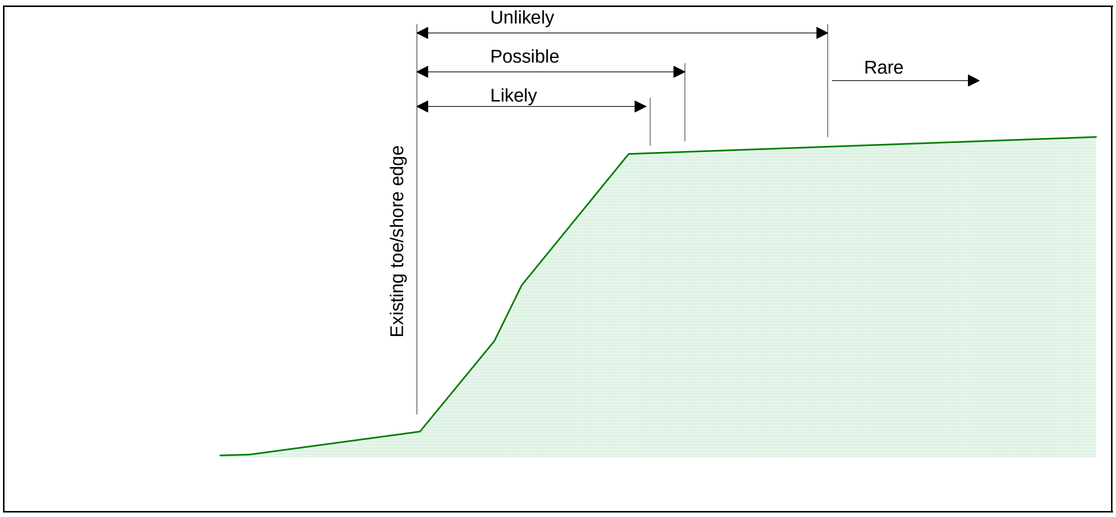
This report provides a regional overview of the area susceptible to coastal erosion in the Auckland Region.

The purpose of the assessment is to provide information on the current and potential scale and extent of the area susceptible to coastal erosion within the region. The area identified as being susceptible to coastal erosion is defined as that land along the coastal margin that may be influenced by coastal erosion over a 100 year planning horizon. The areas identified were based on nationally and internationally accepted methods and used existing data supplemented by field investigations. Almost the entire length of the Auckland coastline is susceptible to coastal erosion, although the extent and level of risk vary.

The identification of the area susceptible to coastal erosion includes an assessment of the risk posed meaning that the identified areas are not areas of certain impact during the planning period, rather the area likely to be impacted. The concept of 'risk' involves considering the physical characteristics of natural events, and the probability of occurrence of the hazard. The identified areas susceptible to coastal erosion indicate the degree of risk using the qualifiers of likely, possible, unlikely and rare. Whereby:

- likely: probably will happen during the 100 year time frame
- possible: might occur during the 100 year time frame
- unlikely: unlikely to occur but possible during the 100 year time frame
- rare: highly unlikely, but conceivable.

Figure 1.1
Likelihood of land area to be susceptible to erosion over the next 100 years



The area susceptible to coastal erosion has been identified as a series of tabulated widths around the region's coastline. The widths are to be applied either from the present position of the cliff toe, or from the vegetation line/upper swash line of beach shores.

Areas susceptible to beach erosion included consideration of the following:

- storm and cyclical coastline change
- long term trends of coastline position
- potential sea level rise/climate change effects
- uncertainty factors.

Tabulated width distances of areas susceptible to coastal erosion for beach locations are included in Table 6.4.

Erosion processes of cliff coastlines included consideration of the following:

- geological structure
- cliff geometry
- long term trends of coastline position
- potential sea level rise/climate change
- uncertainty factors.

Tabulated width distances for areas susceptible to coastal erosion for cliff locations are included in Table 7.8.

The following assumptions and limitations apply to the study:

- the report provides a regional assessment, with a scale of between 500 m to 2km. It does not provide accuracy to house lot scale.
- knowledge on the forcing agents of coastal erosion and their interaction is fragmented and empirical. In addition coastal erosion results from a combination of various factors, both natural and human induced, which have different time and space patterns and have different nature. Uncertainties remain about the interactions of the forcing agents as well as on the significance of non-local causes of erosion requiring a precautionary approach to be implemented (as identified by the NZCPS).
- the study has been carried out using a desktop study approach using simple but robust methodologies, existing information and expert judgment and is limited to assessing the areas susceptible to coastal erosion effects over the next 100 years. The resultant 'areas susceptible to coastal erosion' do not take into account any buffer that may be required for other purposes, such as public access or conservation.
- a timeframe of 100 years has been adopted. All erosion processes can continue past this period, possibly increasing due to climate change effects. Therefore, the 'areas susceptible to coastal erosion' provided do not provide an absolute

landward limit to erosion and should be reviewed and updated periodically (every 10 years, subject to more detailed information being available).

- The assessment does not take into account possible effects of coastal structures unless of regional scale and under public ownership.
- Site specific assessments that consider the key processes affecting erosion supersede the areas identified in this regional assessment.

It is recognised that there are a number of uncertainties in the estimation of the area susceptible to coastal erosion, such as the short term erosion associated with decadal coastline fluctuations, long term erosion trends associated with present coastal processes and the potential impact of sea level rise on coastal erosion. Furthermore, the degree of uncertainty will vary from one site to another. The assessment provided could be refined using more detailed data, subject to the same consideration of erosion mechanisms outlined. A schedule of site-specific refinements to further refine this assessment is included in Section 6.

The 100 year planning period is used to highlight potential areas of impact from coastal erosion over that time frame. A 100 year planning period is commonly used in such assessment as it accommodates the useful life of most buildings and structures, and allows for the effects of relatively infrequent, but severe, erosive storm events. It is also the longest period for which useful predictions are available for potential future changes which could impact on coastal erosion, such as a rise in sea level.

This report also provides a background of the current legislative framework under which the ARC derives its functions and responsibilities, in terms of managing and controlling the natural hazards within the Auckland region.

2 Introduction

2.1 Background

The Auckland Region has over 2,400 km of coastline and development has tended to concentrate along the coast. Much of the urban part of the region is sited on a narrow isthmus between two large harbours. Residential developments and community assets have been undertaken close to the edge of sedimentary cliffs and on dynamic beach systems. As a result there are significant parts of the region's coastline that are exposed to coastal hazards (ARC, 2000). Due to the expected ongoing growth in the Auckland region and the desire of people to be close to the sea, ongoing development adjacent to the coast is expected to continue.

Within the region the coastline has a variety of landforms and sediment types, a variety of orientations and is subject to differing physical processes (rainfall, winds, waves, water levels and currents). All coastal landforms within the region, such as beaches, dunes, cliffs and estuaries, can be prone to erosion. The extent of the area susceptible to coastal erosion is dependent upon the interaction between the combinations of the aforementioned factors.

This report provides a regional overview of the area susceptible to coastal erosion. The area identified as being susceptible to coastal erosion is defined as that land along the coastal margin that may be influenced by coastal erosion over a 100 year planning period. The identified areas susceptible to coastal erosion are not areas of certain impact, rather the area likely to be impacted.

The area susceptible to coastal erosion is identified in a series of widths around the region's coastline. The widths are to be applied either from the present position of the cliff toe, or from the vegetation line/upper swash line of beach shores. At the present point in time the areas susceptible to coastal erosion cannot be accurately mapped using LINZ topographic data as a base due to inaccuracies in the LINZ data. However, they could be mapped using LIDAR survey combined with recent high resolution ortho-rectified aerial photographs as this data becomes available.

The area susceptible to coastal erosion in the Auckland region has previously been identified in the Auckland Regional Growth Strategy - Natural and Physical Constraints. That information however is incomplete, such that regional and local decision makers and the general public are not fully aware of the scale and extent of the coastal erosion hazard they face. This report provides an updated regional overview of the area susceptible to coastal erosion in the Auckland Region. The report summarises existing scientific information on the physical nature of the Auckland's coastal margin, and the susceptibility of that narrow strip of land to coastal erosion. The legislative framework under which ARC derives its functions and responsibilities, in terms of managing and controlling the natural hazards, is summarised.

2.2 Purpose

Coastal processes are part of the natural character of the dynamic coastal environment. Natural hazards[1] arise from the interaction of such processes with human use, property, or infrastructure, and can adversely affect the economy and the health, wellbeing and safety of people and communities. They may also adversely affect vegetation and habitat; public access to and along the coastal marine area; visual character; amenity values; recreation; and aspects of coastal heritage, such as historic buildings and structures. Sites and areas of significance to Tangata Whenua, such as waahi tapu, urupä, middens, and other taonga, may also be at risk from natural coastal hazards.

Success in avoiding, remedying and/or mitigating coastal hazards requires an understanding of the areas susceptible to those hazards, an understanding of the frequency and magnitude of those hazards, and an understanding of the effects of undertaking activities within areas susceptible to coastal hazards.

The purpose of this assessment is to identify the current and potential scale and extent of the area susceptible to coastal erosion within the region, to facilitate long-term cost-effective management of natural and physical resources along the Auckland coastline.

2.3 Approach

The extent of the area susceptible to coastal erosion in the Auckland Region has been determined based upon a review of existing publications available both in the public domain and from Tonkin & Taylor Ltd (T&T) database, supplemented by field inspections where required. This approach is similar to that carried out both by other regional councils within New Zealand and internationally. Examples of this regional approach in New Zealand can be found in the Bay of Plenty and the Hawke Bay – Waikato, Canterbury, & Northland. Information in the public domain used in this study included university theses, journal and conference papers, consultant and council reports and assessments. Within T&T information was available in the form of geotechnical reports, coastal hazard assessments, environmental reports, and coastal structure designs and assessments. Relevant information varied in detail and nature.

Each source was classed according to region and information summarised into an annotated bibliography. Relevant information could then be tabulated and applied to appropriate sections of coastline. Data from external sources was compared to T&T reports relating to the same section of coastline, thus providing verification of the compatibility of the two sources.

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[1] Natural hazard means any atmospheric or earth or water related occurrence (including earthquake, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire or flooding) the action of which adversely affects or may adversely affect human life, property or other aspects of the environment'. RMA, Section 2.

Appendix C includes a summary of T&T Jobs reviewed. Appendix D provides a summary of shoreline characterization based on this information and key external data sources.

A field inspection of the entire region's coastline was carried out by helicopter. A video of the field inspection was taken and used to assist in the assessment. A copy of the DVD is included in Appendix I.

In certain areas, existing data proved too scarce to be able to adequately map coastal hazards. Site-specific field inspections were necessary in those areas. Field inspections were also carried out in areas of adequate data to provide comparisons between our data and existing data. This information is included in Appendix E and J and summarised in Appendix F, G and H.

2.3.1 Expert Opinion

The judgement and experience of appropriately qualified and experienced personnel is essential when providing coastal hazard assessments, due to the lack of detailed information and the limited understanding of existing processes and the likely changes that climate change may cause.

Expert opinion from T&T's coastal and geological team members was used to extend and apply the existing information to the remainder of the region. Team members included Mr. Nick Rogers (Engineering Geologist), Mr. Bernard Hegan (Engineering Geologist) and Mr. Richard Reinen-Hamill (Coastal Engineer).

Dr. Vicki Moon of the University of Waikato has reviewed the methodology and outcomes of the study. A copy of the peer review comments is included in Appendix B.

2.4 Assumptions and Limitations

The prediction of areas susceptible to erosion, including the provision for future coastal evolution is not straightforward. There is no standard universally agreed methodology, and even the kinds of data required to make such predictions are the subject of much scientific debate. A number of predictive approaches have been used (ARC, 2000; National Research Council, 1990), including:

- extrapolation of historical data (e.g., coastal erosion rates)
- numerical modelling
- application of a simple geometric model (e.g., the Bruun Rule)
- application of a sediment dynamics/budget model
- Monte Carlo (probabilistic) simulation based on parameterized physical forcing variables.

Each of these approaches has its shortcomings or can be shown to be invalid for certain applications (ARC, 2000; National Research Council, 1990). However, the relative vulnerability of different coastal environments to coastal processes and future sea-level rise may be quantified at a regional scale using basic information on coastal geomorphology, rate of sea-level rise, past shoreline evolution, and other factors. The approach employed here combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and yields a relative measure of the system's natural vulnerability to coastal erosion and the effects of sea-level rise.

The following assumptions and limitations apply to the present study:

- the report provides a regional assessment, with a scale of between 500 m to 2km. It does not provide accuracy to house lot scale.
- knowledge on the forcing agents of coastal erosion and their interaction is fragmented and empirical. In addition coastal erosion results from a combination of various factors, both natural and human induced, which have different time and space patterns and have different nature. Uncertainties remain about the interactions of the forcing agents as well as on the significance of non-local causes of erosion requiring a precautionary approach to be implemented.
- The study has been carried out using a desktop study approach using simple but robust methodology, existing information and expert judgment and is limited to assessing the areas susceptible to erosion. The resultant zone widths do not take into account any buffer that may be required for other purposes, such as public access or conservation.
- A timeframe of 100 years has been adopted. All erosion processes will continue past this period, possibly increasing due to climate change effects. Therefore, the erosion widths provided do not provide an absolute landward limit to the areas susceptible to erosion and should be updated periodically.
- The assessment does not take into account possible effects of coastal structures unless of regional scale and under public ownership.

2.5 Report Layout

This report summarises all of the information used to derive the landward extent of the coastal areas susceptible to erosion. It is presented in two volumes, the first volume (this report) comprising the main body of the text and the second volume (Volume II) providing additional details of the investigation and assessment.

Section 2 describes the planning context.

Section 3 includes a description of the background information that provided data for the assessment.

Section 4 describes the process of delineating the coastline into coastal cells comprising beaches, and cliffs.

Section 5 details the method and results of the areas susceptible to erosion on beach coasts, taking into account climate change, with the outcome a series of widths with reducing likelihood of erosion the further landward from the sea that the area susceptible to erosion extends.

Section 6 describes the method and results of the areas susceptible to erosion on cliff coasts, including climate change effects. The outcome of this section is also a series of widths with reducing likelihood of erosion the further landward from sea that the area susceptible to erosion extends.

Section 7 outlines our suggested approach for site-specific assessments.

The appendices include the more detailed technical information and tables used for deriving the identified areas. A glossary of terms, based on the USGS coastal glossary, is included in Appendix K (Volume III).

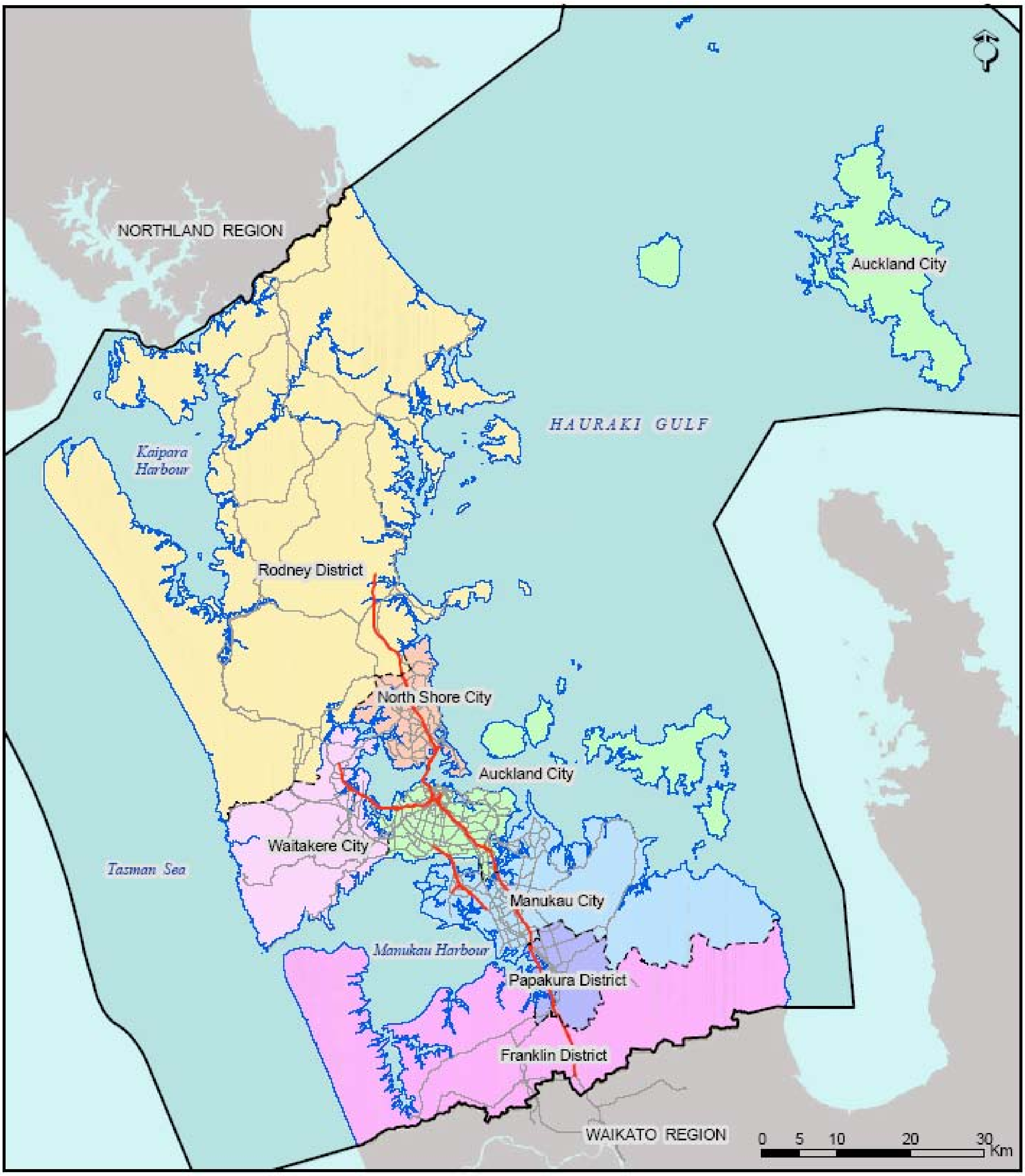
2.6 Intended Use of Results

The resulting output is a series of widths representing areas susceptible to erosion around the region's coastline. It is intended that these widths are to be applied either from the present position of the cliff toe, or from the vegetation line/upper swash line of beach shores. The origin of the areas identified as being susceptible to erosion is required to be established by physical measurement. This could be done by LIDAR survey or obtained from the most recent high-resolution ortho-rectified aerial photographs. The areas susceptible to erosion cannot be accurately applied using the LINZ topographic data as a base.

These identified areas of susceptibility provide a tool to assist in understanding the scale and extent of potential hazards to enable development of appropriate management responses.

Alternatively, revised widths may be derived using more detailed baseline data subject to the same consideration of erosion mechanisms outlined in this report. A schedule of site-specific refinements considered necessary to further refine this assessment is included in Section 7.

Figure 2.1
Regional limits of study



3 Planning Context

3.1 Resource Management Act

The management of natural hazards is undertaken pursuant to the provisions of the Resource Management Act. The avoidance or mitigation of coastal hazards must be undertaken in a manner that achieves the purpose of the Act.

Section 5 of the RMA states:

1) The purpose of this Act is to promote the sustainable management of natural and physical resources.

2) In this Act, 'sustainable management' means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing and for their health and safety while:

    a) Sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations;

    b) Safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and

    c) Avoiding, remedying, or mitigating any adverse effects of activities on the environment.

The Resource Management Act sets out the functions for regional and city/district councils.

Section 30 of the RMA provides:

Functions of regional councils under this Act-

1) Every regional council shall have the following functions for the purpose of giving effect to this Act in its regime

    a) The establishment, implementation, and review of objectives, policies and methods to achieve integrated management of the natural and physical resources of the region:

    b) The preparation of objectives and policies in relation to any actual or potential effects of the use, development, or protection of land which are of regional significance:

    c) The control of the use of land for the purpose of-

        iv) The avoidance or mitigation of natural hazards:

d) In respect of any coastal marine area in the region, the control (in conjunction with the Minister of Conservation) of - …

v) Any actual or potential effects of the use, development, or protection of land, including the avoidance or mitigation of natural hazards…

Section 31 of the Act sets out the functions of territorial authorities under the Act, and includes:

1) b) the control of any actual or potential effects of the use, development, or protection of land, including for the purpose of the avoidance or mitigation of *natural hazards* …

3.1.1 New Zealand Coastal Policy Statement

The New Zealand Coastal Policy Statement (NZCPS, 1994) is a statutory document prepared by the Minister of Conservation to guide regional and territorial councils in the day-to-day management of the coastal environment.

The NZCPS identifies that the coastal environment is particularly susceptible to the effects of natural hazards. It also identifies that the ability to manage activities in the coastal environment in a sustainable manner is hindered by the lack of understanding about coastal processes and the effects of activities. Therefore, an approach that is precautionary but responsive to increased knowledge is required for coastal management.

The NZCPS contains six specific policies relating to the management of the impact of coastal hazards and potential climate change effects:

3.4.1: Local authority policy statements and plans should identify areas in the coastal environment where natural hazards exist.

3.4.2: Policy statements and plans should recognise the possibility of a rise in sea level, and should identify areas which would as a consequence be subject to erosion and inundation. Natural systems which are a natural defence to erosion and /or inundation should be identified and their integrity protected.

3.4.3: The ability of natural features such as beaches, sand dunes, mangroves, wetlands and barrier islands to protect subdivision, use, or development should be recognised and maintained, and, where appropriate, steps should be required to enhance that ability.

3.4.4: In relation to future subdivision, use and development, policy statements and plans should recognize that some natural features may migrate inland as the result of dynamic coastal processes (including sea level rise).

3.4.5: New subdivision, use and development should be so located and designed that the need for hazard protection works is avoided.

3.4.6: Where existing subdivision, use or development is threatened by a coastal hazard, coastal protection works should be permitted only where they are the best practicable option for the future. The abandonment or relocation of existing structures should be considered among the options. Where coastal protection works are the best practicable option, they should be located and designed so as to avoid adverse environmental effects to the extent practicable.

3.1.2 Auckland Regional Policy Statement

The Auckland Regional Policy Statement (ARPS) sets out the broad resource management issues, objectives and policies for the Auckland Region to achieve the integrated management of its natural and physical resources. It functions as an umbrella policy document for environmental planning and policy development within the Auckland region. The ARPS[2] contains several objectives and policies pertaining to coastal hazard management, including:

Policies:

11.4.1.3: Before provision is made enabling significant development or redevelopment of land, including intensification of land use, any natural hazards, particularly flooding, land instability and coastal hazards, and measures to avoid or mitigate their adverse effects shall be identified.

11.4.1.5: Where development or use exists within areas susceptible to natural hazards, construction of mitigation works shall be permitted only where people, property, infrastructure and the environment are subject to unacceptable risk from hazards, the works are the best practicable option, and any adverse effects on the environment are avoided, remedied or mitigated. The abandonment or relocation of existing structures and the use of non-structural solutions shall also be considered among the options.

11.4.1.7: Development shall not be permitted in areas subject to erosion/land instability unless it can be demonstrated that the adverse effects can be avoided or mitigated.

11.4.1.8: In the coastal environment, new subdivision, use or development should be located and designed, so that the need for hazard protection measures is avoided.

11.4.1.9: A precautionary approach shall be used in avoiding, remedying, or mitigating the adverse effects on development, of earthquake, volcanic activity, sea level rise and global climate change.

Methods:

11.4.2.1: The ARC will gather information and undertake or commission research at a regional scale on natural hazards and their risks and impacts. This

[2] Incorporating Proposed Regional Policy Statement change 10 – notified 26 September 2005.

information shall be made available to Territorial Authorities and the general public through a natural hazards database. This will include volcanic, tsunami, earthquake, cyclone, and coastal hazards including the effects of sea level rise and climate change.

3.1.3 Auckland Regional Plan: Coastal

The Auckland Regional Plan: Coastal (ARPC) provides the framework to promote the integrated and sustainable management of Auckland's coastal environment. The ARPC seeks to control the use of land in the coastal environment to ensure the adverse effects of natural coastal hazards are avoided or mitigated. The ARPC contains several provisions pertaining to coastal hazard management, including:

Policies:

21.4.1 New subdivision should be located and designed to avoid interference with natural coastal processes, including those natural coastal features, that have a tendency to change or migrate inland as a result of climate and sea-level changes, so that the need for coastal protection measures is avoided.

21.4.2 Where existing subdivision, use, and development in the coastal environment is adversely affected by coastal hazards, including mean sea level rise, further subdivision, use, and development that exacerbates the coastal hazard, or creates a new coastal hazard, should be avoided.

21.4.3 Natural features such as beaches (including sand dunes and longshore bars), mangroves, and wetlands, which may buffer subdivision, use, and development from coastal hazards, shall be protected.

21.4.8 In assessing the effect that a rise in mean sea level may have on subdivision, use, development and protection of the coastal environment, the best available estimate of mean sea level rise for the locality in question shall be used.

Other Methods:

21.6.1 The ARC will, in consultation with territorial authorities:

a) develop a regional methodology for the identification of natural coastal hazards, including areas which could be subject to erosion or inundation as a result of mean sea level rise; and

b) maintain a database of identified natural hazard areas; and

c) undertake research on the risks and impacts of natural coastal hazards, particularly those that are regionally significant; and

d) undertake research on methods to avoid, remedy, or mitigate natural coastal hazards.

The ARC will make this information available to territorial authorities and the general public.

3.2 Hauraki Gulf Marine Park Act

The Hauraki Gulf Marine Park Act 2000 requires the inter-relationship between the Hauraki Gulf, its islands and catchments and the ability of that inter-relationship to sustain the life supporting capacity of the environment of the Hauraki Gulf and its islands to be matters of national significance.

Section 32 of the Act establishes the purpose of the Park:

a) To recognise and protect in perpetuity the international and national significance of the land and the natural and historic resources within the Park:

b) To protect in perpetuity and for the benefit, use, and enjoyment of the people and communities of the Gulf and New Zealand, the natural and historic resources of the Park including scenery, ecological systems, or natural features that are so beautiful, unique , or scientifically important to be of national significance, for their intrinsic worth:

c) To recognise and have particular regard to the historic, traditional, cultural, and spiritual relationship of tangata whenua with the Hauraki Gulf, its islands and coastal areas, and the natural and historic resources of the Park;

d) To sustain the life supporting capacity of the soil, air, water, and ecosystems of the Gulf in the Park.

3.3 Building Act

The purpose of the Building Act 2004 is to provide controls on building construction and use, and to ensure that buildings are safe, through a Building Code. The Building Code is principally concerned with performance-based criteria relating to methods of construction and building safety. The Building act addresses the question of how a building may be constructed, whereas the RMA addresses whether a building may be constructed on a site.

3.4 Civil Defence Emergency Management Act

The Civil Defence Emergency Management Act 2002 requires regional and city/district councils to plan for hazards across the key areas of reduction, readiness, response or recovery.

4 Background Information

This section summarises the background information used in this study. A range of information sources were used to provide the necessary information to complete this report. An overview of the physical settings considered is included in Appendix H. The following sections summarise the key information sources used.

4.1 Previous Reports

Both ARC's and T&T's data base were searched for external reports, theses and data that would provide useful information on coastline trends and setting. The external reports viewed as part of the background appreciation are listed in the Reference section at the end of this report. External data is summarised in Appendix D.

Tonkin & Taylor projects containing relevant information relating to cliff sites around the Auckland Region were collated into a 'T&T cliff-jobs' spreadsheet (Appendix C). This summary table tabulates the cliff geometry, including geology, slope, erosion rate and depth and slope of weathered material overlying the more competent rock.

4.2 Field Inspections

4.2.1 Heli-inspection

A heli-survey of the majority of Auckland's open coast coastline was undertaken to provide information on cliff surface condition, to assist in the spatial delineation of coastline type and to identify areas currently experiencing high rates of erosion.

Heliflight's AS 350 Squirrel 6-seater helicopter was used for the survey and chartered from Ardmore Airfield. The survey was co-ordinated by a Tonkin & Taylor senior geologist and project peer reviewer. A video record of the entire coastline was also taken for future reference. Notes on geology, cliff surface condition, angles of repose and areas of high or obvious erosion were made during the flight and post-flight from the recorded video by geologists. A copy of the video taken is included in Appendix I.

The survey began on the western Firth of Thames coastline at Kaiaua and traced northwest past Kawakawa and Beachlands before reaching Eastern Auckland. A circuit around Auckland Harbour was followed by a trip up the North Shore and on to Whangaparoa.

Stage two of our three-stage flight comprised Orewa through to Mangawhai including the Mahurangi Harbour and Kawau Bay. We cut across the country at Mangawhai and tracked down Oruawharo River into the Kaipara.

After circuiting the Kaipara, stage three of our survey included Auckland's West Coast and the Manukau. The survey was concluded with a flight down the Awhitu Peninsula to Karioitahi.

4.2.2 Individual site inspection

Over the course of the study, a number of individual coastal sites were visited. Sites inspected included locations where there was limited existing data or where it was considered important to verify that the existing data adequately represented a section of coastline. The sites visited included 20 beaches and 42 cliff sites, scattered fairly evenly throughout the Auckland Region (refer Figure 4.1). Data from these inspections are included in Appendix E.

The inspection differed slightly for beach and cliff sites, but typically comprised a brief walkover examination, photographs, slope measurements and sediment sampling.

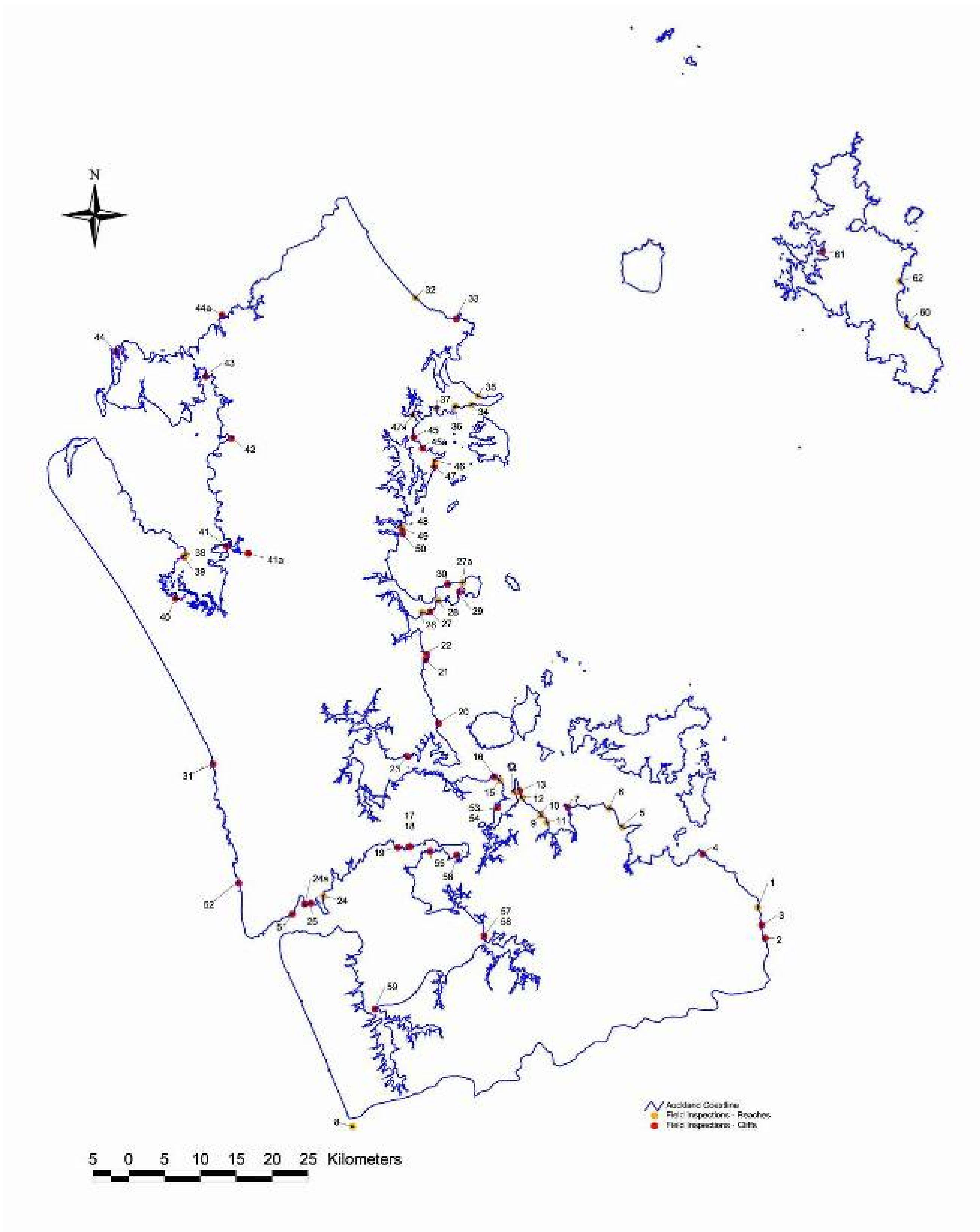
The initial walkover examination allowed for evaluation of existing site conditions, trends and processes. Existing site conditions included the cliff, shore platform or beach topography, the geological makeup and condition of cliffs, sediment type and size of beaches. The assessment of trends and processes were based on signs of long-term or recent coastline movement such as erosion scarps, displaced vegetation or recently prograded, unvegetated areas. Photographs were taken throughout this walkover as an accurate record for future reference. Based on the spatial differences in topography noted during the walkover, a representative platform and cliff or beach and dune transect was chosen for profile. Water level at the time of measurement was taken as datum and the profile shot in increments corresponding to changes in grade or material using a Geosystems MDL LaserAce rangefinder. This instrument has resolution of 1 cm and typical accuracy of ±10 cm.

Cliff heights ranged from less than 1m to over 170m at average slopes of 20 to 70 degrees. Dune heights and slopes tended to be more subdued with heights less than 12m and slopes generally in the 2:1 to 3:1 range, although this varied significantly depending on material, vegetation cover and current accretion or erosion trends.

Sediment samples were taken at beach sites from within the inter-tidal zone, at approximately mean sea level. While this level was only approximate, it gave reasonable consistency to sampling locations. These samples were sieved to 63 microns and their particle size distributions compared on a grading curve. Results of this sediment analysis are summarised in Appendix F.

Figure 4.1

Location of local site inspections



5 Coastline Delineation

This section describes the approach used in defining the various sections of coastline around the Auckland region. The initial consideration was to determine the appropriate baseline for the coastline for the purposes of mapping areas susceptible to coastal erosion.

The Auckland coastline was delineated into two key components; either beach or cliff coastline. Beaches dominate the coastline on Auckland's West Coast, with intermittent stretches of cliff around the Waitakere coastline. Auckland's East Coast and the Hauraki Gulf Islands contain both beaches and hard cliffed coastline dominating the higher energy coastlines and soft cliff-coasts being limited to regions of low wave energy and embayments. Estuaries and harbours are predominantly soft cliff with smaller regions of hard cliffs and beaches.

Prerequisites for each unit were that they were greater than 0.5 km in length, were composed of at least 70% of the predominant geological type and that the majority of the unit had a similar degree of exposure. This initial breakdown of the Auckland coastline was a critical step as these divisions form the basis for the final areas susceptible to erosion zone sections.

5.1 Coastline

Information on the coastline is important both to locate an origin of the area susceptible to erosion as well as to enable the coastline to be broken down into various sub-sections for analysis.

Numerous versions of digitized coastlines were evaluated for this study. Historically, these lines have been digitised by either LINZ or private consultants based on aerial photographs, cadastral surveys, and property boundaries with varying levels of success.

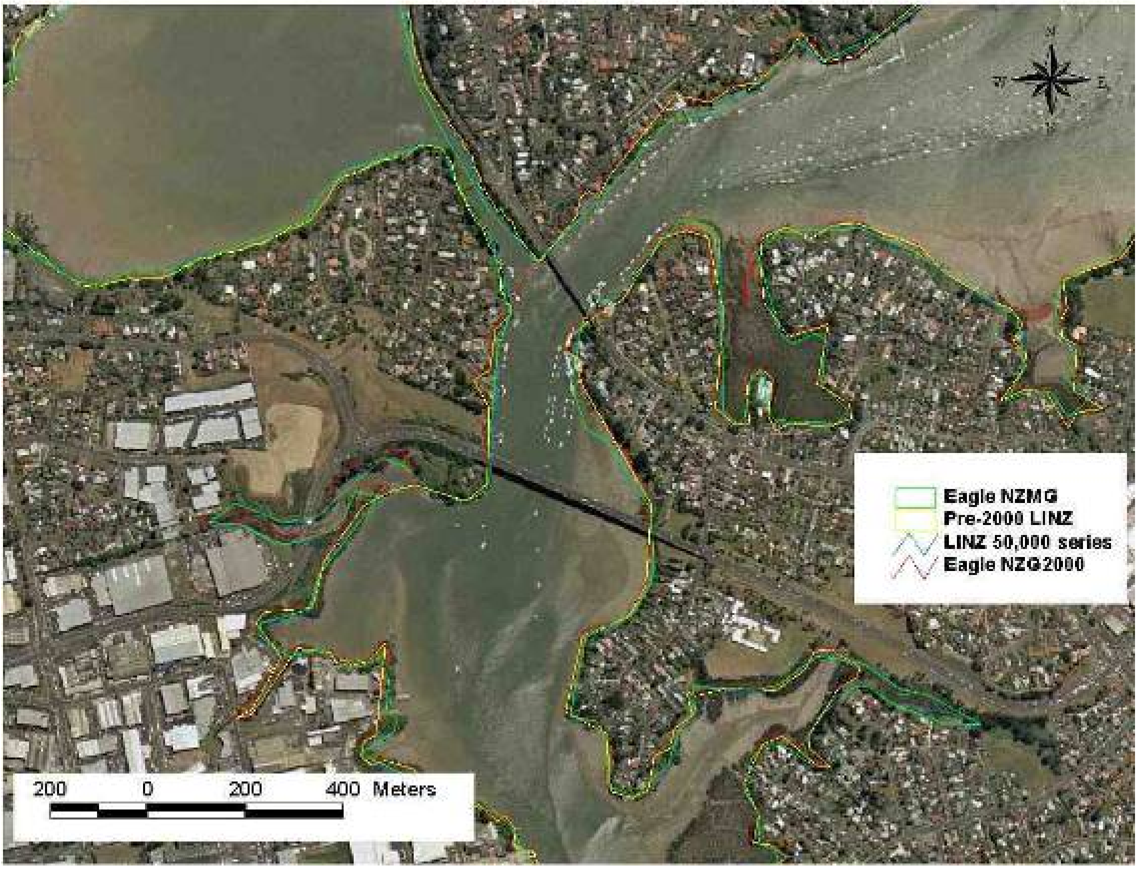
Our inspection showed that delineated coastlines vary in accuracy from area to area as aerial photograph quality and precision changes. LINZ target accuracy for the digitization was 20 to 30 m. In some cases accuracy was significantly better than this. However, in other cases error appeared to be significantly larger. The lack of accurate, region wide coastline data resulted in the decision only to provide an indication of the width of the areas susceptible to coastal erosion, rather than mapping the extent of the area.

Coastlines available for the purposes of this study included a range of LINZ delineated lines. These lines varied in age depending on the series of aerial photographs used for digitization. Earliest coastlines are based on photographs taken over 20 years ago and the most recent from photographs in 2000. Other coastlines available include versions supplied by Eagle Technology. These include an aerial photograph based line and a cadastral boundary based line.

Certain coastlines show a very high level of detail when overlaid on aerial photographs only to be found missing significant areas of coast such as inlets or estuaries. While others, which include all required coastline, lack sufficient detail to be of use. An example of this can be seen in Figure 5.1. This photograph shows substantial differences between the various digitised coastlines and the underlying aerial photograph, with neither coastline accurately representing the aerial photograph coastline. Applying a width from a location which does not accurately identify the actual coastline could result either in no area of coastal erosion being shown on land (when the digitised coastline is seaward of the actual) or a greater extent of hazard area in those locations where the digitised coastline is more landward.

Figure 5.1

Aerial photograph with available digital coastlines overlain showing large variability in the defined location of the coast in certain areas



For the purposes of this study, coastline boundaries are identical to those used in the Proposed Auckland Regional Plan: Coastal which uses the Eagle Technology aerial-photography-based coastline for the LINZ 50,000 series coastline (the blue line in Figure 4.1). Although this coastline clearly showed the effects of digitization, all areas of the coast were covered and it's consistency with the majority of aerial photographs was considered acceptable.

Improvements in the accurate fixing of the coastline will assist in locating the origin of the coastal areas susceptible to erosion zone. The seaward part of the area sensitive to erosion should be established either by physical measurement, such as by LIDAR survey, or interpreted from the most recent high-resolution ortho-rectified aerial photographs.

5.2 Beaches

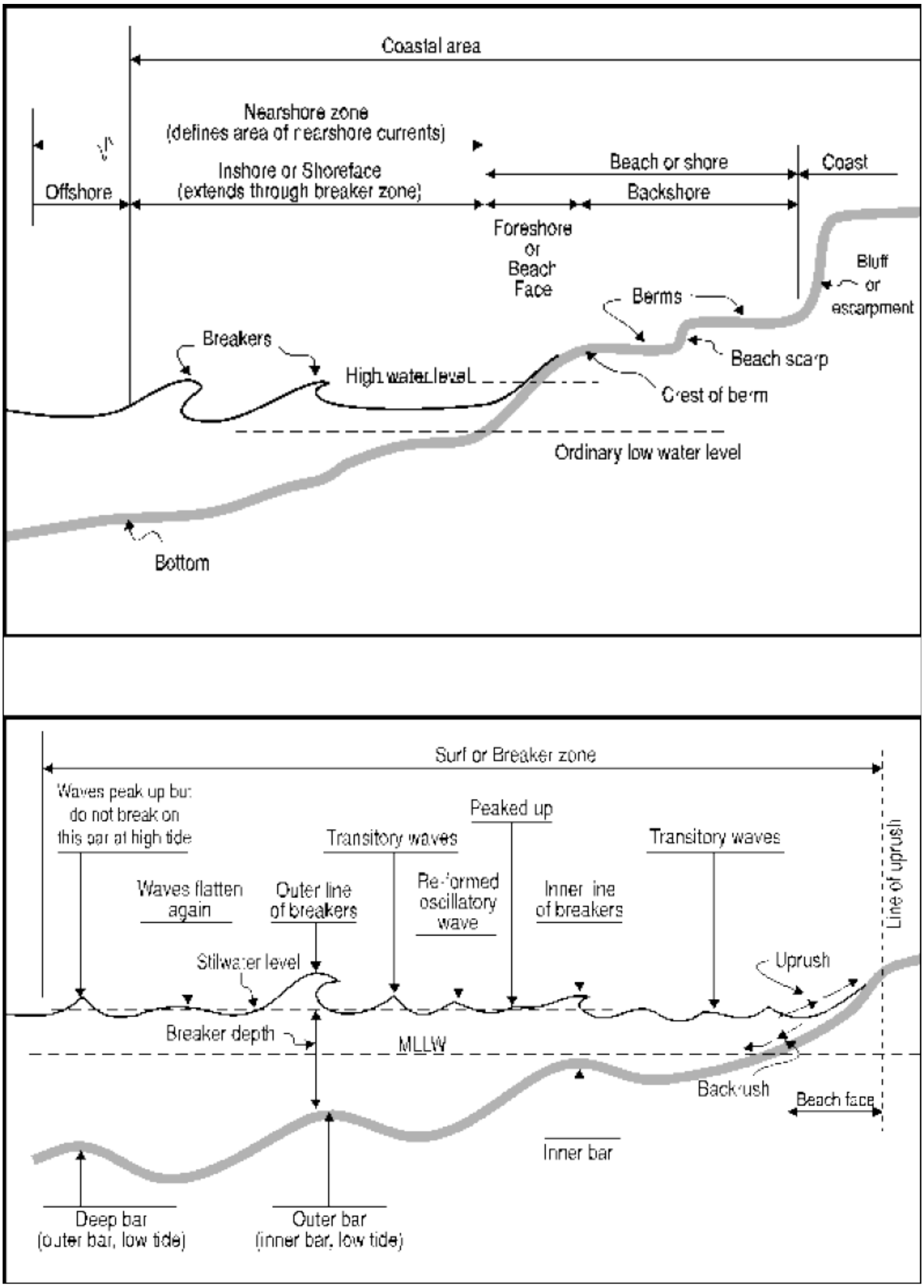
A beach is a deposit of sand or gravel situated on the interface between dry land and the sea (or other large expanse of water) and actively "worked" by present-day hydrodynamic processes (i.e. waves, tides and currents) and sometimes by winds (refer Figure 5.2). It extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation.

Beach type was classified into the following forms:

- Barrier spits *(Photograph 1)*
    - These beaches separate harbours, estuaries and river inlets from higher energy environments. In general, they are the most dynamic of beach forms and therefore the most unpredictable.
- Pocket beaches *(Photograph 2)*
    - Restricted at either end by headlands. These beaches are semi-closed systems which experience limited, if any, sediment exchange with adjacent coastlines.
- Harbour beaches *(Photograph 3)*
    - These beaches comprise locally derived sediments, typically formed over older sediments or rock. They are generally the result of local cliff or bank erosion and/or the accumulation of shell material.
- Open coast beaches *(Photograph 4)*
    - These beaches are generally open to the sea or ocean, without shelter from the seas forces. They are often high-energy beaches with large cross-shore and long-shore transport potential.

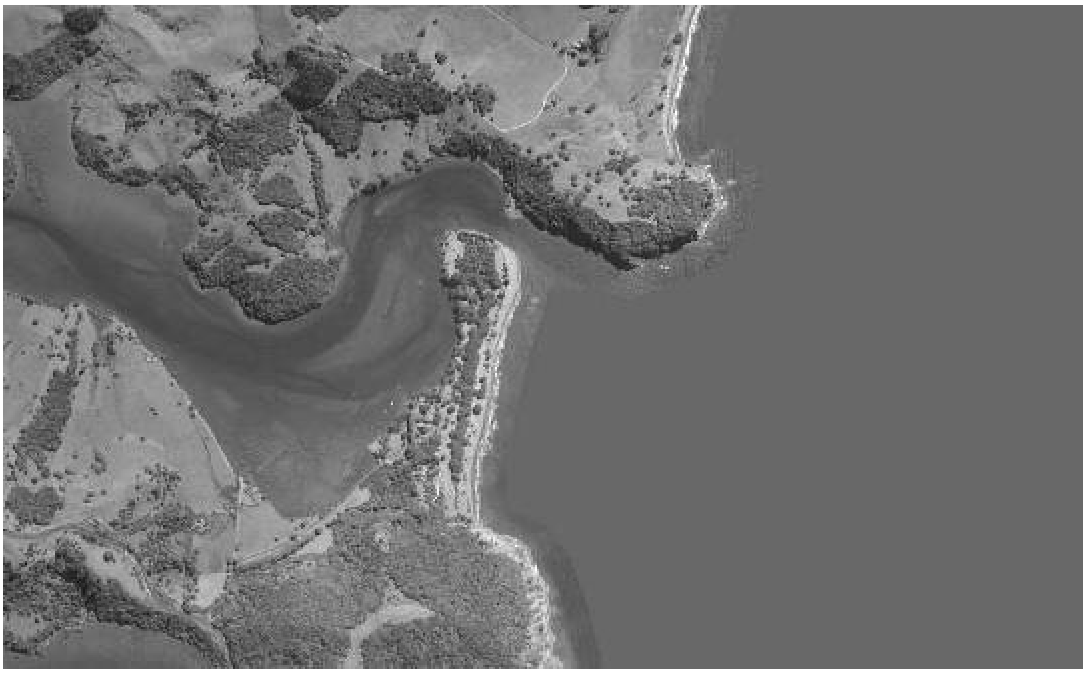
Beach location was established from geological maps where alluvium deposits were indicated. Beach coastlines were defined as having a significant landward component comprising similar characteristics as the beach (i.e. both beach and backshore formed from alluvium and recent deposits), with the ability for development of the backshore on the same sedimentary material. The area susceptible to erosion in areas fronted by a narrow perched beach was made based on the land behind the beach (i.e. either cliff or seawall), as these features control the extent of landward erosion.

Figure 5.2
Definition of beach system (CEM, 2002)



In total 74 beach locations were identified with a total coastline length of 166 km. The location of these beaches is shown in Figure 5.3. Appendix F contains an overview of beach properties for these 74 locations.

Photograph 1
Barrier Beach (Wenderholm)



Photograph 2
Example of pocket beach (Maraetai)

Photograph 3

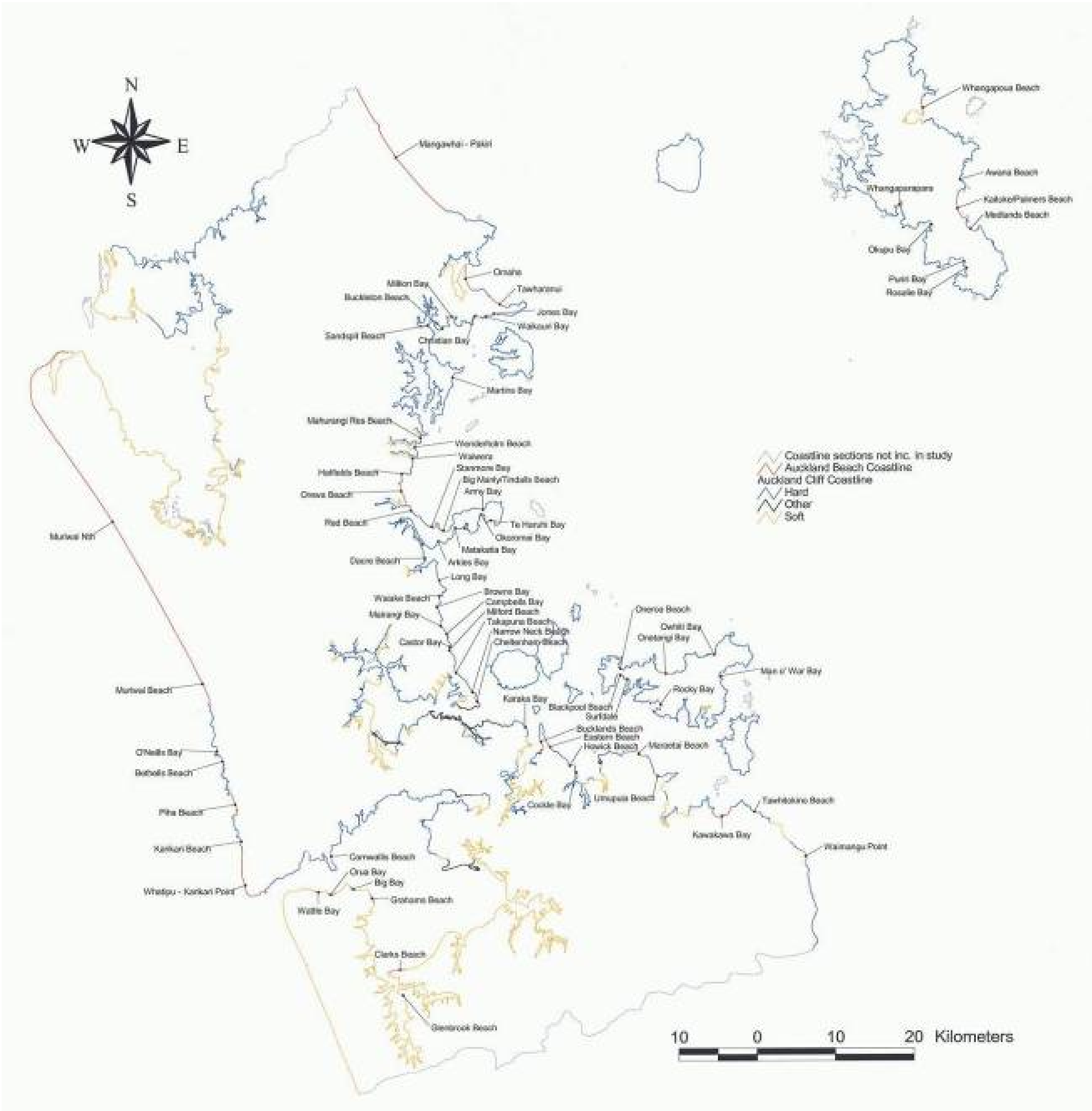
Example of harbour beach (Pt. Chevalier)

Photograph 4

Example of open coast beach (Piha)

Figure 5.3

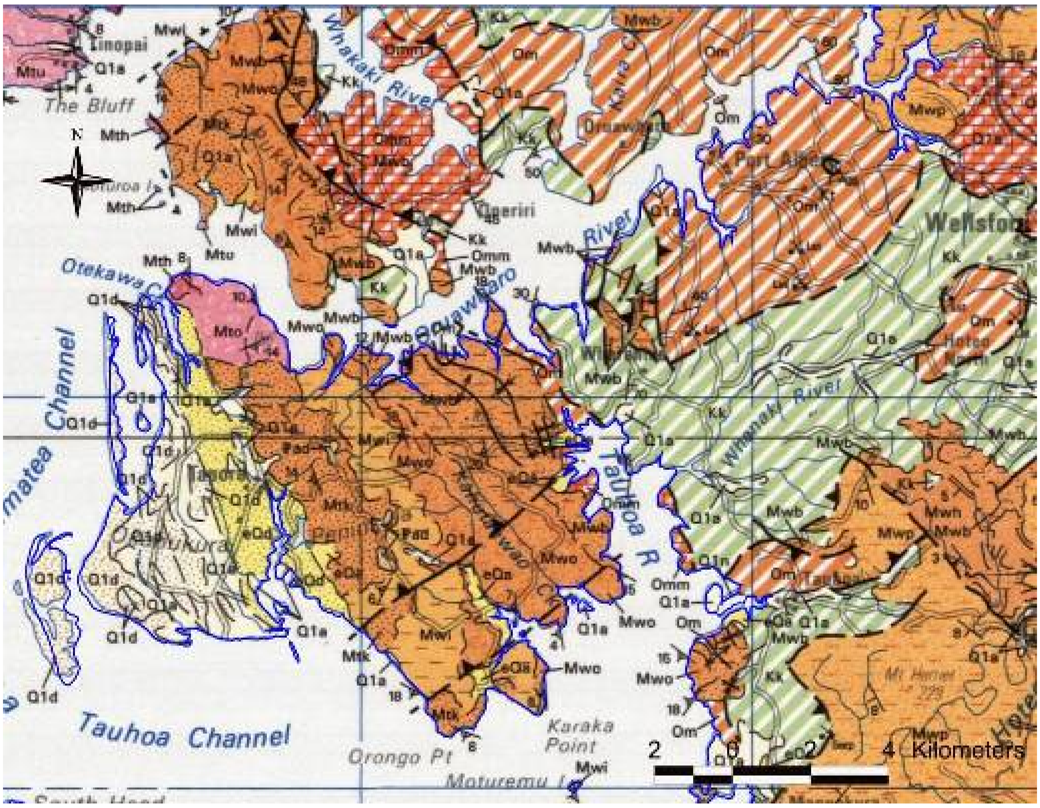
Beach locations



5.3 Cliff coastline

A cliff is typically defined as a significant vertical, or near vertical, rock exposure, although low cliffs (or banks) can be formed of weaker cemented or cohesive materials. Cliffs are categorized as erosion landforms due to the processes of erosion and weathering that produce them. The majority of Auckland's coastline is cliff. The geology of the Auckland cliffed coastline varies considerably, not only in the number of geological types, but also in the close proximity of geologic types over a particular length of coast. For example, on one stretch of coastline, 10 different geological types exist within a distance of about 15km (Figure 5.4). The varied geology can affect generalizing trends of cliff properties over long sections of coastline. The basis of this assessment is to provide a precautionary approach, using the characteristics of the identified lower strength geology within a particular coastal unit.

Figure 5.4
Example of variable cliff geology



5.3.1 Hard cliffs

Geological maps provided the initial identification of cliff areas. However, solely determining the cliff properties from geological units does not take into account weathering and the structure of the rock.

The structure of rock, or rock mass, takes into account the intact rock material, groundwater, as well as joints, faults and other natural planes of weakness that can divide the rock into interlocking blocks of varying sizes and shapes. These discrete blocks may also have been weathered to varying degrees and the contact surfaces between the blocks may vary from clean and fresh to clay covered and slicken-sided.

The Geological Strength Index (GSI) developed by Hoek and Brown (Hoek, 2002) to characterise rock mass description was used to provide a means of differentiating the various hard cliff coastlines, including basement rocks, volcanic rocks, Waitemata Group and displaced rocks. The GSI method assigns a range of values (GSI) for the cliff face based on surface conditions and structure. The GSI provides a system for estimating the rock mass strength for different geological conditions based on visual inspection for rock with GSI values of greater than 25.

Figure 5.5 illustrates the relationship between surface condition, structure and the GSI, with a high number representing good surface conditions and structure and a low number showing poor surface quality and/or structure.

The delineation of the coastline into areas of GSI was carried out with the assistance of the helicopter site inspection and the DVD recording of the site inspection (refer Appendix I for a copy of the DVD). The helicopter site inspection covered the Auckland Isthmus, North Shore, Rodney, Manukau and the West Coast. It did not include the Gulf Islands or all of the coastlines of the Manukau Harbour. In these areas an assessment of GSI was made by comparable lithologies and orientation. More detail on rock properties is included in Appendix H.

Based on the site inspections, spatial differences in the surface condition, cliff face slope and trends in erosion of cliffs of similar lithology were obvious. In particular, greywacke varied from extremely weathered, low strength cliffs in the Firth of Thames to much fresher, more competent material on the more exposed Tawharanui Peninsula. Waitemata group rocks, while more uniform in their weathering, differed markedly in structure. Some were horizontally and uniformly layered, with little apparent defect, other areas intensely deformed and faulted. These intensely deformed and faulted rocks appeared to be of lower heights, flatter slopes and undergoing more recent erosion. This would imply that structure plays an important role in erosion rates and characteristic slopes in these rock types.

There was reasonable variability observed in areas of volcanic rocks. The volcanic basalt is very hard and predominantly unweathered. However, scoria is poorly consolidated and slumping frequently occurs when oversteepened. Tuff and volcanic ash are reasonably soft materials capable of slumping and reasonably prone to erosion. In addition, where there were underlying exposures of less competent rock or sediment, it was these softer more erodible features that controlled the behaviour of the volcanic rock. All Allochthon sedimentary rock weathers rapidly to depths of about 10m. This weathered material is a soft to very soft, high plasticity clay. It generally has very low shear strength and is prone to failure, even on fairly gentle slopes.

A range of GSI's were determined, ranging from very good rock (i.e. intact or massive structure with very good surface conditions) to poor rock (disintegrated with poor surface conditions). A broad GSI zoning was required, reflecting the range of material type observed in each section. Photograph 5 to Photograph 9 show typical areas with the assigned GSI range taken from the helicopter inspection. Appendix G summarises the cliff data for each section. The range of GSI based on structure and surface conditions observed during the site inspection are also shown on Figure 5.5 described in terms of geologic type. This figure shows that the GSI for the various geologies can overlap, although the trend of increasing GSI number with improved surface and structure is apparent.

5.3.2 Soft cliffs

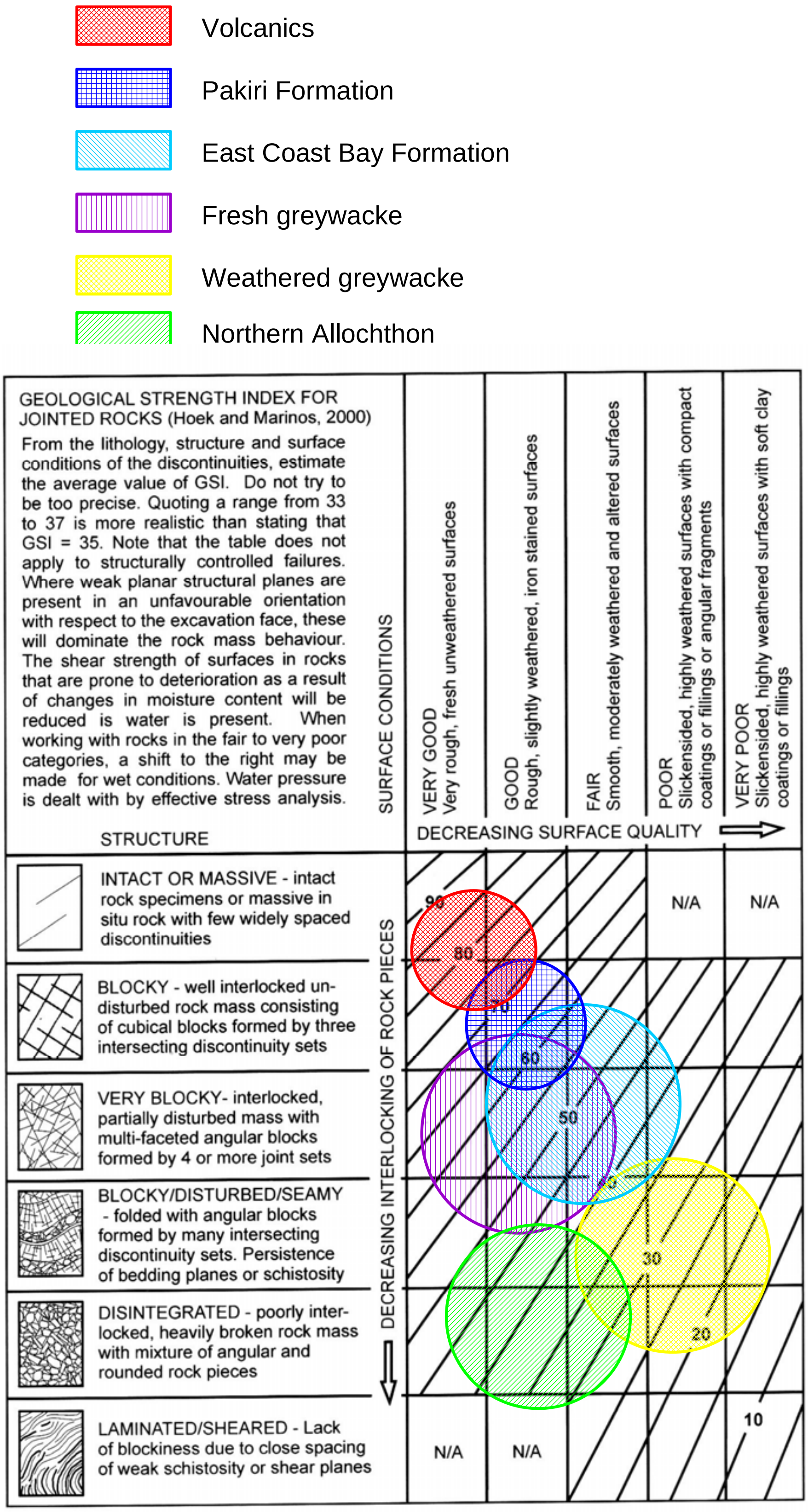
Soft cliffs were defined as generally lightly cemented, cohesive soils consisting of marine, alluvial and organic materials. These materials are typically very young and are often derived from erosion of older formations. Soft-shores are typically characterized by an eroding bank of up to 10 m backing a low inter-tidal flat. These inter-tidal flats are typically submerged at high tide and generally consist of material eroded off the soft bank. Soft-shores primarily exist in estuarine environments such as the Waitemata, Manakau and Kaipara Harbours.

Moderately consolidated dune sands such as on the Awhitu peninsula, south of Manukau Heads appear spatially uniform, with failure appearing to be primarily a result of toe erosion and homogeneous collapse of over-steepened material rather than failure along defect planes. Soft cliff locations were determined directly from geological maps and experience and knowledge of the project team.

The GSI approach was not considered appropriate for these materials, which behave more as a soil than a rock. The behaviour and characteristics of soft cliffs was based on visual inspection and published data on these cliffs.

Figure 5.5

Estimate of Geological Strength index (GSI) based on geological description (*source: Hoek, 2002*)



Photograph 5
GSI 80-95: South of Piha

Photograph 6
GSI 60-85: East of Whatipu

Photograph 7

GSI 55-75: Cockle bay

Photograph 8

GSI 40-55: Castor Bay

Photograph 9

GSI 25-45: Waiti Bay

6 Beach Coastline Change

Coastline change along beaches occurs as a result of short term fluctuations in the beach profile as well as from long term trend of retreat or accretion.

Beach erosion is typically defined as a permanent landward translation of the beach profile. Erosion is typically influenced by sediment supply not being sufficient to replace sediment transported by hydraulic action (waves and currents).

6.1 Methodology

The areas susceptible to coastal erosion is established from cumulative effect of (refer figure 6.1):

$$ASE_{Beach} = (SF \times F_1) + DS + (LTR_H \times T) \times F_2 + SLR_{2100}$$

Where:

SF	=	Horizontal Coastline Fluctuations including storm cut (m). This factor is derived from existing information sources or from interpolation/judgement from adjacent or similar beaches.
F_1	=	Scaling factor based on field investigation analysis of 1.25.
DS	=	Dune Slope is characterized by the horizontal distance from the seaward edge of vegetation to dune crest (m). This was measured directly or based on the height of the dune crest relative to the toe of the dune times by 32 degrees, the typical stable slope angle of sand. Where no significant dune was present a default minimum value of 1 m was applied.
LTR_H	=	Long Term Rate of horizontal coastline movement (m/yr). LTR_H takes into account all losses based on data or expert judgement. Where beaches are controlled by headlands, LTR_H includes the rate of adjacent long-term cliff retreat.
T	=	Timeframe (years). In this instance a period of 100 years was used.
F_2	=	Allowance for uncertainty in the long-term retreat rates of 1.25.
SLR_{2100}	=	Horizontal coastline retreat due to possible accelerated sea level rise (m). This was done using IPCC estimates of SLR of 0.5 m at 2100 based on the Bruun Rule and/or expert judgement. Due to the order of magnitude difference in time scales of the applicability of erosion (100 years) and geologic time scales (1,000s years) combined with the lack of certainty with regard to steady geologic changes over the next 100

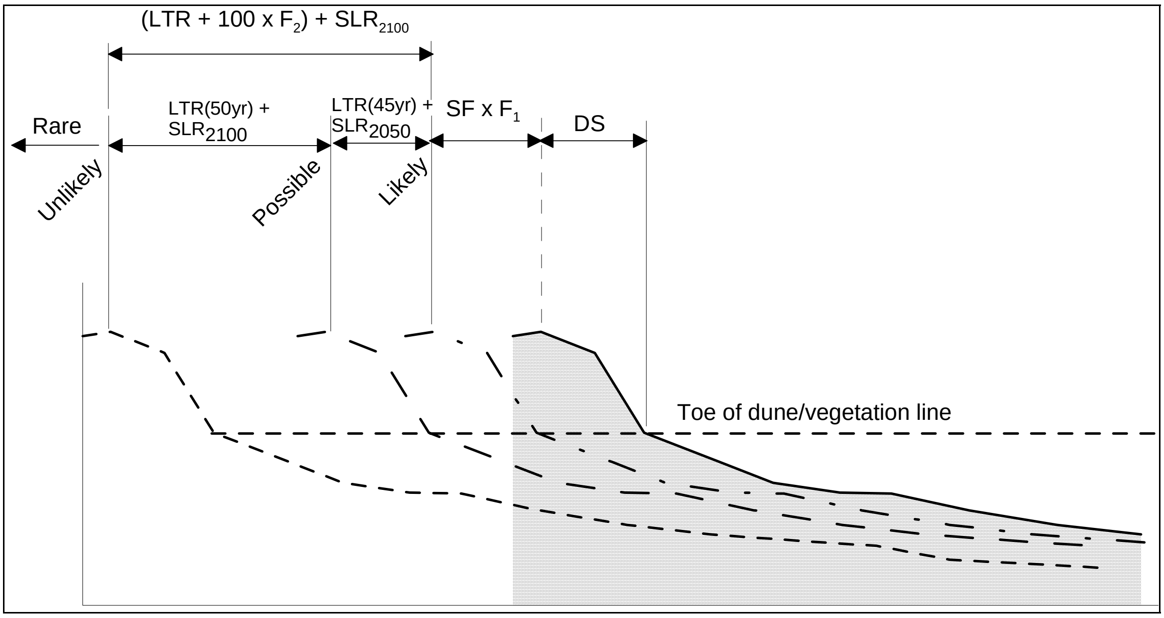
years, no reduction in predicted sea level rise rates was made to take into account any long-term geologic trend.

Figure 6.1 shows the starting point being the toe of dune or vegetation line. The area sensitive to the coastal erosion extends landward from this point based on the addition of the dune slope, the short term fluctuation and future effects of any existing erosion trend along with predicted effects of sea level rise. The short term fluctuation and dune slope factor represent the current erosion risk, excluding future climate change effects or long term trends. We have also considered the erosion risk to 2050 and 2100.

The parameters used to evaluate the areas susceptible to coastal erosion are described in more detail in the following sections.

In areas where ARC has already identified coastal erosion hazard areas, the existing hazard zone widths were compared with the areas susceptible to erosion based on the methods set out in this report. Typically the area sensitive to coastal erosion will be based on the more detailed assessment.

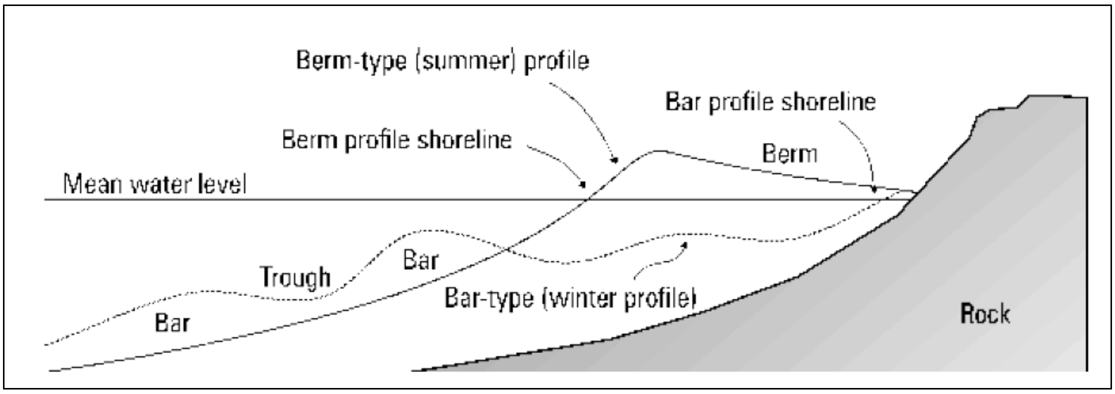
Figure 6.1
Definition of beach areas susceptible to erosion



6.2 Coastline Fluctuations

Coastline fluctuations can occur at different time scales. The most readily apparent is the change in beach profile due to onshore storms, with the beach typically lowering during the storm and rebuilding after the storm has passed. However, there are also longer term variations. Long term variations, typified by the so called "winter" and "summer" profile, results from a range in climatic forcing agents (refer Figure 6.2). In Auckland these variation occur but not necessarily as a direct result of seasonal change. However, these fluctuations are not well understood.

Figure 6.2
Typical summer/winter profile fluctuation (modified from Komar, 1998)



6.2.1 Data used in analysis

There is survey data from fourteen Auckland beaches since as early as 1965. Survey intervals range from around monthly to yearly depending on the objectives of the individual survey. This beach profile database is summarized in Appendix H.

The change in beach volumes have been determined using a range of methods, including assessment of measured beach profiles, comparative assessments on similar beaches and numerical methods. The resulting volume changes have been translated into horizontal distances using the beach's typical profile.

6.2.2 Method of determination

After consideration of the various methods used to determine beach fluctuation the standard deviation of the mean movement was used as this provides a reasonable estimation of expected changes in beach face position. Data on the distribution of the annual change of the coastline at the 1.8 m above Chart Datum (CD) contour level (representative of Mean Sea Level) and the 3 m CD contour level (representative of MHWS) is included in Table H2, Appendix H. The results indicate that the distribution of coastline movement can generally be considered to be normal, although at a number of sites the observed distribution is slightly skewed. The observed skew in the data is likely to be due to the relatively short record length at some of the sites.

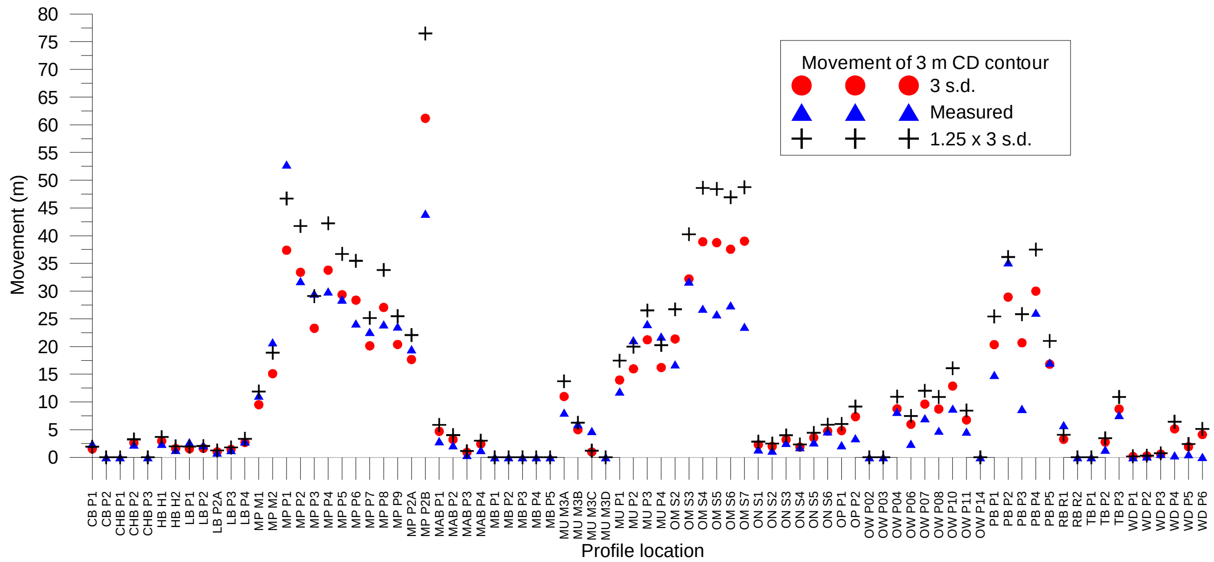
Having largely satisfied the normality of the data, we then used the standard derivations (sd) from the mean as our measure of coastline fluctuation. From normal probability theory, we know that an observation value at 1sd, 2sd, 3sd from the mean will have corresponding probabilities of occurrence of 16%, 2.5%, and 0.5% respectively. Since our data is annual movements, these probabilities can be considered to be equivalent to Annual Exceedance Probabilities (AEP). Therefore, a coastline retreat greater than 2sd is theoretically the same as a 40-year return period event, and greater than 3sd is the same as a 200-year return period event. However, the analysis of the results showed that 3sd events occurred during the relatively short data set at most beaches, suggesting large movements may occur at more frequent return periods than that estimated using the normal distribution approach. Therefore, the statistical approach is probably limited by the short data set, but still provides a means to examine the relative difference between beaches.

For the purposes of this study it was considered important to define a suitably precautionary level of risk. Therefore, the 3sd annual movement of the dune toe was selected to reflect the likely coastline fluctuation component of the upper beach/dune toe. Comparing the range of movement determined by this approach with the recorded movement showed that an additional factor was required to increase the likely range of movement to greater than that observed in the short data sets available. A scaling factor of 1.25 was applied to provide an estimate of short-term fluctuation likely to be greater than a fluctuation with a return period of between 50 and 100 years.

Figure 6.3 shows the resulting movement of the 3 m CD contour based on 3 sd, maximum observed movement and 1.25 x 3 sd. Results obtained using the scaling factor of 1.25 was in good agreement with values determined numerically and empirically by past Tonkin and Taylor investigations. Where differences occurred, preference was generally given to numerical and empirical results of past investigations as were derived from more site specific assessment.

Figure 6.3

Comparison of observed 3 m CD beach contour movement with standard deviation approach



For beaches with limited or no data available, fluctuation widths were interpolated from beaches with data. This was done by assessing the location, geometry and exposure of the beach without data and finding the most appropriate fluctuation width based on other similar beaches.

6.3 Long-Term Retreat Rates

Long term retreat is the progressive landward shift of the average position of the coastline.

6.3.1 Data used in analysis

Existing information has been used where possible to assess this variable. The extensive beach-monitoring program that has been carried out by ARC, summarised in Appendix J, was of particular use with data in excess of 20 years recorded at certain locations. Data of this length can start to be analysed to provide an indication of long-term trends. However, even 20 years does not include sufficient information for the range of climate cycles known to affect coastline stability. Therefore, some uncertainty exists with any trends inferred from these data sets.

6.3.2 Method of determination

Long-term retreat was determined using linear regression to analyse any discernable trend in movement of the 3 m CD (approx. MHWS) and 1.8 m CD contours (approx. MSL). However, it is noted that in most cases the survey periods are insufficiently long to take into account the full range of known cyclical weather patterns associated with the Inter-decadal Pacific Oscillation (IPO), which has a period of some 25 to 30 years.

Other methods, such as aerial photography, only provide broad scale indications of change in areas where change can readily be observed (i.e. rapidly eroding or accreting coasts) due to the scale of the photographs and their resolution. Shoreline changes on beach coasts in the order of 10 to 15 m are not readily identifiable and are within the margin of error of most photographic survey assessments. Along cliff shores vegetation along the cliff edge as well as shadows obscure the location of the cliff crest and toe.

Data are summarised in Table H1-2, Appendix H. The table shows the linear trend in m/yr and the regression coefficient, r2, which is a measure of goodness of fit, representing the proportion of variability of shoreline change over time. Values of r2 close to 1 indicate a good fit. In many cases the regression coefficient r2 is very low, being closer to 0 than 1, indicating a poor fit. The relatively low regression coefficient seen for the majority of locations indicates significant variation is observed with no strong trends. Based on our experience of these beaches, most appear to be in dynamic equilibrium with no discernable long-term movement. Of all the beaches where profiling is carried out, only the southern end of Muriwai Beach appeared to have persistent erosion trends, although even at these locations it is uncertain if the observed erosion may not be part of a larger scale cyclical pattern. Some erosion was also evident along Mangawhai Pakiri. However, as there are areas with accretion and erosion this is also likely to be a cyclical variation in shoreline position, rather than a strong erosion trends.

As the majority of beaches within the Auckland region are headland-controlled, pocket beaches, it is reasonable to assume that over the longer term the adjacent cliff retreat should also control long-term beach movement, with the beach retreating as the cliff headland retreats. Therefore, for the purposes of this study, beaches found to be in dynamic equilibrium, or without any long-term data, were assigned retreat rates equal to those of adjacent cliffs.

In cases of beach systems that are located adjacent to cliffs with differing erosion rates, the larger erosion rate from the cliffs is assigned to the beach. This process was carried out for all beaches apart from Mangawhai-Pakiri and Muriwai.

6.4 Climate Change Effects

There is no universally accepted approach for determining climate change effects and existing data is insufficient to confidently predict future trends even with the assumption that there will be no significant change to existing weather patterns and water levels. However, there is a general acceptance that with a slow and steady rise in sea level there will be a landward retreat of the shoreline, even though there are differences of opinion as to where the sand could be deposited and what processes take place to initiate the change in profile (Davidson-Arnott, 2005).

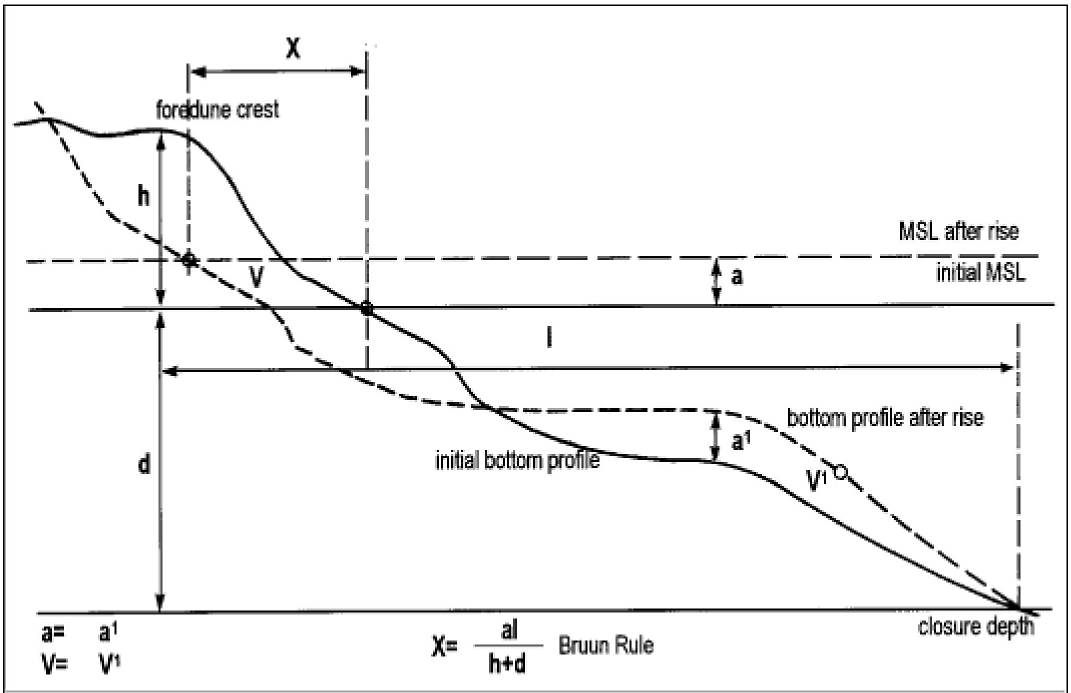
To provide some quantitative assessment of sea level rise effects, empirical models to estimate the potential coastline retreat for a given sea level are still the only consistent approach currently available. The most commonly used and internationally recognised empirical model is the Bruun Rule and its various modifications (Figure 6.4).

The rule simply suggests that with a rise in sea level there is a corresponding upward and landward movement of the coastline. The formula provides the extent of landward retreat based on the assumption of a closed sediment system between the beach and closure depth. Closure depth is the seaward limit of the typical wave induced sediment transport. The formula also assumes that the profile maintains its shape during a period of sea level rise.

Therefore, if sea level rises "a", the extent of the seabed influenced by wave action is "l" and "h+d" is the height of the active beach profile, the coastline recession "S" due to an increase in water level 'a" is determined by:

$$S = \frac{(l \times a)}{(h + d)}$$

Figure 6.4
Predictions of coastline change due to sea level rise using the Bruun Rule (Gibb, 1998)



This model is a very simple mechanism for attempting to define and quantify a very complex process. The limitations of the Bruun Rule have been clearly identified by Bruun (1988), many reviewers and specialists (Komar et al. 1991), as well as the recent review of the NIWA report (Brookes & Benson 1999). Key limitations include:

- the coastline retreat is based on simple profile geometry for sand beaches
- the model is two-dimensional and care should be taken in expanding it three-dimensionally
- the theory is one of erosion not accretion

Although the Bruun Rule has been the subject of intense debate since the early 1970's, the general consensus is that the rule still has an overall general validity (Komar et al. 1991). The use of the Bruun Rule has also survived challenge within Environment Court in New Zealand (Tauranga District Council vs Skinner).

It was considered that the Bruun Rule could be applied to provide an estimate of the component of coastline change that could possibly occur due to accelerated sea level rise.

Closure depth was determined by measuring the distance to the end of the littoral zone (d_l) as determined by the inner Hallermeier limit, where:

$$d_l = 1.75\ H_{s(0.137)}$$

$H_{s(0.137)}$ is the annual significant wave height exceeded by 13.7% of waves (approximately 12 hours per year). The use of the Hallermeier limit to identify closure depth has been evaluated at Mangawhai-Pakiri and the resulting depth of around 7 to 10 m represents the seaward limit of typical sand movement.

Many of the beaches within the Auckland Region do not fit neatly the criteria for estimating closure depth with the Hallermeier limit. Most commonly, Auckland beaches consist of perched beaches overlying harder strata or different sediment type, with low backshores and a wide, shallow nearshore which gives a very long distance to closure depth and hence a very flat slope. The resulting flat slope results in an unrealistically large predicted coastline retreat.

The approach therefore, has been to apply the Bruun Rule to those beaches which comprise sand to past closure depth. Beaches assessed included Onetangi Beach and Long Bay in the Inner Hauraki Gulf, Omaha, Mangawhai-Pakiri and Awana Beach in the Outer Hauraki Gulf and Muriwai and Piha Beach on the West Coast. The results for the Inner Hauraki Gulf beaches indicated coastline retreats of 8m at 2050 and 20m at 2100. The Outer Hauraki Gulf predicted retreats of 10m to 2050 and 25m to 2100. The West Coast indicated slightly larger values of 15m to 2050 and 38m to 2100.

Results of this assessment were compared to previous assessments of Auckland Beaches and to assessments by Environment Waikato (2002) for beaches of the Coromandel. Previous assessments of SLR effects in the Inner Hauraki Gulf ranged from 10 to 30 m, while SLR effects to 2100 on beaches on the outer Hauraki Gulf ranged from 12 to 18 m. Environment Waikato estimated 20 m recession due to sea level rise for dune-barrier beaches and 15 m for pocket beaches.

Judgement was used combining these various rates to provide estimates of potential sea level rise effects for the remaining beach areas. Table 6.1 sets out possible sea level rise effects to 2050 and 2100 for beaches on various coastline areas. The potential recession to 2100 is some 2.5 times the potential recession to 2050, matching the predicted increase in accelerated sea level rise from 2050 to 2100.

Table 6.1

Effects of future sea level rise

Coastline	Potential recession (m)	
	due to SLR to 2050	due to SLR to 2100
Inner Hauraki Gulf/Harbour environments	**8**	**20**
Outer Hauraki Gulf	**10**	**25**
West Coast	**15**	**38**

6.5 Assessment of Uncertainty

The identification of areas susceptible coastal erosion necessitates forecasting future coastline positions. Simple forecast methods, such as end-point rate and linear regression have been proposed in the coastal literature and are widely used. However, for sandy coasts, other factors, such as storm cut and fluctuations of beach width need to be considered as well. In addition, the consideration of the effect of future climate change, particularly accelerated sea level rise, needs to be included. For cliff shorelines the complex and uncertain sequence of recession events needs to be taken into account.

The cumulative approach of adding the various factors, such as storm cut, shore fluctuations, erosion trends and sea level rise effects, which are all likely contributors to coastal erosion, provides a level of conservatism in establishing the areas susceptible to erosion. However, consideration of uncertainty also requires the application of factors on some of the values used.

Reasonable quality information on coastline fluctuations exists for some of the beaches included in this study. However, in the context of coastlines evolving over 100's of years, it is still quite short-term, with the greatest length of record being some 40 years and most being in the 5 – 15 year range. A scaling factor was applied to these values to provide a fluctuation for each coastline that matched or slightly exceeded 3 s.d.

Similarly, the long-term beach retreat rate is not clearly discernable from the surveyed information currently available. A long-term erosion rate based on the adjacent cliff erosion rate has been applied to those beaches that appear dynamically stable. Due to the short term records, an allowance factor (F_2) of 1.25 has been applied to the LTR_H.

No additional uncertainty allowance was applied to the dune crest width or sea level rise effects as the approach used is considered suitably conservative at this point in time. However, it is acknowledged that should sea level increase to the upper ranges predicted (i.e. 0.9 m rather than the 0.5 m used to 2100), greater retreat rates may be realised than those used in this study.

6.6 Likelihood

In terms of the likelihood of erosion affecting a particular backshore area, the potential for the areas susceptible to erosion eventuating over the 100 year planning period is indicated in Figure 5.1 and defined Table 6.2 based on the recommended approach in the Coastal Hazards Guidance Note from Ministry of the Environment (2004).

It is unusual for an engineer or coastal scientist to have access to the quantity or quality of data that many of theoretical techniques to quantify risk require (Pugh, 2004). In addition, there are different parameters requiring an understanding of the joint probability of a number of natural processes. Typically estimates of risk are based on only limited observations so that extrapolation of the available data in both time and space is inevitable. Skill is necessary to decide how valid it will be to use data from another location, and the best way to make the transfer.

Table 6.2
Likelihood of beach erosion

Likelihood	Description
Likely	Includes the coastline fluctuation and width of dune slope. Will probably happen several times during the 100 year timeframe.
Possible	Includes coastline fluctuation, width of dune slope and long-term erosion and sea level rise effects to 2050. Might occur some time during the period of concern.
Unlikely	Includes coastline fluctuation, width of dune slope and long-term erosion and sea level rise effects to 2100. Unlikely to occur but possible during the period of concern.
Rare	Coastline change past the 2100 line. Highly unlikely within 100 year timeframe, but conceivable.

Although there are no probabilities provided in the above table, values can be assigned considering design risk as a way of illustrating the possible limits. The design risk is related to the annual exceedence probability according to the statistical relationship:

$$\text{Risk} = 1 - (1 - Q(Z))^{T_L}$$

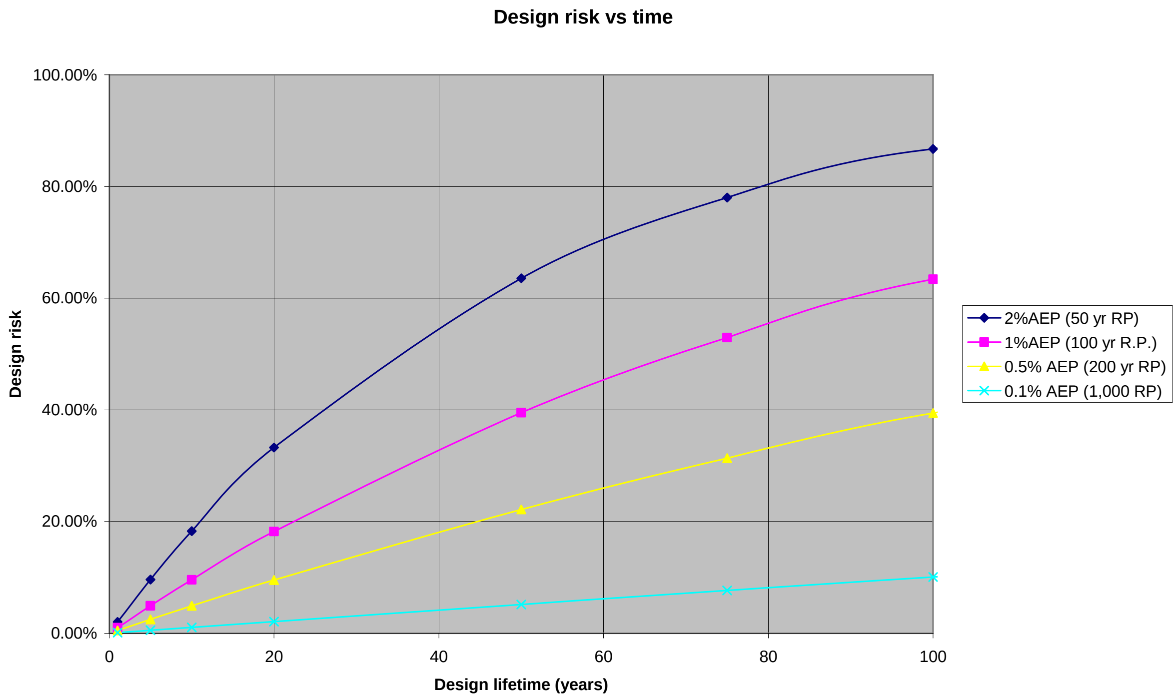
Where T_L is the design lifetime and Q(Z) is the probability of an erosion setback being exceeded in a single year. The relationship between the risk of encountering an extreme erosion event with approximate return periods of 50, 100, 200 and 1,000 years and the expected planning period is shown in Figure 6.5.

Figure 6.5 shows that there is a probability of 63% of encountering a level that has a return period equal to its design life, i.e. the event is more likely than unlikely to occur. The probability of a 2% AEP event occurring within the 100 year period is 87%, while the possibility of 0.5% and 0.1% AEP events occurring are around 40% and 10% respectively. Using the design risk approach, "certain" is equivalent to the 2%AEP event, "likely" is equivalent to the 1% AEP event, "possible" is equivalent to 0.5% and "unlikely" could be considered erosion up to the 0.1% AEP line. Erosion past the 0.1% line could be classed as "rare". We note that the selection of an appropriate design risk is dependent upon the value of the structure or development being considered.

For the coastal protection of the Netherlands a 1% design risk (i.e. 0.01% AEP) is used and for many British coastal protection schemes a design risk of 10% (i.e. 0.1% AEP) is typically applied (Pugh, 2004).

Figure 6.5

The relationship between the risk of encountering an extreme erosion with a return period of 50, 100, 200 and 1,000 years and the expected planning period.



6.7 Assessment of Areas Susceptible to Erosion

Table 6.3 summarises the dimensions of the various components of beach erosion susceptibility. Table 6.4 provides the width of the areas susceptible to erosion extending landward from the toe of the dune or vegetation line. The likely, possible and unlikely scenarios have been assessed taking into account the coastline fluctuations, the dune-slope distance, the long-term rate of retreat and the retreat based on sea-level rise.

Beach areas “likely” to be susceptible to erosion over the next 100 years range from 6m landward of the vegetation line at stable beaches with low/limited dune systems, to 55m at more variable beaches with highly developed dune systems.

“Possible” areas influenced by beach erosion range from 16 m at sheltered, stable beaches bounded by hard, erosion resistant, basement rock to 124 m at more highly exposed, rapidly eroding west coast beaches.

“Unlikely” beach areas susceptible to erosion zone widths range from about 30m to over 200m at very highly exposed, rapidly eroding west coast beaches.

Table 6.3

Summary of components of beach erosion assessment

Beach No.	Beach Name	Length (km)	Easting - Midpoint	Northing - Midpoint	Coastline Fluctuations, SF (m)	Dune-slope allowance, DS (m)	Long-term retreat, LTR_H (m)	SLR retreat to 2050 (m)	SLR retreat to 2100 (m)
1	Waimangu Point	2.83	2713756	6465118	5	1	5	8	20
2	Tawhitokino Beach	0.89	2707113	6470815	5	2	5	8	20
3	Kawakawa Bay	3.56	2703152	6470451	5	2	4	8	20
4	Umupuia Beach	1.25	2694667	6475489	5	3	5	8	20
5	Maraetai Beach	2.85	2692226	6478632	5	1	5	8	20
6	Rocky Bay	1.79	2695241	6484337	5	2	4	8	20
7	Man o' War Bay	0.66	2702737	6488297	5	2	4	8	20
8	Owhiti Bay	0.45	2702180	6490781	15	5	3	8	20
9	Onetangi Bay	1.84	2695887	6488350	22	6	3	8	20
10	Surfdale	0.55	2690934	6487743	5	2	4	8	20
11	Blackpool Beach	0.81	2689980	6488245	5	2	4	8	20
12	Oneroa Beach	1.21	2689882	6489098	15	5	3	8	20
13	Cockle Bay	0.51	2684359	6475996	5	1	4	8	20
14	Howick Beach	0.47	2683512	6476900	5	1	4	8	20
15	Eastern Beach	1.44	2681046	6479145	5	1	4	8	20
16	Bucklands Beach	2.15	2680052	6479676	5	1	4	8	20
17	Karaka Bay	0.27	2677909	6481692	5	2	4	8	20
18	Cheltenham Beach	0.66	2671740	6484987	3	4	4	8	20
19	Narrow Neck Beach	0.39	2671139	6486107	5	4	4	8	20
20	Takapuna Beach	1.12	2669052	6488660	9	4	4	8	20
21	Milford Beach	0.72	2668321	6491198	9	4	4	8	20
22	Castor Bay	0.34	2668343	6491935	5	4	4	8	20
23	Campbells Bay	0.47	2667832	6493599	3	4	4	8	20
24	Mairangi Bay	0.98	2667214	6494618	5	4	3	8	20
25	Browns Bay	0.99	2666792	6497031	5	4	3	8	20
26	Waiake Beach	0.35	2666988	6498340	5	4	4	8	20
27	Long Bay	1.36	2666910	6500298	3	6	3	8	20
28	Dacre Beach	0.51	2665000	6503197	5	1	3	8	20
29	Arkles Bay	0.52	2666803	6505269	5	1	3	8	20
30	Matakatia Bay	0.43	2669106	6507041	5	1	3	8	20
31	Okoromai Bay	0.58	2672417	6508839	5	1	3	8	20
32	Te Haruhi Bay	1.07	2673684	6508050	5	2	5	8	20
33	Army Bay	0.68	2672543	6509476	9	2	5	8	20
34	Big Manly/Tindalls	1.41	2667822	6506636	9	2	4	8	20

Beach No.	Beach Name	Length (km)	Easting - Midpoint	Northing - Midpoint	Coastline Fluctuations, SF (m)	Dune-slope allowance, DS (m)	Long-term retreat, LTR_H (m)	SLR retreat to 2050 (m)	SLR retreat to 2100 (m)
	Beach								
35	Stanmore Bay	0.76	2666103	6507077	9	2	4	8	20
36	Red Beach	0.47	2663372	6509372	9	2	5	8	20
37	Orewa Beach	2.76	2662244	6511551	9	2	10	8	20
38	Hatfields Beach	0.58	2662260	6513846	3	2	3	8	20
39	Waiwera	0.69	2663456	6515839	9	2	10	8	20
40	Wenderholm Beach	0.81	2663924	6517548	9	2	10	8	20
41	Mahurangi Res Beach	0.66	2664529	6518648	9	2	10	8	20
42	Martins Bay	0.79	2668689	6526514	5	3	3	8	20
43	Sandspit Beach	0.60	2665582	6532941	5	2	10	8	20
44	Buckleton Beach	0.56	2667278	6532772	5	2	3	8	20
45	Million Bay	0.98	2668506	6533873	5	2	3	8	20
46	Christian Bay	1.18	2671516	6534148	5	2	4	8	20
47	Waikauri Bay	0.58	2672854	6534214	5	2	4	8	20
48	Jones Bay	0.46	2673742	6534309	5	1	4	8	20
49	Tawharanui	2.82	2674688	6535541	20	9	5	10	25
50	Omaha	3.86	2670338	6538809	35	11	10	10	25
51	Mangawhai - Pakiri	19.86	2660974	6555049	30	10	85	10	25
52	Whangaparaparaoa	1.78	2725966	6548408	5	2	3	8	20
53	Okupu Bay	0.97	2729771	6545770	5	2	3	8	20
54	Puriri Bay	1.13	2733924	6541017	5	2	3	8	20
55	Rosalie Bay	0.53	2734454	6540109	5	2	3	8	20
56	Medlands Beach	2.16	2734703	6545121	30	14	3	10	25
57	Kaitoke/Palmers Beach	3.31	2733252	6547639	30	14	3	10	25
58	Awana Beach	0.68	2733473	6551579	30	14	3	10	25
59	Whangapoua Beach	2.17	2728618	6560469	30	8	10	10	25
60	Papakanui Spit	3.52	2617856	6529284	25	15	10	15	35
61	Shelly Beach	0.59	2633880	6513477	5	1	10	8	20
62	Muriwai Beach	15.30	2634614	6491198	25	15	100	15	38
62a	Muriwai Nth	35.89	2621667	6513161	25	15	10	15	38
63	O'Neills Bay	0.80	2638628	6478741	35	10	2	15	38
64	Bethells Beach	1.57	2639237	6477385	35	10	2	15	38
65	Piha Beach	3.06	2640967	6471741	35	10	1	15	38
66	Karikari Beach	0.74	2641540	6467051	35	10	2	15	38
67	Whatipu - Karikari	8.71	2642024	6461652	35	10	2	15	38

Beach No.	Beach Name	Length (km)	Easting - Midpoint	Northing - Midpoint	Coastline Fluctuations, SF (m)	Dune-slope allowance, DS (m)	Long-term retreat, LTR_H (m)	SLR retreat to 2050 (m)	SLR retreat to 2100 (m)
	Point								
68	Cornwallis Beach	1.91	2653092	6464932	5	1	3	8	20
69	Glenbrook Beach	0.29	2662347	6447460	5	1	10	8	20
70	Clarks Beach	2.29	2661512	6450642	5	1	10	8	20
71	Grahams Beach	1.39	2658454	6459666	5	1	10	8	20
72	Big Bay	0.92	2655844	6460956	5	1	10	8	20
73	Orua Bay	1.22	2653149	6460213	5	1	10	8	20
74	Wattle Bay	0.90	2651310	6460538	5	1	10	8	20

Table 6.4

Widths of coastal area on beach coastlines susceptible to erosion

Beach No.	Beach Name	Length (km)	Easting - Midpoint	Northing - Midpoint	"Likely" erosion width from vegetation line (m)	"Possible" erosion width from vegetation line (m)	"Unlikely" erosion width from vegetation line (m)
1	Waimangu Point	2.83	2713756	6465118	7	18	34
2	Tawhitokino Beach	0.89	2707113	6470815	8	19	35
3	Kawakawa Bay	3.56	2703152	6470451	8	19	33
4	Umupuia Beach	1.25	2694667	6475489	9	20	36
5	Maraetai Beach	2.85	2692226	6478632	7	18	34
6	Rocky Bay	1.79	2695241	6484337	8	19	33
7	Man o' War Bay	0.66	2702737	6488297	8	19	33
8	Owhiti Bay	0.45	2702180	6490781	24	34	48
9	Onetangi Bay	1.84	2695887	6488350	34	43	57
10	Surfdale	0.55	2690934	6487743	8	19	33
11	Blackpool Beach	0.81	2689980	6488245	8	19	33
12	Oneroa Beach	1.21	2689882	6489098	24	34	48
13	Cockle Bay	0.51	2684359	6475996	7	18	32
14	Howick Beach	0.47	2683512	6476900	7	18	32
15	Eastern Beach	1.44	2681046	6479145	7	18	32
16	Bucklands Beach	2.15	2680052	6479676	7	18	32
17	Karaka Bay	0.27	2677909	6481692	8	19	33
18	Cheltenham Beach	0.66	2671740	6484987	8	18	33
19	Narrow Neck Beach	0.39	2671139	6486107	10	21	35
20	Takapuna Beach	1.12	2669052	6488660	15	26	40

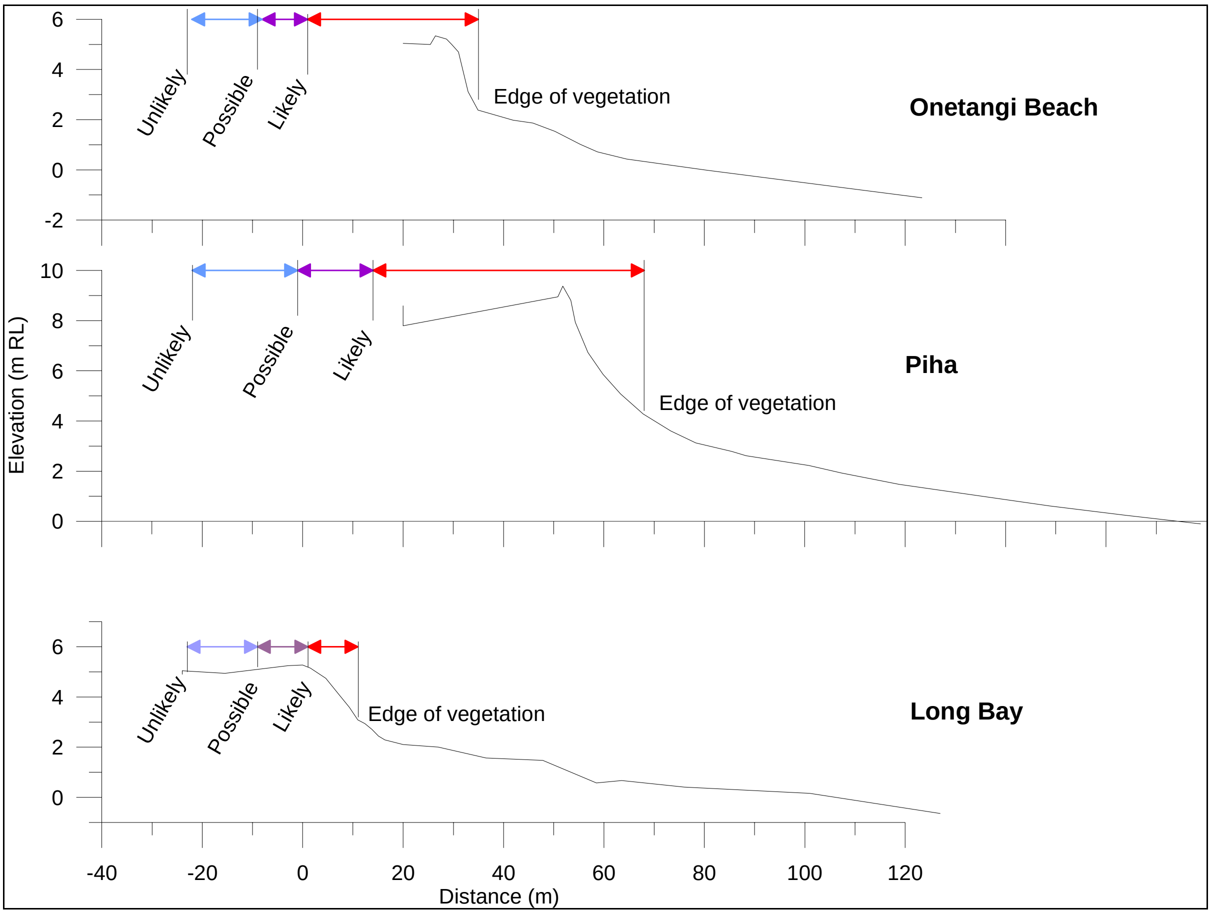
Beach No.	Beach Name	Length (km)	Easting - Midpoint	Northing - Midpoint	"Likely" erosion width from vegetation line (m)	"Possible" erosion width from vegetation line (m)	"Unlikely" erosion width from vegetation line (m)
21	Milford Beach	0.72	2668321	6491198	15	26	40
22	Castor Bay	0.34	2668343	6491935	10	21	35
23	Campbells Bay	0.47	2667832	6493599	8	18	33
24	Mairangi Bay	0.98	2667214	6494618	10	20	34
25	Browns Bay	0.99	2666792	6497031	10	20	34
26	Waiake Beach	0.35	2666988	6498340	10	21	35
27	Long Bay	1.36	2666910	6500298	10	20	34
28	Dacre Beach	0.51	2665000	6503197	7	17	31
29	Arkles Bay	0.52	2666803	6505269	7	17	31
30	Matakatia Bay	0.43	2669106	6507041	7	17	31
31	Okoromai Bay	0.58	2672417	6508839	7	17	31
32	Te Haruhi Bay	1.07	2673684	6508050	8	19	35
33	Army Bay	0.68	2672543	6509476	13	24	40
34	Big Manly/Tindalls Beach	1.41	2667822	6506636	13	24	38
35	Stanmore Bay	0.76	2666103	6507077	13	24	38
36	Red Beach	0.47	2663372	6509372	13	24	40
37	Orewa Beach	2.76	2662244	6511551	13	28	46
38	Hatfields Beach	0.58	2662260	6513846	6	16	30
39	Waiwera	0.69	2663456	6515839	13	28	46
40	Wenderholm Beach	0.81	2663924	6517548	13	28	46
41	Mahurangi Res Beach	0.66	2664529	6518648	13	28	46
42	Martins Bay	0.79	2668689	6526514	9	19	33
43	Sandspit Beach	0.60	2665582	6532941	8	23	41
44	Buckleton Beach	0.56	2667278	6532772	8	18	32
45	Million Bay	0.98	2668506	6533873	8	18	32
46	Christian Bay	1.18	2671516	6534148	8	19	33
47	Waikauri Bay	0.58	2672854	6534214	8	19	33
48	Jones Bay	0.46	2673742	6534309	7	18	32
49	Tawharanui	2.82	2674688	6535541	34	47	65
50	Omaha	3.86	2670338	6538809	55	71	92
51	Mangawhai - Pakiri	19.86	2660974	6555049	48	111	179
52	Whangaparapara	1.78	2725966	6548408	8	18	32
53	Okupu Bay	0.97	2729771	6545770	8	18	32
54	Puriri Bay	1.13	2733924	6541017	8	18	32
55	Rosalie Bay	0.53	2734454	6540109	8	18	32

Beach No.	Beach Name	Length (km)	Easting - Midpoint	Northing - Midpoint	"Likely" erosion width from vegetation line (m)	"Possible" erosion width from vegetation line (m)	"Unlikely" erosion width from vegetation line (m)
56	Medlands Beach	2.16	2734703	6545121	52	63	80
57	Kaitoke/Palmers Beach	3.31	2733252	6547639	52	63	80
58	Awana Beach	0.68	2733473	6551579	52	63	80
59	Whangapoua Beach	2.17	2728618	6560469	46	62	83
60	Papakanui Spit	3.52	2617856	6529284	46	68	94
61	Shelly Beach	0.59	2633880	6513477	7	22	40
62	Muriwai Beach	15.30	2634614	6491198	46	124	206
62a	Muriwai Nth	35.89	2621667	6513161	46	68	94
63	O'Neills Bay	0.80	2638628	6478741	54	70	91
64	Bethells Beach	1.57	2639237	6477385	54	70	91
65	Piha Beach	3.06	2640967	6471741	54	69	90
66	Karikari Beach	0.74	2641540	6467051	54	70	91
67	Whatipu - Karikari Point	8.71	2642024	6461652	54	70	91
68	Cornwallis Beach	1.91	2653092	6464932	7	17	31
69	Glenbrook Beach	0.29	2662347	6447460	7	22	40
70	Clarks Beach	2.29	2661512	6450642	7	22	40
71	Grahams Beach	1.39	2658454	6459666	7	22	40
72	Big Bay	0.92	2655844	6460956	7	22	40
73	Orua Bay	1.22	2653149	6460213	7	22	40
74	Wattle Bay	0.90	2651310	6460538	7	22	40

Examples of the widths of areas susceptible to erosion in terms of actual beach profiles are shown in Figure 6.6. This figure shows the identified zones presented in Table 6.4 for Onetangi, Piha and Long Bay beaches. These plots demonstrate the increased area of potential risk is largely a function of exposure and ongoing trends, with higher energy shorelines more susceptible to larger fluctuations.

Figure 6.6

Examples of extent of areas susceptible to erosion for soft shores



7 Cliff Erosion

There is much debate in the scientific community over the major causes of cliff erosion, with various reports giving more or less importance to different mechanisms. The main causes of erosion observed in the Auckland area, in no particular order of significance, include:

- Marine erosion
  - Mechanical erosion, whereby the movement of rock and sand by wave action causes abrasion of cliff surfaces.
  - Hydraulic action, by which the shock force of breaking waves and rapid increases and decreases of pressure in cracks and crevices cause rock to break down.
  - Hydraulic action of both waves and tidal flows also play a major part in clearing away debris caused by other forms of erosion from the toe of cliffs.
- Bio-erosion
  - Generally thought to be of most significance in tropical climates but shown by Healy (1967) to play a role in erosion within the Auckland area. Results in weakening of the portion of cliff within the intertidal zone, causing undercutting of the cliff and block failure and slides.
- Weathering
  - Mechanical weathering involves processes such as wet/dry cycles, water absorption, unloading and frost and salt weathering (Brodnax, 1991).
  - Chemical weathering from chemical reactions e.g. breaking down the existing rock structure to clay particles.

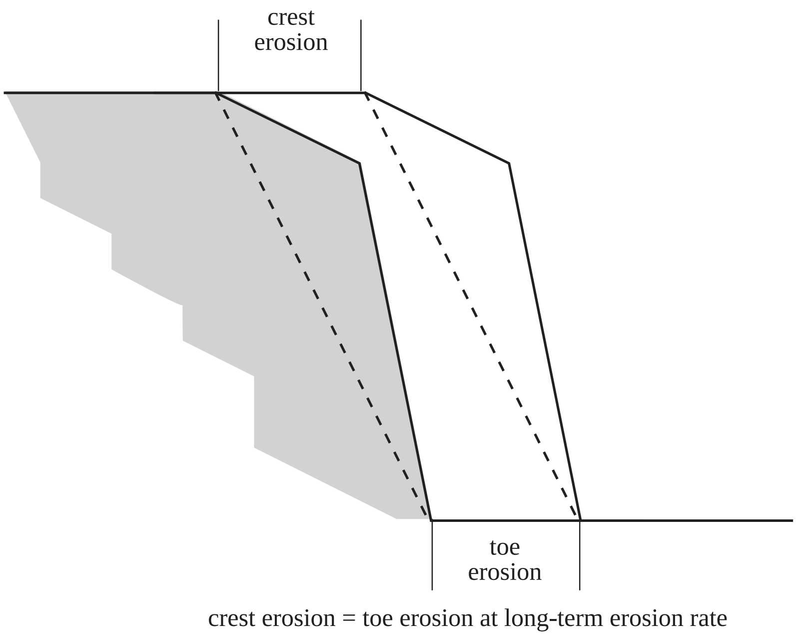
  Weathering originates at the surface and progressively works its way into the rock. It is generally a function of geological type, age and rock defect proportion. Rock altered by weathering takes on entirely different properties and is generally less stable than unweathered rock. Typically, eroded cliff material in the Auckland region breaks down to silts and clays, providing very little material likely to remain within the beach system.
- Sub-aerial processes
  - Mass Movement; generally includes falls, topples, slides, spreads and flows. These movements occur primarily along defects or after other erosional processes have weakened or destabilised sections of cliff.
  - Rain-wash; more a process of removal of loose and semi-loose material rather than a direct mechanism for erosion. Weathering or mass movement may initiate this loose material.

- Wind erosion; another process for removal of loose and semi-loose material from a cliff face or toe.

Cliff erosion typically has two components; a gradual retreat caused by weathering, marine and bio-erosion processes, and episodic failures due to cliff lithology and geologic structure. A cliff face erodes back episodically at a rate not less than the rate of cliff toe retreat (Figure 7.1). However, the cliff top can erode back faster than the toe due to cliff lithology and geologic structure.

Due to the weakly cemented nature of the material, erosion of a soft-cliff shore is much more vulnerable to weathering and coastal processes than hard cliffs. Due to the soft, readily erodible nature of the soft-cliff, rates of erosion therefore tend to be significantly higher than hard cliff shores, and potentially may increase due to sea level rise (Defra, 2002), with more hydraulic action acting on the face of the cliff.

Figure 7.1
Minimum extent of long term retreat of cliff shore where uniform lithology and structure is present



7.1 Methodology

7.1.1 Hard cliffs

The area susceptible to erosion for hard cliff coastlines was established from the cumulative effect of (refer Figure 7.2):

$$ASE_{Cliffs} = \left[(LTR_H \times T) \times F + \left(\frac{H_t + 2.5}{\tan \alpha} \right) \right]$$

Where:

LTR_H = Historic long-term retreat (regression rate), m/yr, based on published data sources and judgement. Where lawful council owned and managed seawalls are present along the cliff toe over a length of more than 500 m, this term is set to zero.

T = Timeframe; 100 years.

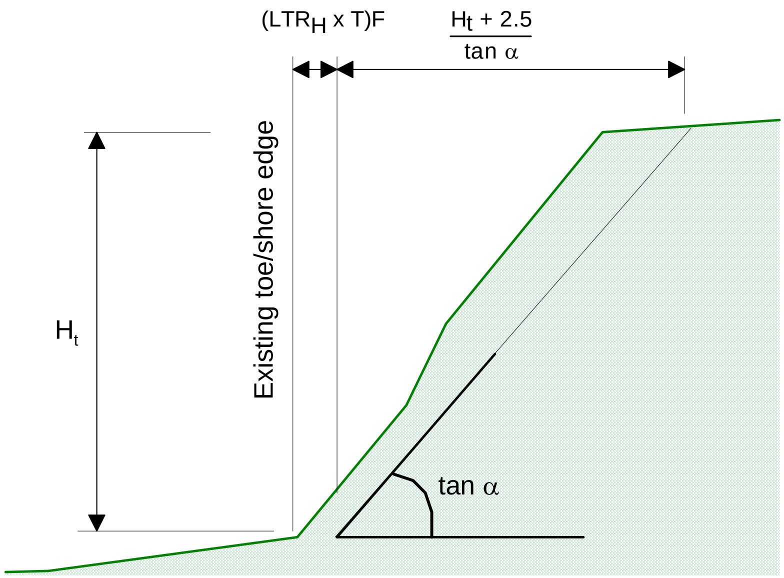
F = Allowance for uncertainty associated with long-term retreat rates.

H_t = Height (m) of cliff from LINZ topomap or site data, m.

2.5 = Error associated with the height of the cliff, m based on standard error of LINZ topomap.

α = The characteristic slope angle of the cliff surface measured from the horizontal. This angle varies according to the likelihood of failure, defined in Table 7.1.

Figure 7.2
Definition section for cliff shores



If the toe of a cliff is held constant (i.e. LTR = 0) the remainder of that cliff may continue to erode. This process is evident along cliffs that are fronted by seawalls that prevent ongoing coastline retreat at the toe. An example of this can be seen at Bastion Point, along Tamaki Drive, where in spite of seawall protection at the toe, the cliff crest and face continues to erode. Erosion of the upper section of cliff will continue until the cliff reaches a more stable angle.

The cliff slope angle tends to be controlled by a cliff's lithology and structure. This means that if a characteristic angle can be determined for a certain GSI for a particular stability scenario, the same angle can be applied to other cliff areas with the same GSI. Deviations in characteristic angle occur due to bedding orientations, defect proportions and other local irregularities. For the purposes of this study, two angles were derived to provide a range of likelihoods.

In terms of the likelihood of erosion affecting a particular area, the potential for the areas susceptible to erosion eventuating over the 100-year planning period is indicated in Figure 7.3 and defined in Table 7.1. The steeper angle is more typical of the characteristic angle of a rock mass with fewer defects and the probability of the cliff reaching that angle is quite high. The flatter slope is more representative of the characteristic angle for rock with significant defect control and provides a slope which is less likely to be reached. We note that the area of greatest susceptibility (the "Likely" definition on Table 7.1) is based on the translation of the existing profile, solely takes into account the long-term retreat rate. This situation is shown in Figure 7.1. There is insufficient detailed topographic information to measure the existing cliff slope accurately. Therefore, the width of this zone is not able to be measured in this region wide assessment. At a site-specific level it could be established from the crest of the cliff, inclusive of the weathered slope as shown in Figure 7.1.

Using LTR_H solely gives no allowance for the single, large events that may cause large excursions in localised areas. If a precautionary approach is used some allowance should be made for these one-off events. This assessment includes the identification of widths based on the "possible" and "unlikely" characteristic angles, which provides a maximum extent of the areas susceptible to cliff areas susceptible to erosion over the next 100 years and takes into account those other processes not represented by LTR_H.

An example of these zonings can be seen in Figure 7.4. This figure shows an example of local cliff failure and the representation of the various delineations on risk in relation to the cliff edge. While long term retreat is likely along the entire cliff edge over the planning period, there can be localised events that could occur creating erosion landward of the "likely" area.

Figure 7.3

Cliff areas susceptible to erosion

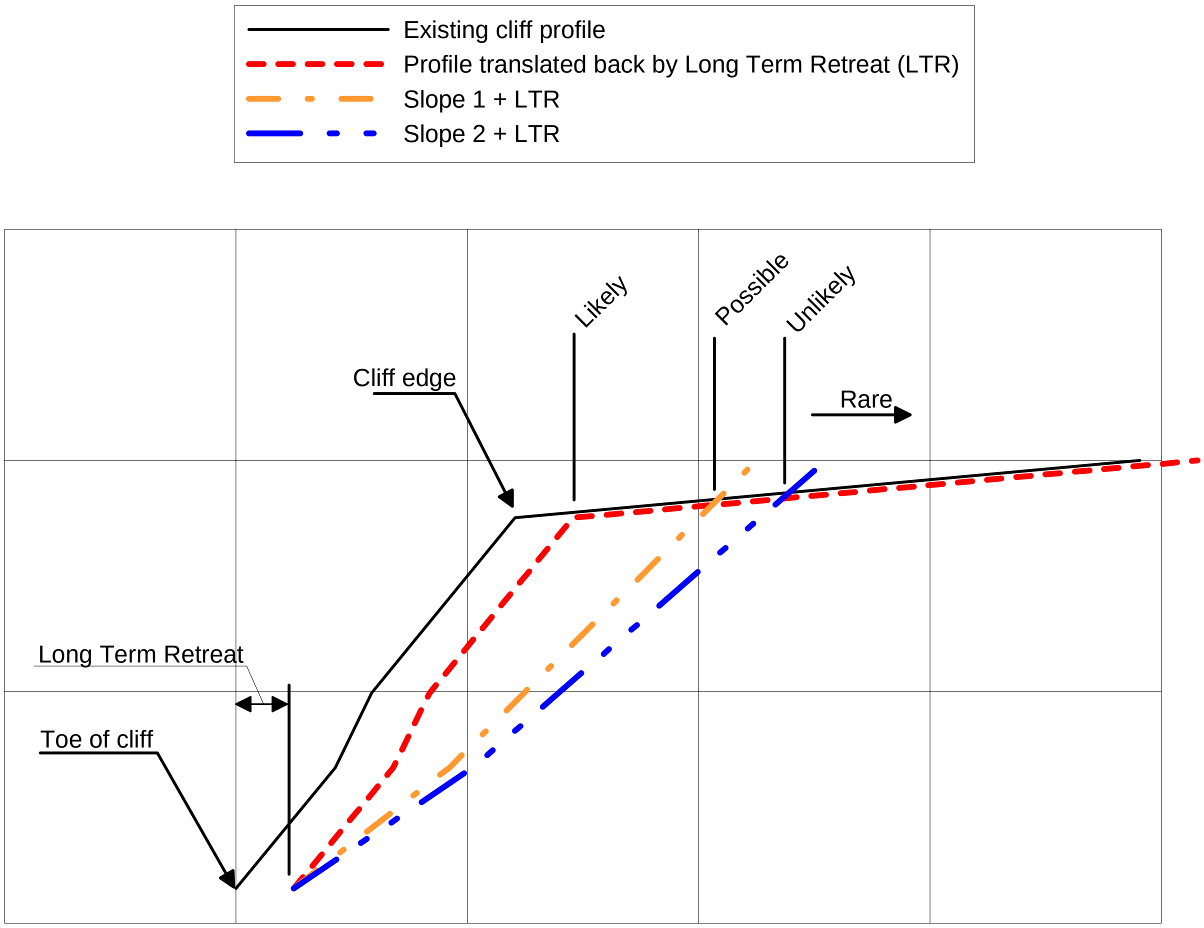
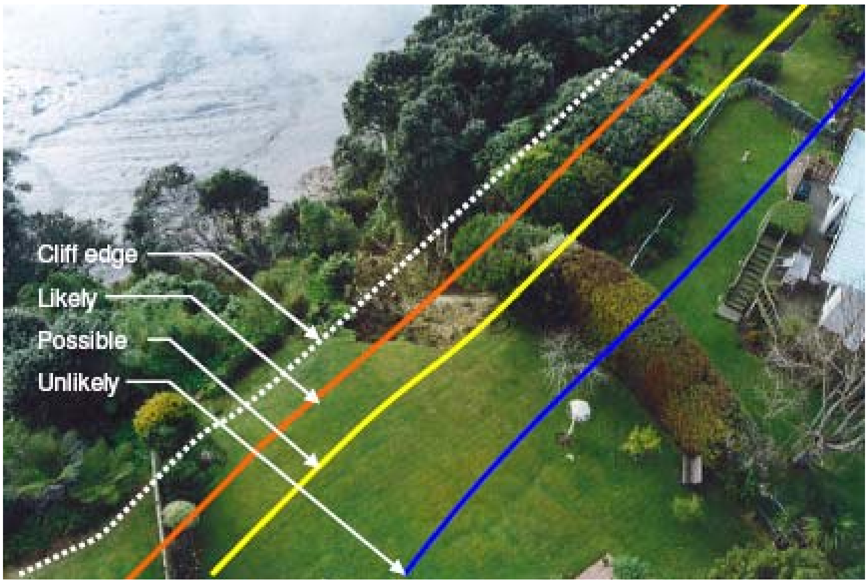


Table 7.1

Likelihood of cliff erosion

Likelihood	Description
Likely	Translation of existing profile by the LTR over 100 years. Will probably happen during the 100 year timeframe.
Possible	LTR over 100 years and slope angle 1. Might occur some time during the period of concern.
Unlikely	LTR over 100 years and slope angle 2. Unlikely to occur but possible during the period of concern.
Rare	Coastline change landward of LTR and slope angle 2 line. Highly unlikely within 100 year timeframe, but conceivable.

Figure 7.4
Illustration of the location of the areas susceptible to coastal erosion



7.1.2 Soft cliffs

Areas susceptible to erosion in soft cliff areas were determined using similar methodology to that used for hard cliffs. However, soft cliffs are likely to respond to sea-level rise and therefore allowance needs to be included for accelerated sea level rise effects. This was done by applying a factor to the historic long term retreat rate based on the predicted relative increase in sea level. The formula for accelerated sea-level rise induced retreat is given as:

$$LTR_{2100} = \left(LTR_H \times \left(\frac{SLR_F}{SLR_H} \right) \right)$$

Where:

LTR_{2100}	=	Horizontal coastline retreat due to possible accelerated sea-level rise (m)
SLR_H	=	Historic sea-level rise rate for Auckland (1.3mm/yr, Hannah, 2004)
SLR_F	=	Future sea-level rise rate - 4.5 mm/yr, based on 0.50m increase at 2100 from 1990 levels (IPCC, 2001)

This formula is used by the National Research Council in the UK to assess cliff erosion effects of sea level rise (Defra, 2002). The formula assumes that future erosion will be proportional to the ratio of future to past sea-level rise.

This gives an area susceptible to erosion for soft cliffs defined by of:

$$ASE_{Soft\_Cliffs} = \left[\left(\left(LTR_{2100} \right) \times T \right) \times F + \left(\frac{H_t + 2.5}{\tan \alpha} \right) \right]$$

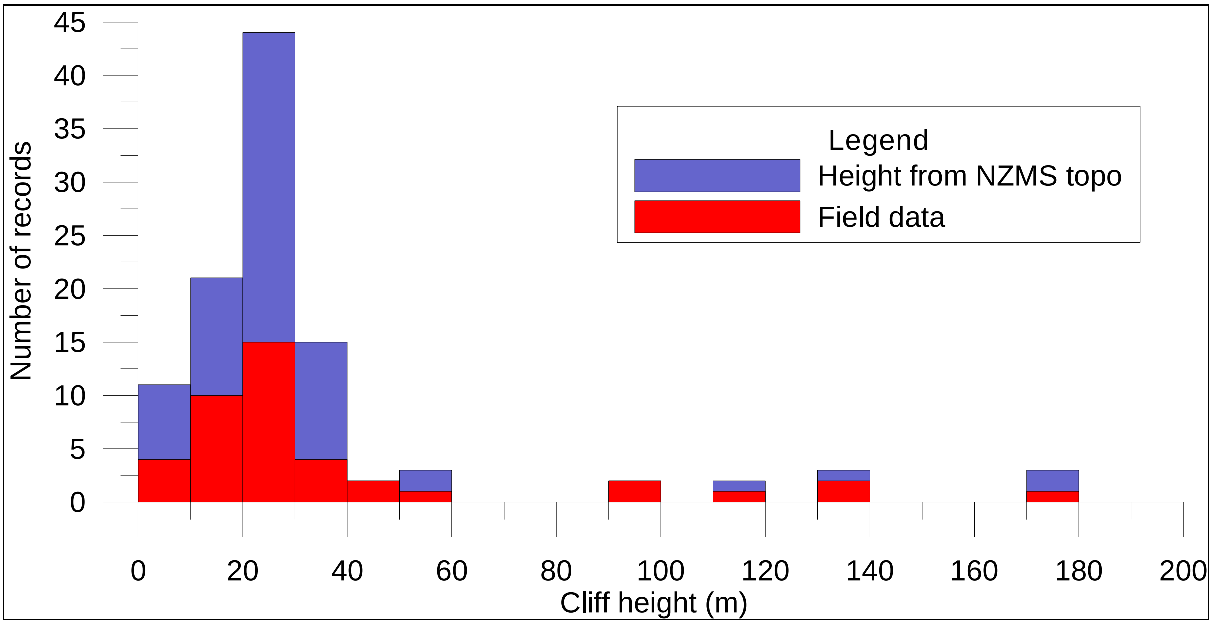
7.2 Characteristic Slope Angles

Measurements of cliff slopes were obtained from locations throughout the Auckland area. Appendix E has the tabulated cliff height and measured slope angle data.

Figure 7.5 shows the cliff height distribution of these 40 observations. Also included in this plot is the distribution of cliff heights from the cliff coastline delineations used for this study based on LINZ data. A comparison of the field data sites with the LINZ data shows the field data represents the typical distribution of cliff heights within the Auckland region.

Figure 7.5

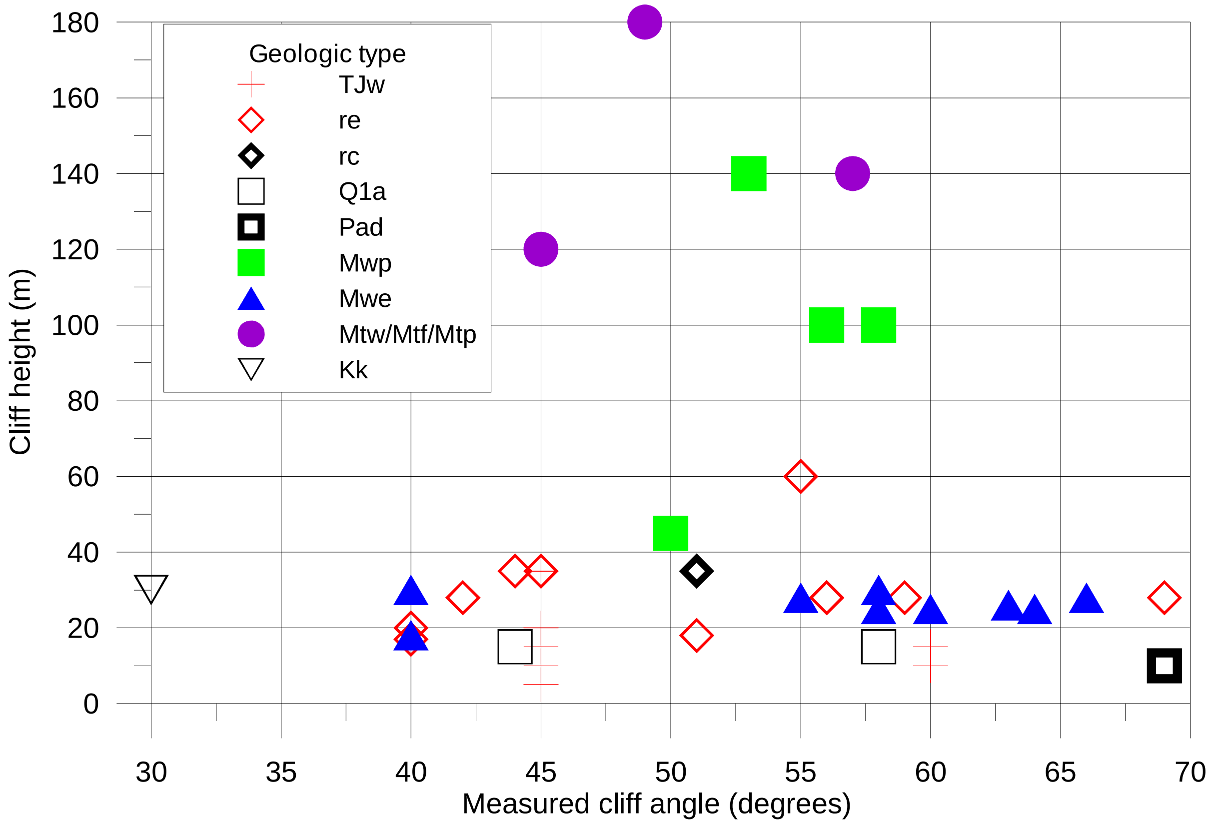
Histogram showing cliff height distribution both from field data and as measured from LINZ topo data



The majority of the cliffs are less than 40 m, with a median height of 28 m. Figure 7.6 shows the relationship between cliff slope and cliff height based on the attributed geology for each area. Table 7.2 provides definitions of the geological types. The higher cliffs are typically volcanic or Pakiri Formation and the lower cliffs are formed from Tauranga Group materials. Typically the only cliffs higher than 40 m are volcanic in origin, although there is one East Coast Bays Formation with a height of 60 m from the Whangaparaoa Peninsula. These results show that no clear relationship is observable about the relationship between cliff height and slope based on geologic type. However, it was observed that other factors such as structure and surface conditions influence the slope angle of the cliff face, particularly for the non volcanic rock types.

Figure 7.6

Measured cliff angle versus cliff height



Further examination of the relationship between height and slope was based on the GSI values attributed to various cliff areas. Table 7.3 shows the results of statistics for each GSI range, including all slopes for that range as well as the 1 and 2 standard deviation slopes and the maximum and minimum slopes. Figure 7.7 shows the resulting fit for the average, 1 sd and 2 sd lines. This figure shows that the lack of data points in both the 60-85 and the 25-45 GSI range provide results that are unlikely to be statistically accurate.

The results show that there is a trend of increasing slope for increasing GSI classification. However, there was no obvious progression of increasing slope with geological type. This suggests that there may not be a strong relationship between slope and intact rock strength, the slope being more controlled by local defects, particularly the presence of interbedded silt layers.

Table 7.2

Definitions of geological types

Symbol	Description	Formation/subgroup	Group	Geology
TJw			Waipapa	Basement
re		East Coast Bays	Waitemata	Waitemata
rc	Cornwallis Formation	Warkworth	Waitemata	Waitemata
Q1a	Alluvial/colluvial deposits		Tauranga	Poorly consolidated alluvium/marine
Pad	Cemented dune facies		Awhitu	Moderately consolidated alluvium/marine deposits
Mwp		Pakiri	Waitemata	Waitemata
Mwe		East Coast Bays	Waitemata	Waitemata
Mtd	Waiatarua Formation	Manukau Subgroup	Waitakere	Volcanic
Mitt	Tirikohua Formation	Manukau Subgroup	Waitakere	Volcanic
Mtp		Piha Formation		Volcanic
Kk		Mangakahia Complex	Northland Allochthon	Displaced

The numerical model SLIDE was used to investigate the relationship between inferred GSI and slope angle, particularly the effect of local defects, in order to assess potential slope stability for a range of cliff scenarios. SLIDE is a 2D slope stability program for evaluating the stability of circular or non-circular failure surfaces in rock slopes. SLIDE calculates safety factors for circular slope failure surfaces, based on two widely used limit equilibrium techniques: Bishop or Janbu simplified analyses. Individual slip surfaces can be analyzed, or search methods can be applied to locate the critical slip surface for a given slope.

Slope stability analysis was carried out for a 30 m high drained cliff with a Hoek & Brown constant, mi = 7, representative of siltstone and a unit weight of 22 kN/m3. This representative cliff was of a height that matched the median measured height and was considered typical of the soft sedimentary rock cliff conditions of the East Coast Bays. It was assumed that hydraulic processes would remove all slope debris (i.e. no talus slope), which is representative of the observed situation around the majority of Auckland's coastline. The presence of silt lenses within the cliff slope regulates the erosion rate of the more competent rock material. The disturbance factor was set to 0, representative of an undisturbed rock mass.

The slope stability was analysed for a range of GSI values and with unconfined compressive strengths of 1.0, 1.5 and 5.0 Mpa with a Factor of Safety of 1.0 and 1.5. The results of this analysis are shown in Table 7.4 and Figure 7.8.

Table 7.3

Slope statistics for each GSI range

GSI	Average slope[1]	Standard deviation	Number of data points	Average – 1 SD	Average – 2 SD	Minimum recorded slope	Maximum recorded slope
80-95	No data	No data	No data	No data	No data	No data	No data
60-85	50.3	6.1	3	44.2	38.1	45	57
55-75	55.1	7.0	14	48.1	41.1	40	66
40-65	52.4	10.0	16	42.4	32.4	40	69
25-45	47.0	6.5	6	40.5	34.0	42	60

1. From measured data sources

Figure 7.7

Average slope and range for each GSI range

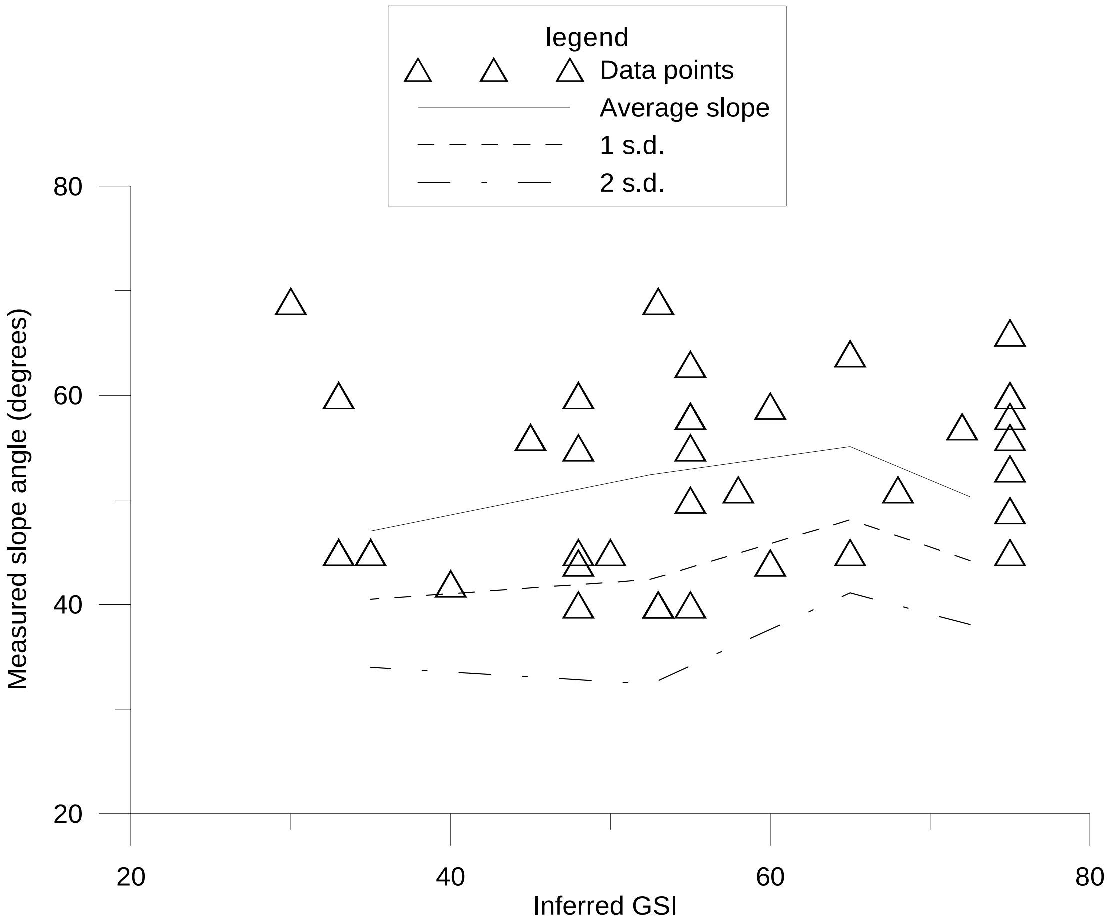


Table 7.4

Slope angles based on SLIDE analysis

Unconfined Compressive Strength (Mpa)	GSI	Slope angle with FoS = 1.0	Slope angle with FoS = 1.5
	20	32	20
1	40	43	32
	60	55	39
	80	80	51
	20	33	21
1.5	40	50	33
	60	70	43
	80	85	64
	20	50	34
5	40	70	50
	60	85	72

The results of the SLIDE analysis showed steeper slope angles for increased intact rock strength and improved surface conditions, with the 1 MPa line (FOS = 1.5) providing a lower bound to the majority of the measured data. The SLIDE results appear more representative of what would be expected than the statistical data based on limited data points.

The results show that F=1.5 lies just below the data set and approximates the -2 s.d. line. F = 1.0 is in the centre of the data set, close to the average. The results of this process suggest the 1.0 MPa (FOS = 1.5) represents the slopes that would be "unlikely" to occur over the 100 year planning horizon, while the 1.0 MPa (FOS = 1.0) represent the slopes that would "possibly" occur over the 100 year planning horizon. This provides a precautionary approach that can be refined with more site specific assessment.

Table 7.5 and Figure 7.9 show the resulting slopes for each GSI range. Table 7.5 also shows the slope angles inferred for Tauranga Group and recent alluviums. These characteristic slopes were derived based on our long term experience with these materials. Figure 7.7 shows that the slope angle selected applies to the entire range of GSI, providing a stepwise increase in slope angles, with a constant slope for each GSI range.

Figure 7.8

SLIDE results

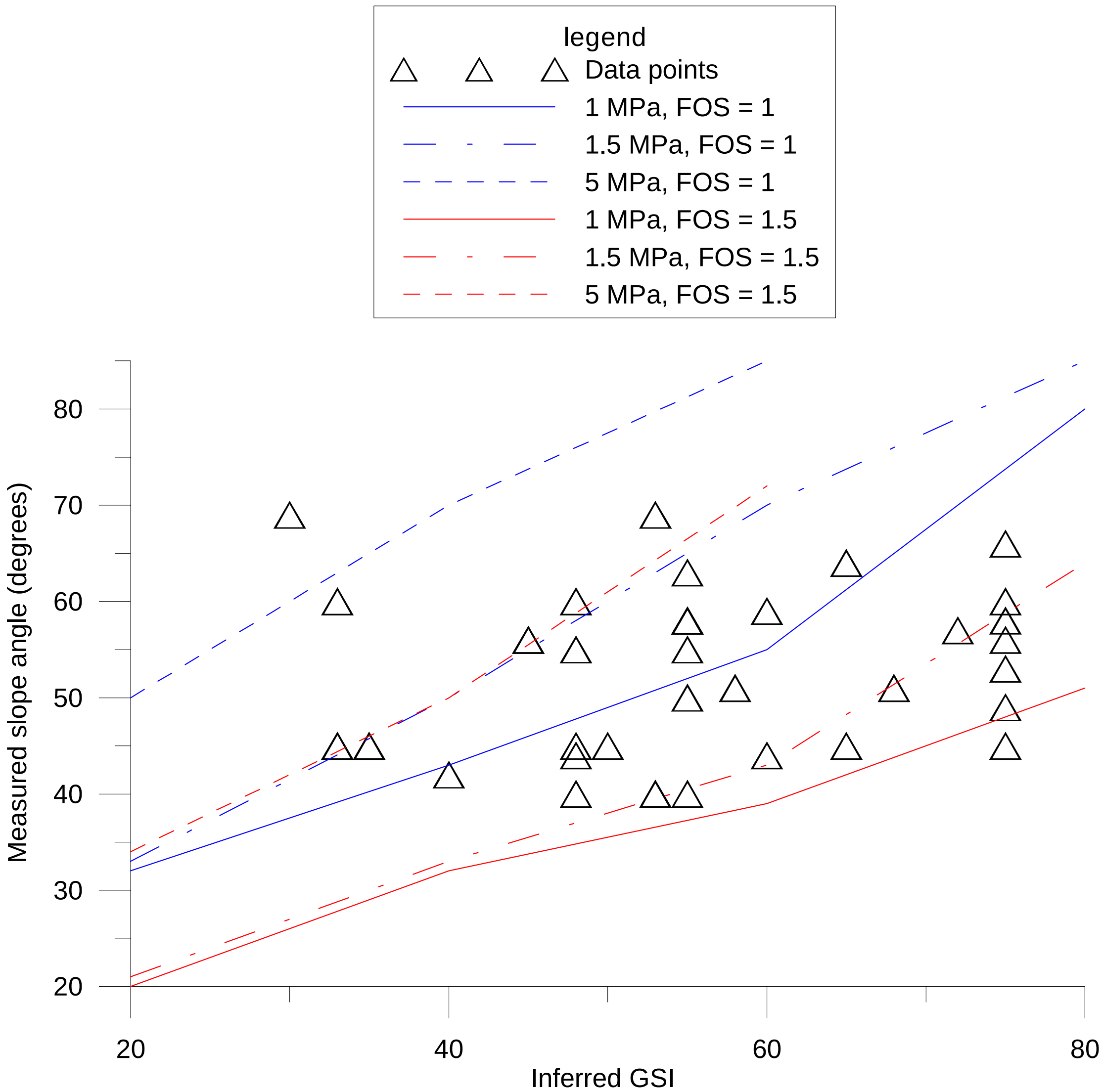


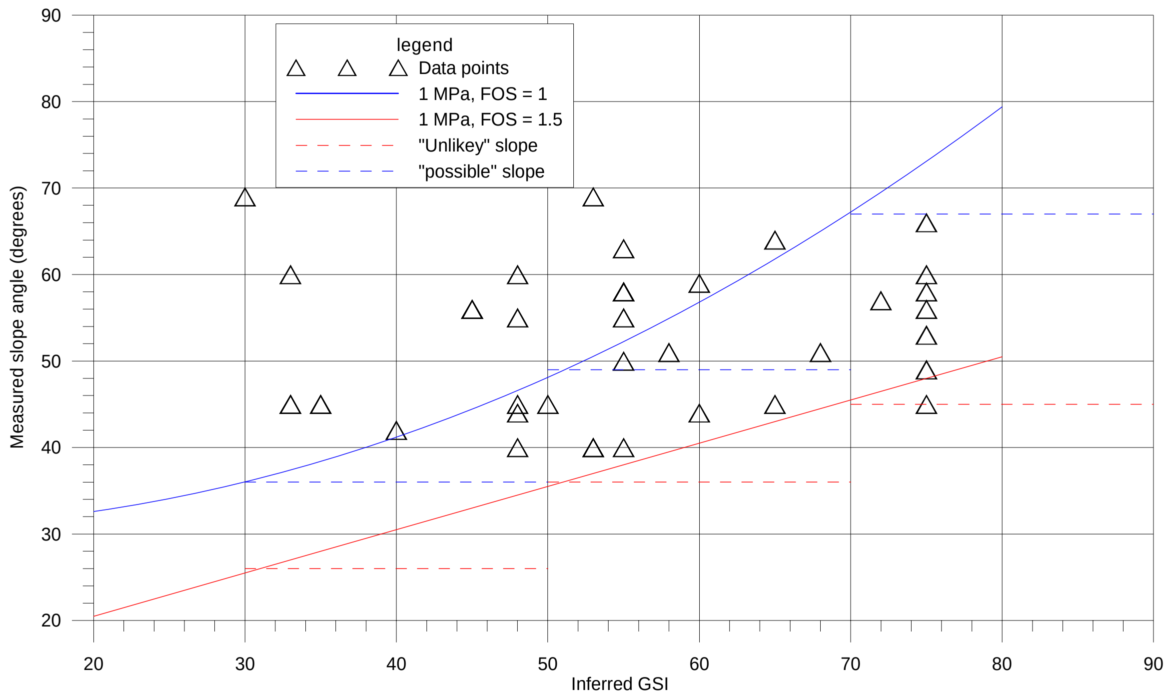
Table 7.5

Slope angles for determining coastal areas susceptible to erosion

GSI/category (average value and range)	Slope angles (°)	
	Possible	Unlikely
Alluvium	26	18
Coastal sediments	32	22
20 ± 10	32	22
40 ± 10	36	26
60 ± 10	49	36
80 ± 10	67	45

Figure 7.9

Derived characteristic slope angles for possible and unlikely erosion events during planning period



7.3 Cliff Heights

The amount of land potentially affected landward of the cliff is a function of both the characteristic slope angle and the height of the cliff (refer Figure 7.2). Cliff heights were determined for each coastline section based on field data and the LINZ 20 m contour data. The average height of the highest one third of cliffs within each coastal cell was used as a general guide to represent the typical height of the cliff section to provide a realistic but conservative height, while excluding extremes.

Due to the limited nature of available data, both in extent and accuracy, over-precision was avoided and heights were given in 5 m intervals with an error allowance of 2.5 m included in the calculations. In areas where height varied considerably along a section, the section was divided to create smaller cells with more representative heights. Heights vary considerably around the Auckland region with many low, banked areas having heights of less than 1m, and other areas having cliffs well over 150m high. The typical height of each coastal cliff section, along with other factors determining the areas susceptible to the coastal areas susceptible to erosion zone, is included in the table in Appendix G.

7.4 Long-Term Retreat Trends

The Long-Term Retreat (LTR) rate is an estimate of the average shoreline retreat at the toe of the cliff. The LTR for specific coastlines tend to fall into one of the following categories:

1. No data exists. No estimates on erosion rates by suitably qualified persons exist.
2. No data exists. One or more estimates on erosion rates have been made by suitably qualified persons.
3. Limited data exists. Suitably qualified persons have used this to make informed estimates on erosion rates.
4. Substantial local data has been analysed (>50 years) to calculate long-term erosion rates.

Suitably qualified persons include experienced engineers, scientists and members of the public with very long site-specific associations. Reliability of long-term erosion data tends to increase from 1 through to 4.

Data on long-term retreat rates may come from aerial and cadastral surveys, man-made structure measurements and geological markers. Each method has advantages and disadvantages and associated errors and inaccuracies:

- Aerial surveys: These generally date back to 1940 or earlier, satisfying the 50yr+ requirement. They are relatively easy and cheap to carry out and cover a wide area. For these reasons they have been carried out at fairly regular intervals. Vertical aerial photographs can be used to quantitatively identify erosion. However, slightly oblique photographs have perspective distortion resulting from their viewing geometry. This distortion is corrected by transforming (rectifying) the photographs into a vertical view. Errors may occur during this transformation giving slightly inaccurate ground positions. This may translate into errors in cliff position of metres or more, giving inaccurate erosion rates. It should also be noted that aerial survey based erosion rates tend to be determined by crest retreat not movement of the cliff toe, therefore they are much more sensitive to landslides and other large-scale mass-movement processes and more typically provide higher rates of retreat than would be expected at the cliff toe.
- Cadastral surveys: These rely on the accuracy of surveyors and survey equipment and the reliability of ground based markers. In some places these have been carried out since the 19th century. However, cadastral surveys typically only cover a relatively small area, are carried out at different time periods and often have different definitions of MHWS or the coastline.
- Man-made structures/trees: Cliff face positions have been measured relative to particular structures or significant trees since 1926. These types of measurement can provide very accurate retreat rates for very specific cliff areas. However, they rely heavily on the integrity of the particular structure.
- Geological markers: Shore-platform width can be used as an indicator of long-term erosion rates. The assumption is that sub-surface rock erosion is negligible in a

horizontal direction. This means that since sea-level stabilised at its current level approximately 6500BP, the width of shore platform gives a useful indication on the extent of erosion occurring since this time.

Based on our evaluation of the data for this study, it appears that where several methods have historically been used to determine LTR, aerial surveys typically give values at the upper end of the range of rates estimated, while shore platform widths typically give values at the lower end. Man-made structure measurements and cadastral survey rates tend to fall in between these two. An example of this is on Auckland's North Shore where a range of erosion rates have been determined using various methods:

- Aerial Surveys: Brodnax (1991) compared aerial photographs since 1940 and found rates of erosion to vary between 50 and about 300mm/yr. Average rates were found to be ~150mm/yr.
- Cadastral Surveys (1920 – 1980): Brickell Moss Raines & Stevens Ltd. in Riley (2001) found rates of 50 – 100mm/yr, averaging 75mm/yr.
- Man-made structures: Riley (2001), Brodnax (1991) and Glassey (2003) analysed a variety of structures dating back to 1926 and found rates varying between 0 and 82mm/yr. Their average rate was around 40mm/yr.
- Geological markers: Moon and de Lange (2003) used 7,400 years as their available time for shore platform development. Platform widths between Waiake Beach and Browns Bay were measured at 10 – 100m giving erosion rates of 4 – 20mm/yr.

For the purposes of this study erosion rates derived by shore platform width were evaluated based on a combination of GSI and exposure. An exposure rating of 1 to 4 was derived, with a rating of 4 for the most exposed areas, being the west coast and the outer Hauraki Gulf. A rating of 3 was applied to the inner Hauraki Gulf, Firth of Thames and the Tamaki Straits. A rating of 2 was applied to the Upper Waitemata, Manukau and Kaipara Harbours, with a rating of 1 applied to the smaller estuaries and tributaries. Table 7.6 shows the calculated average erosion rate based on shore platform width for the entire GSI range as well as for each exposure grouping. The table includes the number of observations and the maximum and minimum values obtained.

The average erosion rate for the combined GSI group shows low erosion rates for high GSI numbers and increasing erosion rates for decreasing GSI. This result is consistent with expectation. While data are not extensive the results show a general trend of increasing erosion rate with increasing exposure for the majority of GSI classes, although for the high GSI values this trend is not apparent.

These results suggest that the dominant factor affecting long-term retreat in cliffs is the structure and surface condition of the rock mass, rather than the exposure. This appears to be substantiated by high erosion rates being observed even in sheltered areas compared to similar geological types with better structure and surface condition. The key marine process affecting cliff erosion is therefore expected to be associated more with the removal of talus and debris that would otherwise form at the toe of the slope.

Table 7.6

Erosion rate from observed shore platform width

GSI range	Average rate excluding exposure (m/100 yr)	Exposure	Average rate (m/100yr)	Number of observations	Maximum rate (m/100 yr)	Minimum rate (m/100 yr)
80-95	< 0.3	4	< 0.3		< 0.3	< 0.3
65-85	0.4	4	< 0.3		< 0.3	< 0.3
		3	0.3	1	0.3	0.3
		2	0.5	1	0.5	0.5
		1	1.7	1	1.7	1.7
55-75	1.5	4	2	1	2	2
		3	1.4	5	1.5	1.2
		2	1.6	27	3.1	0.9
		1	1.1	5	1.5	0.9
40-65	1.6	4	No 40-65 GSI cliffs within this exposure rating			
		3	2.5	1	2.5	2.5
		2	1.6	17	3	0.9
		1	1.3	6	2.3	0.9
25-45	1.7	4	No 40-65 GSI cliffs within this exposure rating			
		3	2.5	1	2.5	2.5
		2	2	2	3.1	0.9
		1	1.3	4	1.8	1.1
< 25	No platforms readily evident due to large scale erosion and sedimentation. Rates of between 5 m and 10m/100 yr reported based on aerial photograph assessment.					

Based on the above results and our expert judgement, the following long-term retreat rates were determined and are presented in Table 7.7. All numbers have been rounded up to the nearest whole number.

Table 7.7

Inferred historic Long Term Retreat (LTR)

GSI range	Historic long term retreat rate (m/100 years)
>80	1
75 ± 5	2
65 ± 5	3
52.5 ± 7.5	4
35 ± 10	5
<25, soft cliffs	10

7.5 Climate Change Effects

The key climate change effects affecting cliff erosion include the potential for increased rainfall intensity and frequency as well as accelerated sea level rise. Rainfall effects are taken into account by using a range of characteristic slope angles.

Sea-level rise is thought to have an effect on soft, poorly consolidated cliffed coastlines (soft cliffs), but not on more competent rock with GSI values greater than 25. To acknowledge the risk on soft cliffs an extra factor for 'erosion due to sea-level rise' has been included in the establishment of areas susceptible to erosions for all soft cliff areas. This factor is calculated as shown in Section 6.1.1 and is controlled by the ratio of past to predicted future sea level rise and historic retreat rates (Defra, 2002).

The effect of other climatic changes are expected to be minimal but may be included in future assessments should information become available.

7.6 Assessment of Uncertainty

The key parameters for establishing the cliff areas susceptible to erosion are:

- long term retreat
- characteristic slope angle
- cliff height

The historic long-term cliff retreat rate assessment involves considerable unknowns in terms of the actual values of LTRH as the spatial and temporal data of long term erosion is limited. However, the magnitude of LTRH is reasonably well accepted for hard cliffs in the Auckland region, with all estimates given in Table 7.7 in the range of 0 – 11 m/century, and most < 4 m /century. Due to the relatively low erosion rates, errors in the LTRH estimate will not have a very significant impact on the final width as derived. However, due to the lack of information and knowledge, a Factor of Safety of

1.25 has been applied to the LTRH. This causes an increase of between 0.25 m to 2.5 m depending upon the inferred long term retreat rate.

Characteristic slope angles have been determined based on a combination of statistical assessment of measured data, judgement and numerical modelling. By using the slope from the lowest GSI value in the range, and by having reasonably wide and overlapping GSI categories, a precautionary approach is provided and no additional factor of safety is required for this parameter.

Cliff heights are derived from a combination of LINZ data and measured data, with the assessed average height rounded to the nearest 5 m interval and a single height representative of the majority of cliff length is applied over the entire coastal cell. Vertical accuracy of the LINZ data is between +/- 5m and +/- 10m, with the lower value for well-defined points, which should include the cliff edge. For the lower cliffs (less than 20 m) measured data has been used. The influence of this uncertainty varies depending upon the slope used, with a greater influence for flatter slopes and a smaller influence for steeper slopes. The resulting increase in horizontal width varies depending upon the characteristic slope, but using +2.5 m (half the expected vertical accuracy range) the increase is typically around 5 m for the maximum "possible" slope and is 8 m for the maximum "unlikely" slope. These increases in horizontal width have been applied to derive the final areas susceptible to areas susceptible to erosion.

7.7 Assessment of Areas Susceptible to Erosion

Table 7.8 shows the results of the cliff areas susceptible to erosion assessment, providing the width of the area susceptible to erosion effects extending landward from the toe of the cliff for both the "possible" and unlikely conditions taking into account the cliff category (GSI, alluvium or consolidated coastal sediment), cliff height, the characteristic slope and the Long Term Retreat Rate.

Table 7.8

Widths of coastal area of cliff shores susceptible to erosion

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
1	11.0	2714718	6453043	2714025	6462609	37	52
2	1.5	2713782	6463854	2714025	6462609	37	52
3	1.4	2711773	6466882	2712768	6465944	23	32
4	4.5	2709184	6469421	2711773	6466882	80	108
5	9.1	2696069	6472281	2695760	6469888	30	34
6	1.4	2708563	6470017	2709184	6469421	37	52
7	0.5	2708200	6470241	2708563	6470017	23	32
8	3.2	2697235	6470882	2698848	6470638	39	46
9	15.5	2675344	6472771	2675945	6471035	39	46

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
10	1.0	2707528	6470653	2708200	6470241	37	52
11	3.4	2695760	6469888	2697235	6470882	29	41
12	11.0	2675945	6471035	2677063	6472188	10	20
13	1.3	2698848	6470638	2699172	6471456	29	41
14	1.2	2699172	6471456	2700327	6471484	11	14
15	1.4	2706042	6471599	2706734	6471046	23	32
16	3.0	2704164	6471302	2706042	6471599	22	31
17	5.1	2700327	6471484	2701894	6470567	29	41
18	15.8	2683189	6474265	2685480	6473783	16	22
19	1.3	2695802	6473405	2696069	6472281	29	41
20	10.3	2686685	6474903	2687590	6475809	34	40
21	2.1	2695882	6474637	2695802	6473405	30	34
22	28.2	2677063	6472188	2676144	6474835	34	40
23	1.8	2685480	6473783	2685808	6474736	39	46
24	7.9	2675545	6476070	2675344	6472771	6	10
25	2.5	2684528	6475843	2683189	6474265	25	36
26	1.2	2685808	6474736	2686685	6474903	20	29
27	2.9	2676144	6474835	2676882	6475165	5	8
28	1.2	2676262	6475726	2675545	6476070	9	17
29	4.6	2695224	6475244	2695882	6474637	58	83
30	0.8	2687590	6475809	2687565	6476550	16	22
31	3.7	2676882	6475165	2678430	6477168	49	62
32	2.4	2676879	6477585	2676262	6475726	5	9
33	1.1	2683733	6476848	2684185	6476165	36	55
34	22.1	2658150	6481280	2658856	6480462	39	46
35	0.4	2687565	6476550	2687631	6476938	32	37
36	2.4	2687631	6476938	2687431	6477608	0	0
37	3.9	2678430	6477168	2679514	6478432	29	41
38	2.7	2693280	6478033	2694283	6475954	30	42
39	2.7	2681514	6478603	2683363	6477022	38	57
40	7.3	2705952	6475438	2706213	6480622	58	90
41	1.4	2679514	6478432	2680106	6478760	0	0
42	5.6	2687431	6477608	2690962	6478440	30	42
43	4.5	2659620	6479916	2661507	6478334	32	37
44	8.0	2678095	6480446	2676879	6477585	41	49
45	2.3	2661507	6478334	2662346	6479514	12	15

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
46	6.4	2671822	6480404	2672565	6480275	8	15
47	8.8	2662346	6479514	2659620	6479916	0	0
48	1.3	2680315	6480900	2680723	6479785	36	55
49	1.8	2670572	6480468	2671603	6480574	25	36
50	0.7	2672565	6480275	2672065	6480652	49	62
51	0.9	2669905	6480496	2670572	6480468	39	46
52	0.6	2672065	6480652	2671730	6481112	10	20
53	1.4	2678008	6481601	2678095	6480446	91	133
54	4.1	2661854	6479791	2662737	6481379	14	19
55	1.0	2679790	6480652	2679781	6481642	38	57
56	1.7	2670232	6481975	2669905	6480496	25	36
57	4.5	2662737	6481379	2663088	6481456	39	46
58	0.7	2671730	6481112	2671369	6481604	4	5
59	2.0	2679781	6481642	2680315	6480900	58	83
60	1.8	2663088	6481456	2664219	6482097	15	21
61	8.0	2671603	6480574	2670232	6481975	0	0
62	2.1	2676343	6482041	2677818	6481792	91	133
63	6.5	2671360	6481640	2676343	6482041	0	0
64	1.4	2657045	6482238	2656392	6482977	43	52
65	3.5	2658510	6484308	2658150	6481280	45	56
66	8.7	2654751	6481782	2657045	6482238	34	40
67	2.7	2664219	6482097	2665577	6483496	19	28
68	15.5	2665577	6483496	2669949	6482217	0	0
69	3.3	2671880	6484174	2669312	6484504	0	0
70	3.8	2656392	6482977	2657636	6484996	23	32
71	8.7	2657131	6486243	2654751	6481782	41	59
72	2.1	2669312	6484504	2669210	6484758	25	36
73	0.9	2671926	6484714	2671880	6484174	21	45
74	2.2	2666647	6485702	2666211	6485330	13	18
75	1.6	2657636	6484996	2658510	6484308	39	46
76	3.2	2669210	6484758	2670156	6485476	34	40
77	2.6	2668985	6485752	2668782	6486139	22	32
78	2.3	2666211	6485330	2664870	6485219	32	47
79	7.2	2664220	6485193	2660934	6487279	48	69
80	1.2	2664870	6485219	2664220	6485193	20	29
81	1.0	2671309	6486012	2671557	6485262	37	52

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
82	2.2	2670156	6485476	2668985	6485752	16	22
83	1.4	2657297	6486792	2657131	6486243	0	0
84	0.9	2670558	6486990	2670998	6486233	48	69
85	6.1	2668782	6486139	2668292	6488300	13	18
86	4.0	2659374	6487771	2657565	6487457	53	68
87	0.8	2657565	6487457	2657297	6486792	23	32
88	11.0	2668292	6488300	2666647	6485702	34	40
89	0.8	2670129	6487628	2670558	6486990	32	47
90	1.0	2669416	6488237	2670129	6487628	48	69
91	2.5	2660934	6487279	2660216	6488805	48	69
92	3.3	2657136	6489346	2657376	6488954	19	26
93	5.8	2657848	6488623	2659374	6487771	17	22
94	0.7	2657376	6488954	2657848	6488623	39	46
95	15.1	2660216	6488805	2659025	6491039	48	69
96	2.1	2653775	6490840	2654088	6490600	43	52
97	2.2	2668555	6490933	2668826	6489158	6	10
98	7.8	2654088	6490600	2657136	6489346	17	22
99	7.1	2656390	6492954	2653580	6492039	48	69
100	10.9	2660979	6494701	2656336	6491915	51	73
101	3.4	2653165	6492116	2653775	6490840	19	26
102	4.0	2659025	6491039	2660428	6491777	49	62
103	0.3	2668269	6491784	2668220	6491528	50	72
104	0.7	2660428	6491777	2660081	6492301	37	52
105	2.5	2656336	6491915	2656390	6492954	49	62
106	2.2	2653580	6492039	2653165	6492116	43	52
107	1.9	2667989	6493432	2668481	6491971	52	76
108	3.7	2660081	6492301	2660979	6494701	59	77
109	0.5	2667467	6494205	2667689	6493774	32	48
110	0.5	2667407	6495363	2667081	6495080	28	42
111	1.5	2666792	6496678	2667407	6495363	28	42
112	1.0	2667012	6498178	2667011	6497412	28	42
113	1.6	2667869	6499129	2667056	6498434	29	41
114	1.2	2667133	6499876	2667869	6499129	28	42
115	5.1	2663160	6501739	2663742	6501391	39	46
116	1.9	2666754	6502673	2666678	6500918	28	42
117	4.3	2663742	6501391	2666018	6502808	15	21

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
118	4.0	2665103	6502971	2663160	6501739	28	42
119	1.0	2666018	6502808	2666754	6502673	28	42
120	1.0	2664916	6504323	2664873	6503399	28	42
121	1.2	2666627	6505093	2665823	6504459	30	46
122	1.6	2668069	6505676	2667024	6505388	30	46
123	8.0	2663134	6507385	2664916	6504323	19	28
124	2.0	2668915	6506947	2668069	6505676	30	46
125	5.4	2665823	6504459	2662823	6508325	32	48
126	1.9	2671949	6507178	2670785	6506703	43	61
127	0.8	2669937	6507085	2669311	6507075	28	42
128	2.1	2666446	6507163	2667193	6506747	43	61
129	14.1	2662823	6508325	2663134	6507385	23	32
130	1.8	2668418	6506975	2668680	6508438	36	51
131	2.8	2670785	6506703	2669937	6507085	0	0
132	2.0	2672153	6508739	2671949	6507178	28	42
133	1.7	2673177	6507936	2672691	6508766	48	69
134	3.2	2663503	6509181	2665747	6507203	28	42
135	0.9	2668680	6508438	2669176	6508993	44	63
136	1.0	2669176	6508993	2670000	6509218	29	43
137	2.4	2670000	6509218	2672207	6509497	44	63
138	7.0	2672824	6509653	2674130	6507792	48	69
139	0.6	2662926	6509909	2663271	6509585	19	28
140	10.7	2660628	6510776	2662926	6509909	19	26
141	4.0	2662686	6510245	2660628	6510776	34	40
142	1.1	2662141	6513588	2661791	6512740	23	35
143	1.3	2663346	6514130	2662381	6514104	32	48
144	1.7	2663479	6515536	2663346	6514130	57	82
145	4.3	2660704	6516658	2663593	6516137	49	62
146	1.5	2663870	6517152	2663736	6516225	93	145
147	3.9	2663736	6516225	2660704	6516658	32	48
148	7.3	2660784	6518728	2663965	6517928	53	68
149	0.8	2664484	6518324	2664228	6517931	28	42
150	6.4	2664228	6517931	2660784	6518728	28	42
151	1.8	2664731	6519698	2664803	6518909	23	35
152	2.3	2663759	6519757	2664576	6518947	49	62
153	1.7	2664803	6518909	2663759	6519757	19	28

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
154	0.3	2664725	6520014	2664731	6519698	15	20
155	2.0	2666334	6521004	2665955	6521326	57	82
156	2.6	2663948	6521699	2664725	6520014	36	51
157	1.0	2666972	6521545	2666334	6521004	36	51
158	3.7	2665998	6523528	2665407	6523795	57	82
159	5.5	2668596	6526131	2666972	6521545	45	69
160	22.6	2661956	6524945	2663948	6521699	36	51
161	12.5	2665955	6521326	2665998	6523528	25	35
162	5.0	2665407	6523795	2665401	6527426	57	82
163	0.8	2668160	6527868	2668748	6527372	22	31
164	3.7	2668748	6527372	2668882	6526847	30	46
165	2.0	2667046	6528097	2668160	6527868	47	68
166	21.1	2663594	6528874	2661956	6524945	50	72
167	0.7	2666644	6528684	2667046	6528097	17	22
168	0.8	2666263	6529227	2666644	6528684	50	72
169	7.6	2665401	6527426	2663594	6528874	21	28
170	2.5	2665713	6531156	2666263	6529227	17	22
171	2.3	2665663	6532679	2665713	6531156	28	42
172	1.5	2667160	6532521	2666268	6533056	23	35
173	0.9	2665319	6532947	2665679	6533224	34	40
174	1.3	2671136	6533734	2670860	6533220	50	72
175	0.6	2670860	6533220	2670316	6533288	32	48
176	3.3	2669859	6533316	2668960	6533736	32	48
177	2.5	2668053	6533955	2667521	6532768	28	42
178	1.0	2670316	6533288	2669859	6533316	12	17
179	1.0	2672675	6533991	2671837	6534014	29	43
180	0.6	2673616	6534153	2673088	6534136	29	43
181	8.8	2675778	6535209	2673927	6534436	36	55
182	25.5	2666268	6533056	2665319	6532947	21	31
183	0.9	2673037	6536889	2673561	6536370	23	32
184	16.3	2666879	6539246	2670230	6540705	32	37
185	2.1	2671390	6537348	2673037	6536889	50	72
186	3.3	2667977	6541028	2666879	6539246	36	51
187	2.5	2672067	6541173	2670788	6541133	14	30
188	1.0	2671811	6541949	2672067	6541173	41	62
189	8.9	2670788	6541133	2667977	6541028	22	32

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
190	1.5	2672345	6542983	2671811	6541949	32	48
191	0.9	2672951	6543565	2672345	6542983	32	48
192	2.6	2673359	6544294	2672951	6543565	28	42
193	2.2	2674082	6545124	2673359	6544294	28	42
194	3.1	2672225	6546432	2674082	6545124	32	48
195	5.5	2667590	6547790	2672225	6546432	128	200
196	11.4	2705936	6475439	2704458	6479942	14	20
197	15.6	2704458	6479942	2706213	6480622	58	90
198	16.6	2702704	6487972	2701024	6483869	51	77
199	1.9	2694579	6483295	2694981	6483861	25	36
200	3.8	2701024	6483869	2700347	6484038	49	62
201	18.1	2700347	6484038	2694579	6483295	38	57
202	3.2	2722529	6562572	2691135	6487554	29	43
203	8.9	2683745	6484690	2683745	6484690	29	43
204	20.6	2694745	6485000	2690774	6485596	29	43
205	6.3	2689028	6486721	2687458	6488943	29	43
206	1.9	2689612	6488130	2689028	6486721	51	77
207	0.9	2690719	6487724	2690367	6488125	29	43
208	3.8	2681179	6488303	2679755	6489953	57	82
209	31.1	2679755	6489953	2686643	6485416	6	10
210	0.9	2694487	6489146	2694991	6488549	41	62
211	8.8	2690393	6488820	2694558	6490642	35	53
212	11.2	2704849	6491958	2702943	6488454	67	104
213	1.3	2694381	6489957	2694487	6489146	32	48
214	0.8	2694558	6490642	2694381	6489957	54	83
215	10.5	2687458	6488943	2689813	6489639	36	55
216	11.1	2696732	6488367	2701980	6490677	36	55
217	10.2	2682505	6493962	2681180	6488310	48	73
218	3.2	2679733	6490028	2680126	6492493	57	82
219	1.6	2702300	6490965	2702576	6492251	45	69
220	1.8	2704316	6493119	2679733	6490028	45	69
221	4.5	2702576	6492251	2704316	6493119	67	104
222	5.6	2680126	6492493	2682494	6493963	36	55
223	7.9	2684105	6495095	2684108	6495098	28	42
224	3.4	2678800	6528859	2678773	6526301	75	117
225	35.3	2678773	6526301	2675913	6532336	77	119

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
226	5.9	2675918	6532329	2678800	6528859	91	133
227	12.9	2737234	6536076	2734375	6539904	49	76
228	0.8	2734282	6540230	2734092	6540591	41	62
229	16.0	2733735	6541322	2729964	6545465	58	90
230	17.1	2735675	6544876	2737234	6536076	110	172
231	9.9	2729527	6546124	2726016	6548177	49	76
232	1.3	2734175	6546444	2734288	6546011	75	117
233	9.8	2725234	6548149	2721313	6549693	75	117
234	3.9	2733604	6551292	2733188	6549225	36	55
235	53.3	2721313	6549693	2718711	6559395	45	69
236	2.5	2734056	6553620	2733625	6551815	36	55
237	2.1	2734988	6553839	2734056	6553620	41	62
238	9.1	2733019	6556753	2734988	6553839	71	110
239	24.5	2698583	6550000	2698584	6550000	80	185
240	7.4	2728834	6558528	2733019	6556753	62	97
241	9.1	2728772	6559493	2728834	6558528	35	42
242	6.6	2718711	6559395	2721190	6560800	67	104
243	9.5	2721190	6560800	2722731	6562631	45	69
244	22.4	2726539	6569383	2728554	6561509	62	97
245	17.5	2722731	6562631	2726539	6569383	162	255
246	27.8	2639014	6546740	2643673	6551476	30	42
247	10.1	2638968	6546536	2638967	6546534	30	42
248	3.8	2635628	6542569	2637391	6545341	34	48
249	7.3	2633752	6541731	2635628	6542569	37	52
250	7.1	2625064	6542507	2629008	6541360	42	63
251	15.9	2629008	6541360	2633752	6541731	50	72
252	28.5	2638505	6532343	2635734	6537281	21	28
253	13.8	2635734	6537281	2634479	6533403	18	24
254	39.6	2629690	6534242	2625064	6542507	35	42
255	4.2	2632236	6531332	2629690	6534242	37	52
256	5.2	2634479	6533403	2632236	6531332	37	52
257	3.3	2621132	6529684	2622690	6526964	123	178
258	18.6	2637514	6523936	2638505	6532343	39	46
259	3.5	2622690	6526964	2624280	6524275	51	67
260	14.9	2619476	6529612	2621132	6529684	35	42
261	3.4	2638068	6522071	2637514	6523936	58	83

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
262	6.1	2624280	6524275	2626329	6520011	99	141
263	6.5	2638384	6519165	2638068	6522071	69	92
264	1.7	2638729	6518323	2638384	6519165	37	52
265	1.0	2638419	6518167	2638729	6518323	39	46
266	15.3	2626329	6520011	2633232	6514570	39	46
267	5.8	2640280	6515299	2638419	6518167	39	46
268	2.8	2641368	6515916	2640280	6515299	37	52
269	1.2	2633232	6514570	2633873	6513767	43	54
270	2.0	2633764	6513209	2632402	6512343	43	54
271	21.6	2632402	6512343	2635173	6507824	39	46
272	66.5	2635173	6507824	2641368	6515916	34	40
273	2.3	2638070	6482813	2637443	6484555	54	125
274	2.5	2638239	6480906	2638070	6482813	54	125
275	2.5	2638512	6479104	2638239	6480906	63	145
276	1.9	2638914	6477994	2638507	6478399	27	60
277	7.9	2640374	6473092	2639395	6476888	79	184
278	3.4	2673371	6472156	2671294	6472927	9	13
279	6.4	2662576	6473457	2658733	6471155	36	55
280	4.4	2671294	6472927	2668183	6473680	0	0
281	8.4	2668183	6473680	2662576	6473457	36	55
282	7.0	2671029	6471083	2673371	6472156	41	49
283	5.2	2657069	6469934	2656617	6469346	32	48
284	3.9	2658733	6471155	2657069	6469934	36	55
285	20.3	2666640	6465234	2671029	6471083	6	10
286	10.9	2656617	6469346	2653137	6465875	36	55
287	2.7	2641029	6468408	2640868	6470450	79	184
288	1.8	2641433	6467389	2641029	6468408	80	185
289	0.9	2641747	6465917	2641571	6466706	28	64
290	1.1	2650343	6465266	2649794	6465760	39	46
291	43.0	2675549	6460672	2671247	6464787	45	56
292	1.5	2667943	6464728	2666640	6465234	39	46
293	4.8	2652549	6464897	2650343	6465266	36	55
294	11.7	2671247	6464787	2667943	6464728	0	0
295	3.7	2653362	6464041	2652549	6464897	18	40
296	8.7	2649794	6465760	2644843	6460586	63	145
297	0.6	2655103	6461599	2655506	6461255	49	62

Cliff id no.	Length (km)	Start of Section		End of Section		Possible erosion extent width from cliff toe (m)	Unlikely erosion extent width from cliff toe (m)
		Easting	Northing	Easting	Northing		
298	1.9	2653729	6460366	2655103	6461599	91	128
299	1.8	2649491	6461007	2650924	6460688	91	128
300	2.3	2656243	6460769	2658098	6460243	67	91
301	10.2	2677470	6459202	2675584	6459598	45	56
302	2.6	2647250	6460184	2649460	6461010	347	524
303	1.1	2651742	6460539	2652619	6460455	83	116
304	0.5	2675475	6460205	2675549	6460672	45	56
305	0.6	2675584	6459598	2675475	6460205	45	56
306	1.3	2646953	6459021	2647250	6460184	251	376
307	1.6	2678346	6459085	2677470	6459202	49	62
308	126.4	2662651	6450675	2678346	6459085	49	62
309	5.0	2648398	6454500	2646953	6459021	251	376
310	6.7	2650929	6448766	2648398	6454500	251	376
311	11.1	2664590	6448649	2660453	6450270	39	46
312	0.7	2665102	6448263	2664590	6448649	39	46
313	96.8	2658576	6458996	2662753	6445168	49	62
314	2.5	2662753	6445168	2662436	6447349	49	62
315	36.6	2662238	6447552	2665102	6448263	49	62
316	10.1	2654489	6440203	2650929	6448766	251	376
317	6.1	2656752	6434739	2654489	6440203	219	326

The extent of areas susceptible to coastal erosion range in width from about 5m in low, competent volcanic cliffs to 235m in high, weakly consolidated cliffs. The following figures show the effect of the derived slopes for a range of different geologic types. Figure 7.10 shows the potential erosion susceptible areas for the “likely”, “possible” and “unlikely” probabilities for Tauranga Group material. Figure 7.11, Figure 7.12, Figure 7.13 and Figure 7.14 show the same approach for consolidated dunes, East Coast Bays Formation, Pakiri Formation and volcanics.

We note that there is a reasonable talus deposits at the base of Maori Bay cliff (Figure 7.14). Therefore the actual toe of the cliff has been determined based on the intersection of the cliff slope with the nearshore slope seaward of the talus slope.

These figures illustrate the distance from the crest of the cliff varies depending upon GSI type, with reasonably narrow distances for Waitakere Volcanics of around 9 m and 33 m for “possible” and “unlikely” respectively. Similarly the “possible” and “unlikely” widths are around 8 m and 22 m for GSI 75 strength cliffs, 17 m and 55 m for GSI 65 strength cliffs, 26 m and 45 m for GSI 48 strength cliffs, 17 m and 70 m for high consolidated dunes around 17 and 27 m for Tauranga Group cliffs.

Figure 7.15 and Figure 7.16 show the frequency distribution of both the "possible" and "unlikely" areas. Figure 7.15 shows that 52% of all cliff sections have zones "possibly" susceptible to the areas susceptible to erosion of less than 30 m from the cliff toe while 95% of all cliff sections have zones less than 80 m. Figure 7.16 shows 62% of all cliff sections have zones "unlikely" to be susceptible to erosion over the next 100 years of 50 m or less, while 95% of all cliff sections have zones less than 120 m. The larger cliff heights are typically responsible for the larger areas susceptible to erosion.

Figure 7.10

Identification of potential areas susceptible to erosion for Glenross Drive, Tauranga Group

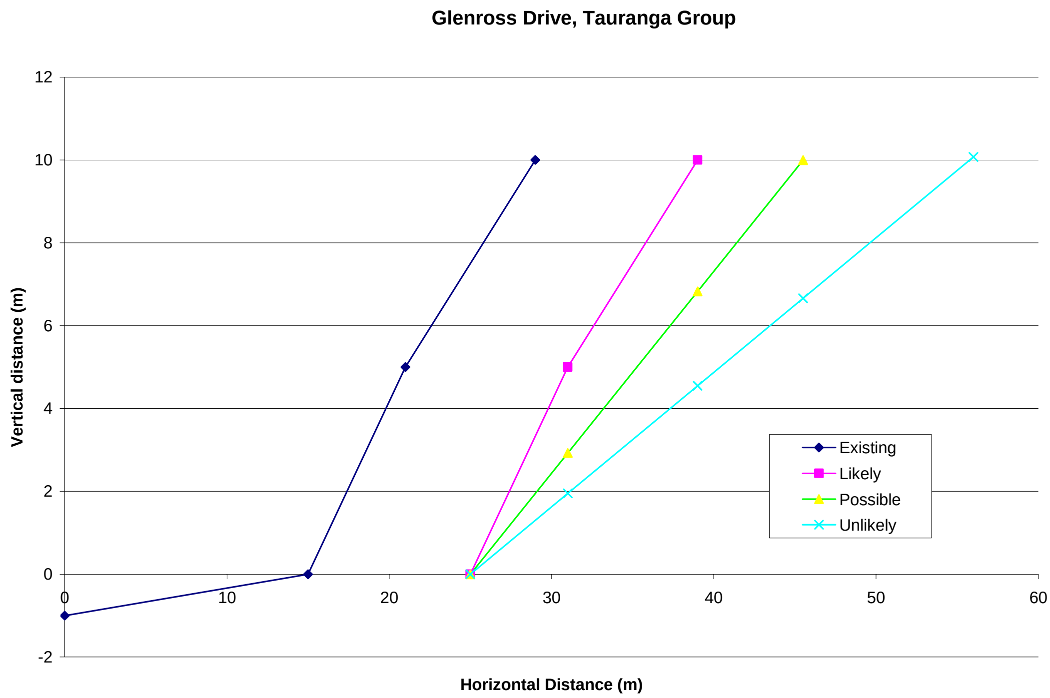


Figure 7.11

Identification of potential areas susceptible to erosion for Karitahi, Consolidated Dune

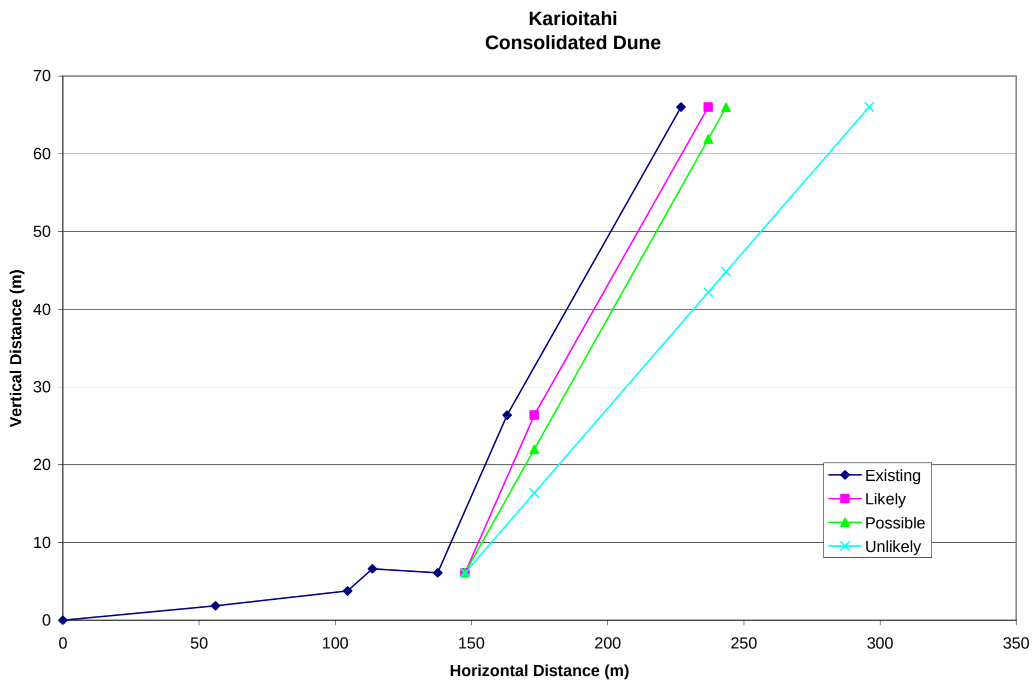


Figure 7.12

Identification of potential areas susceptible to erosion, West of Fisherman's Reserve, East Coast Bays Formation (GSI 48)

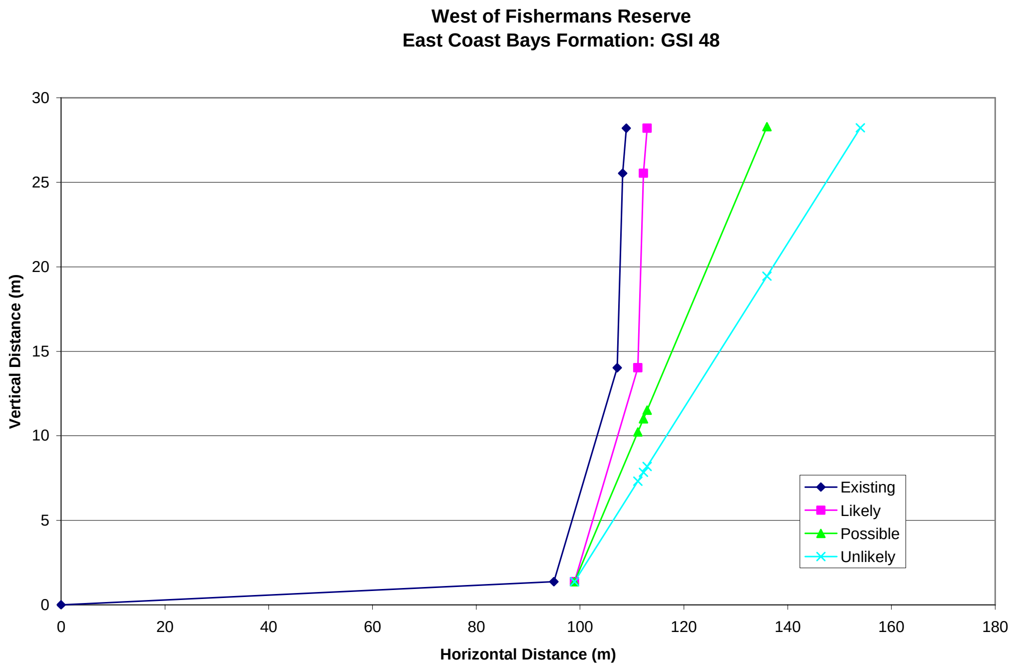


Figure 7.13

Identification of potential areas susceptible to erosion south of Wenderholm, Pakiri Formation (GSI 65)

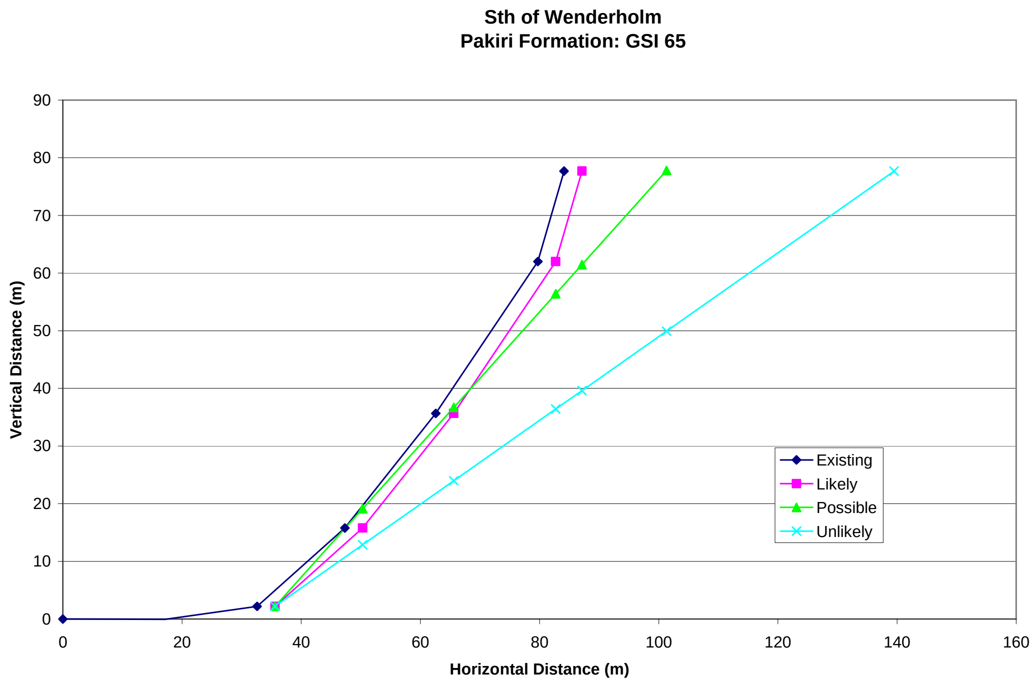


Figure 7.14

Identification of potential areas susceptible to erosion for Maori Bay, Waitakere Volcanics (GSI 75)

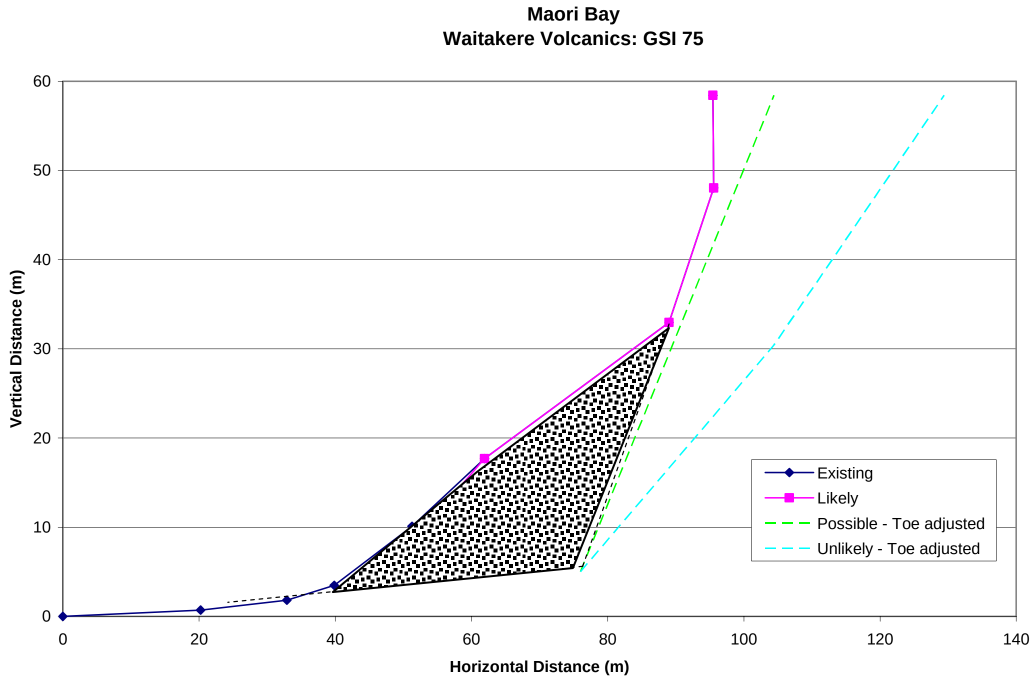


Figure 7.15

Frequency distribution of "Possible" areas susceptible to erosion as measured from cliff toe

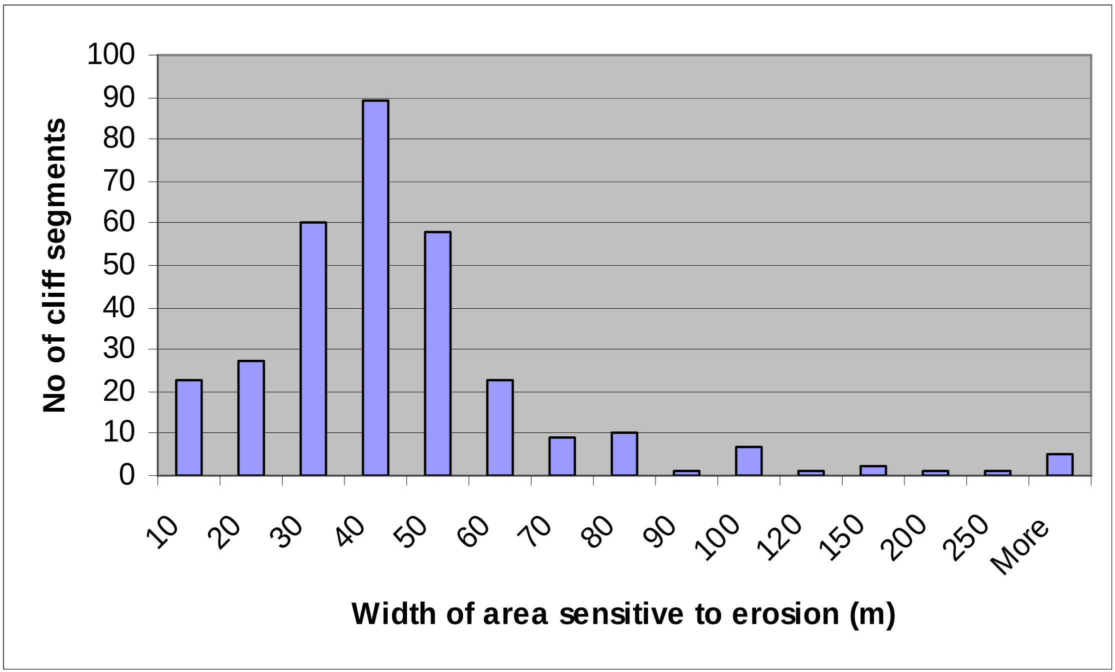
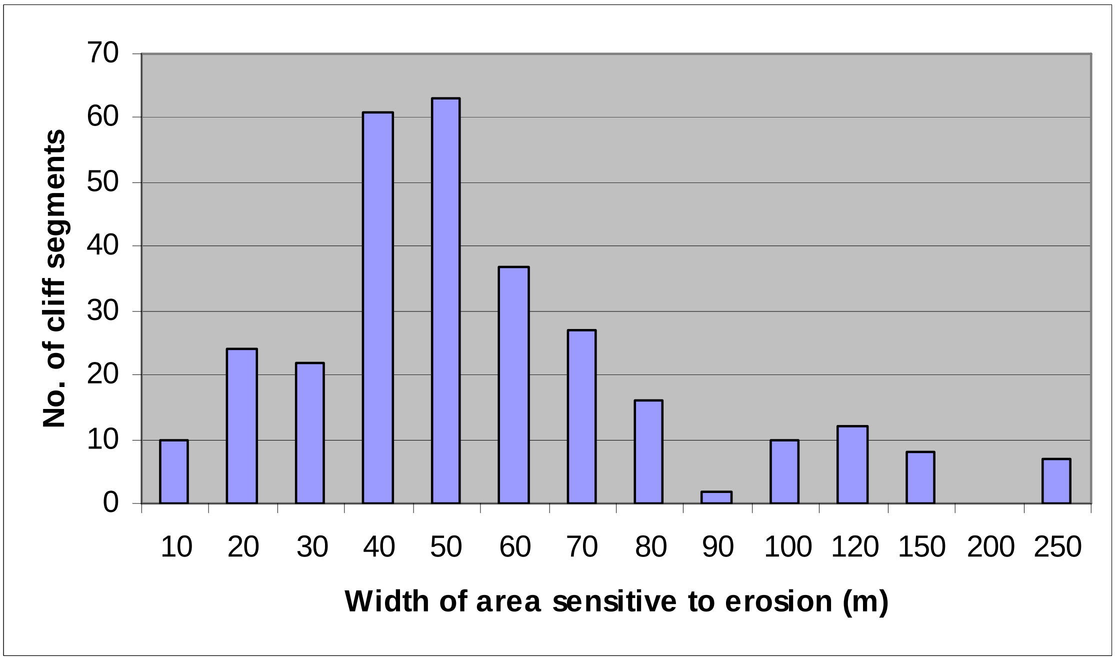


Figure 7.16

Distribution of width of "Unlikely" areas susceptible to erosion



8 Suggested Approach for Site Specific Assessments

The methods and resulting width of areas sensitive to the coastal erosion provide a broad scale and conservative assessment of those areas potentially affected by coastal erosion within the Auckland region. For those areas where the area susceptible to coastal erosion is required to be refined, more detailed assessments should be carried out.

Data required and suggested sources for refining the area sensitive to coastal erosion for beaches are outlined in Table 8. and for cliffs in Table 8.. It is not necessary to provide additional information on all variables. However, if information is not provided on any particular variable, the information included in this report should be used.

Table 8.1

Requirements for a site-specific beach assessment

Variable	Information Required	Source
Coastal processes	Identification of "cell", or the area considered representative, sources of sediment supply and loss, forcing agents (wind, waves tide) for sediment movement.	Aerial photographs, surveys, site inspections by appropriately qualified professional.
Coastline fluctuations	1% AEP coastline fluctuation distance and storm cut	Beach profiles/wave climate models/aerial photograph analysis/ coastline response models
Dune slope distance	Detailed beach geometry including historic profiles	Beach profiles/detailed topography
Long-term Retreat	Historic long-term retreat rates, over (at least) 30 years, preferably longer.	Long-term beach profile data/photos/topographic models/field investigations for geologic/human markers.
Climate change/sea-level rise	Predicted future sea-level rise/detailed beach geometry including offshore areas	Climatic change and beach response models
Uncertainty/errors	Statistical review of errors/uncertainty	

Table 8.2

Requirements for a site-specific cliff assessment

Variable	Information Required	Source
Spatial extent of area	Identify geological controls for the site, which may extend beyond local area under investigation	Site inspection, review of geological data by suitably qualified and experienced geologist
Current cliff profile including crest and toe	Current cliff profile	Site-specific survey or detailed local area survey (i.e. LIDAR).
Geological Strength Index (GSI)	Surface condition of cliff, structure of cliff	Site-specific cliff mapping by suitably qualified Geologist
Stable angle of cliff repose	Current cliff geometry, predicted GSI	Site-specific investigation/survey, slope stability models
Cliff height	Cliff geometry	Site-specific survey/detailed local contour information
Large-scale cliff defects	Size, orientation and nature of large-scale structural defects.	Site-specific inspection by suitably qualified Geologist
Overlying weathered layer	Depth and strength of overlying weathered layer	Site-specific inspection, bore holes, geophysical investigations
Long-term erosion rates	Long-term rates of retreat for cliffs of interest, preferably over 50 years.	Aerial photographs, historic profiles/measurements
Climate change/sea-level rise induced erosion rates	Predicted future sea-level rise/cliff geometry and geology	Climatic change and cliff response models

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10 Appendices A-J

Appendices A – J are published separately in Volume 2, available in hardcopy or from www.arc.govt.nz

Appendix A: Consultants Brief

Appendix B: Peer reviewer's comments

Appendix C: Summary of Relevant Tonkin & Taylor Jobs

Appendix D: Summary of Shoreline Characterization

Appendix E: Field Investigation Data

Appendix F: Summary of Regional Beach Properties

Appendix G: Summary of Regional Cliff Properties

Appendix H: Description of Physical Setting

Appendix I: Heli-Survey DVDs (Contact ARC Librarian)

Appendix J: Analysis of Beach Profile Changes