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Natural Hazards and their Impacts

Auckland Region

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Reviewed by:

Name: Ryan Paulik

Position: Natural Hazards Management Advisor

Organisation: Auckland Regional Council

Date: 13/08/ 2009

Approved for ARC Publication by:

Name: Alastair Smaill

Position: Group Manager Environmental Policy and Planning

Organisation: Auckland Regional Council

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Natural Hazards and their Impacts

Auckland Region

Kim Wright[1]
Marina Baldi[2]
Jan Lindsay[3]
Russ Van Dissen[1]
Jim Salinger[2]
Grant Dellow[1]
Mike Page[1]
William Power[1]
Darren King[2]

Prepared for

Auckland Regional Council

[1] GNS Science, PO Box 30368, Lower Hutt.

[2] National Institute of Water and Atmospheric Research, PO Box 11114, Hamilton.

[3] University of Auckland, Private Bag 92019, Auckland.

Contents

1. Introduction

Auckland's physical setting and large metropolitan area means it is exposed to a wide range of natural hazards. To effectively manage threats posed by natural hazards, information on their location, frequency and magnitude needs to be readily available to resource managers. Information on natural hazards is often held in a variety of forms and scattered amongst central and local government departments, universities, consultants, landowners and specialist scientific and interest groups. This document provides an up to date summary of information from these sources to present an introduction to natural hazards and their consequences in the Auckland region.

Fifteen Chapters comprise this document, covering all natural hazards that affect the Auckland region. The second chapter *Auckland Region* provides a background on the region's physical environmental setting. This includes descriptions of the geology, geomorphology, climate, population and land use which combines to form the landscape we see today. Understanding the current state of Auckland's physical environment is important as the interaction of natural or anthropogenic processes direct where natural hazards and risk occurs in the region. We can then develop a better idea on why natural hazards occur in certain locations and how to reduce the consequences when an event occurs.

Chapters three to fifteen present information on natural hazards in the Auckland region. Natural hazards can be broadly placed into the categories below however, it is important to acknowledge that a range of different environmental and anthropogenic influences can contribute to the physical hazard process.

Geological and Geomorphic	Meteorological and Hydrological
• Earthquakes	• Flood
• Volcanic eruption	• Drought (agricultural and water supply)
• Land Instability	• Cyclone
• Tsunami	• Wildfire
• Erosion (coastal, fluvial and slope)	• Tornado
	• Climate Change (various hazards)
	• Storm Surge
	• Sea Level Rise
	• Erosion (coastal, fluvial and slope)

Each natural hazard chapter contains four main subsections. These are Hazard Characteristics; Location, Frequency and Magnitude; Key Vulnerabilities and Impacts; and References and Additional Reading. *Hazard Characteristics* provides detailed descriptions on the physical environmental or anthropogenic influences which contribute to forming the specific natural hazard. *Location, Frequency and Magnitude* provides information on where and how the natural hazard occurs in the Auckland region. *Key Vulnerabilities and Impacts* describe the potential consequences for society and the environment that may arise should a natural hazard impact on the Auckland region. Finally, *References and Additional Reading* will provide a comprehensive list of resources that can be drawn upon to improve understanding of natural hazards and their impacts in the Auckland region.

The main purpose of this document is to raise awareness and improve the understanding of natural hazards in the Auckland region. The information presented is intended for staff within Auckland's regional and territorial (district and city) councils who directly or indirectly deal with the day to day management of natural hazards. This may include; planners, building technical staff, engineers, hazard analysts, civil defence emergency management officers, environmental monitors, information providers and Geographical Information Systems (GIS) operators and analysts. The document contents are of particular relevance to the following:

Staff	Roles
• Planners and technical staff	• Processing consent applications • Preparing strategic, regional, district, catchment and structure plans • Policy implementation • State of the Environment monitoring • Property information management including hazard registers
• Engineers	• Consent condition enforcement and monitoring • Assessment of building permit applications
• GIS Operators/analysts and Property Information Staff	• Risk/consequences assessment • Data capture/entry • Software development • Property information maintenance
• Hazard Analysts	• Hazard assessment and risk analysis • Hazard management policy development and implementation

• Civil Defence/Emergency Management Officers	• Emergency management policy and plan development and implementation • Land use management and hazard reduction advice
• Elected Representatives/Councillors	• Policy setting • Resource consent decision making • Risk management decisions making

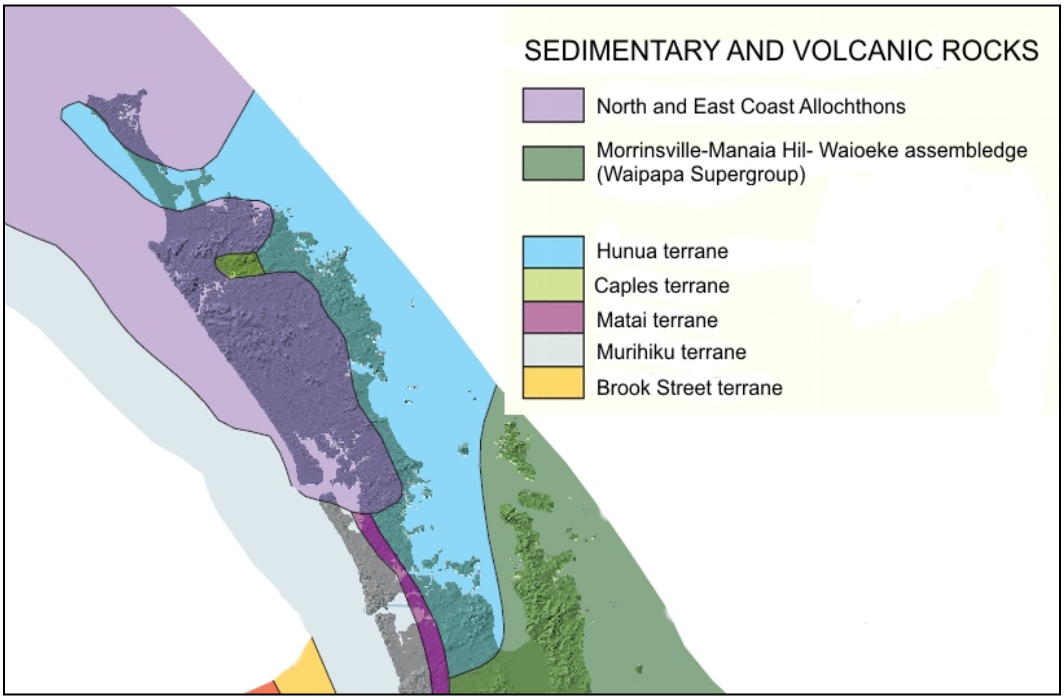
2. Auckland Region

2.1 Geology, Geomorphology and Hydrology

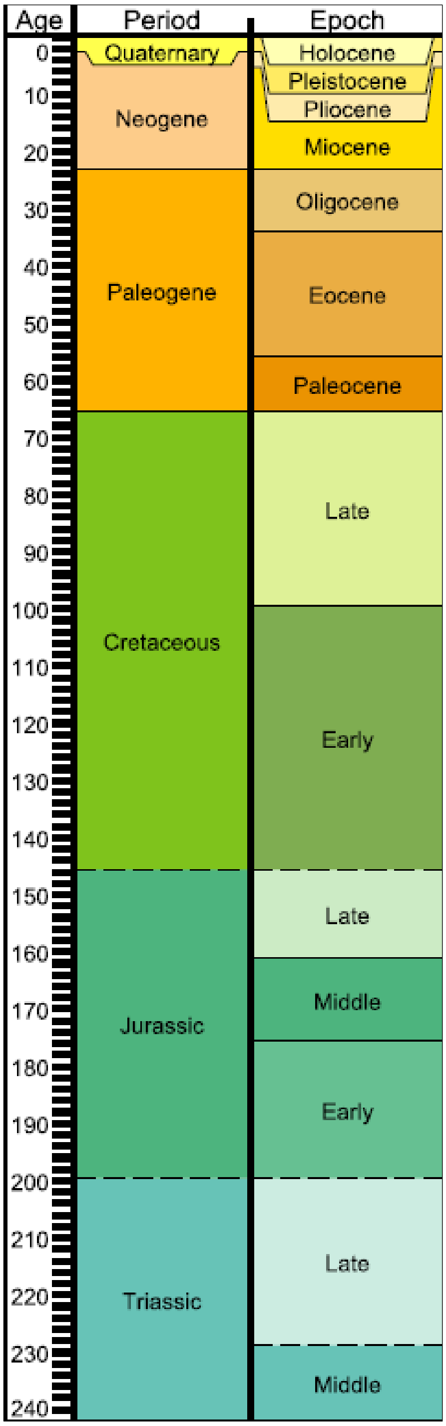
2.1.1 Geology

Auckland region lies on the Australian tectonic plate, 300-500 km northwest of the active plate boundary of the Australian and Pacific Plates. The region's position means it occupies one of the lowest areas of earthquake activity in New Zealand. Auckland's subsurface geology is mainly comprised of 'greywacke' terranes and Northland Allochthon sedimentary rocks (Figure 2.1). Greywacke is a hard sedimentary rock formed by fine sand and mud washing off the Gondwanaland 'super-continent' and settling in a deep water environment (Press and Siever, 2001 [1]; Kenny and Hayward, 1993 [2]). These are the regions oldest rocks and appear on the earth's surface today due to tectonic uplift occurring over millions of years. Where greywacke has been exposed the rock eventually breaks down by weathering to form soils mainly composed of soft clays. Due to the age of greywacke, in many areas of the region they are overlain by younger sedimentary and volcanic rocks (Edbrooke, 2001[3]).

Figure 2.1 Basement rocks of the Auckland region. Four greywacke terranes are represented: Waipapa Group (oldest), Hunua, Murihiku and Matai (Youngest). The Northland Allochthon occurs in the regions northeast. *Source: Mortimer and Smith-Lyttle, 2001* [4].



The Northland Allochthon (known 'Onerahi Chaos breccia') forms part of the northern region's basement rocks and is visibly exposed around Wellsford and Silverdale. The Allochthon comprises sheets of deepwater sedimentary and submarine basalt rock that were uplifted as sheets of rock and then overturned by tectonic activity generated by pacific plate movement under the region. In the Auckland region the allochthon's is generally <1000m thick and forms highly unstable soils in the Rodney District known as 'Onerahi Chaos'.



Overlying the basement rocks and dominating the modern Auckland surface geology in much of the region are younger marine and terrestrial sediments (Figure 2.3). Periods of volcanism also formed some of the more distinctive features on Auckland's landscape including; Waitakere Ranges, Little and Great Barrier Islands and other volcanic landforms (basaltic scoria cones, lava flows and maar craters) which are surface manifestations of activity in the Auckland and South Auckland Volcanic Fields (Smith and Allen, 1993[5]; Neall, 2001[6]).

Figure 2.2 Geologic Time Scale (age = millions of years (or ma)) relevant to formation of Auckland region rocks and landforms *Source: Lugowski and Ogg, 2007* [7].

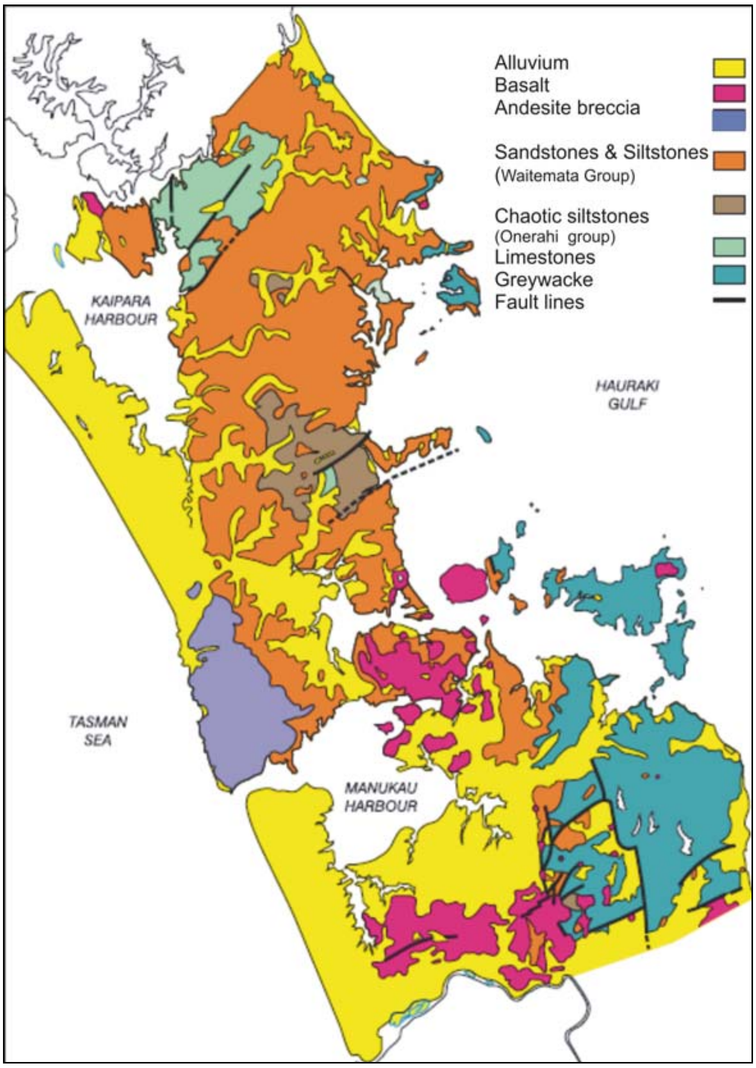
Overlying the basement rocks and dominating the modern Auckland surface geology in much of the region are younger marine and terrestrial sediments (Figure 2.3). Periods of volcanism also formed some of the more distinctive features on Auckland's landscape including; Waitakere Ranges, Little and Great Barrier Islands and other volcanic landforms (basaltic scoria cones, lava flows and maar craters) which are surface manifestations of activity in the Auckland and South Auckland Volcanic Fields (Smith and Allen, 1993[5]; Neall, 2001[6]).

2.1.2 Geomorphology

Natural landforms visible today in Auckland region were formed by environmental processes over the last ten million years. The processes governing landform development (mainly climate and tectonics) can be hazardous where they interact with humans and development. These processes vary on both spatial and temporal scales, and in type around the region to create a variety of landforms. Regional geomorphology can be characterised into four major units:

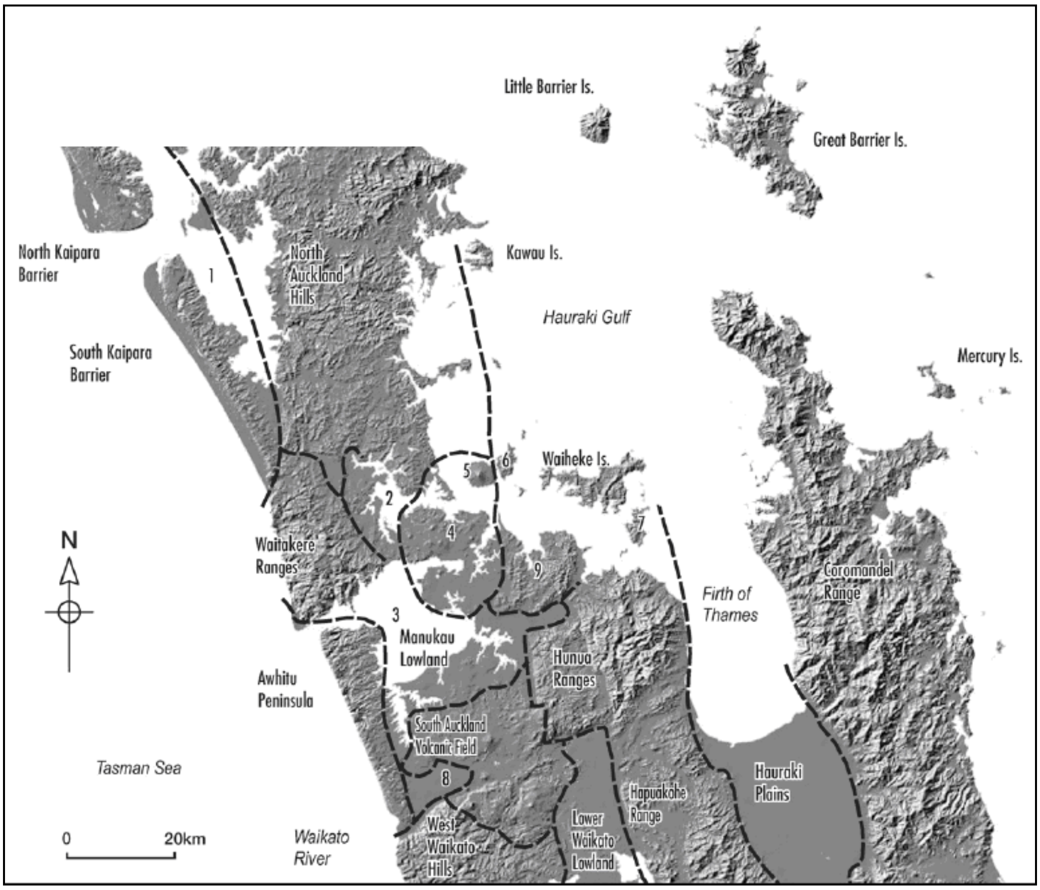
- Sedimentary (greywacke) and volcanic highlands such as the North Auckland Hills, Waitakere Ranges, Hunua Ranges, and Great Barrier and Waiheke Islands.
- Pliocene (5.3-1.8 ma) and Quaternary sand barrier dune formations such as the South Kaipara Barrier and Awhitu Peninsula.
- Quaternary lowlands such as Manukau Lowland and Aka Aka Plain; and
- Quaternary basalt fields such as the Auckland Volcanic Field and South Auckland Volcanic Field (Figure 2.4).

Figure 2.3 Surface geology of the Auckland region: scale is from youngest (yellow) to oldest (teal blue) sediments. *Source: ARC, 2002* [8].



The present Auckland landscape mainly consists of rolling hill country formed upon weathered sedimentary rocks. Older greywacke rocks generally covered by a surface of loose rock and clay up to 20m deep that is often susceptible to erosion. The erosion of these surfaces provides a somewhat uniform landscape of close-set, steep-sided valleys, with long straight hillslopes. In some areas (such as the Hunua Ranges) beds of more resistant greywacke form prominent "hog-back" ridges that protrude outward into surrounding low land areas.. Freshly exposed greywacke beds along coastlines form shore platforms and cliffs, where they have been eroded by marine (waves and tides) and weathering processes.

Figure 2.4 Major geomorphologic features of the Auckland region and north Waikato: 1) Kaipara Harbour, 2) Waitemata Harbour, 3) Manukau Harbour, 4) Auckland Volcanic Field, 5) Rangitoto Island, 6) Motutapu Island, 7) Ponui Island, 8) Aka Aka Plain, and 9) East Auckland Hills. *Source: Edbrooke et al. 2003* [9].



Older sedimentary rocks exposed on the landscape are generally soft sandstones and siltstones that can have many defects (particularly the Allochthonous rocks) and are prone to slope failure in the form of debris sliding, deep-seated creeping, shallow flows, or slumping. These rocks form the gently to moderately rolling hills in eastern and northern areas. In general, hill slopes formed in sedimentary rocks are highly prone to change particularly when incised or cut (or in the Allochthonous rocks) cut by the many rivers in streams in the region (Edbrooke et al. 2003). Sediment lost from these slopes by landslides and erosion is transported across the landscape by rivers to form floodplains and are deposited within estuarine and beach systems.

The Auckland Volcanic Field (AVF) covers about 100km^2 of Auckland urban area contains distinctive landforms formed in response to volcanic activity occurring over thousands of years. Common landforms visible on the landscape include; lava and scoria cones (e.g. Mt Eden, Mt Mangere Rangitoto Island); lava flows (e.g. Te Tekoroa flow in Waitemata Harbour); explosion craters (e.g. Lake Pupuke, Pukaki Lagoon); ash and lapilli beds (e.g. around Three Kings volcanoes, tuff rings (e.g. around Browns Island, One Tree Hill). Many volcanic features were altered or removed during recent quarrying and development, though protection is now given to remnant features of the AVF. Although it is not known when or where the next eruption in the AVF will occur, any new eruption will create new volcanic landforms in the Auckland region as well as produce a range of hazardous effects.

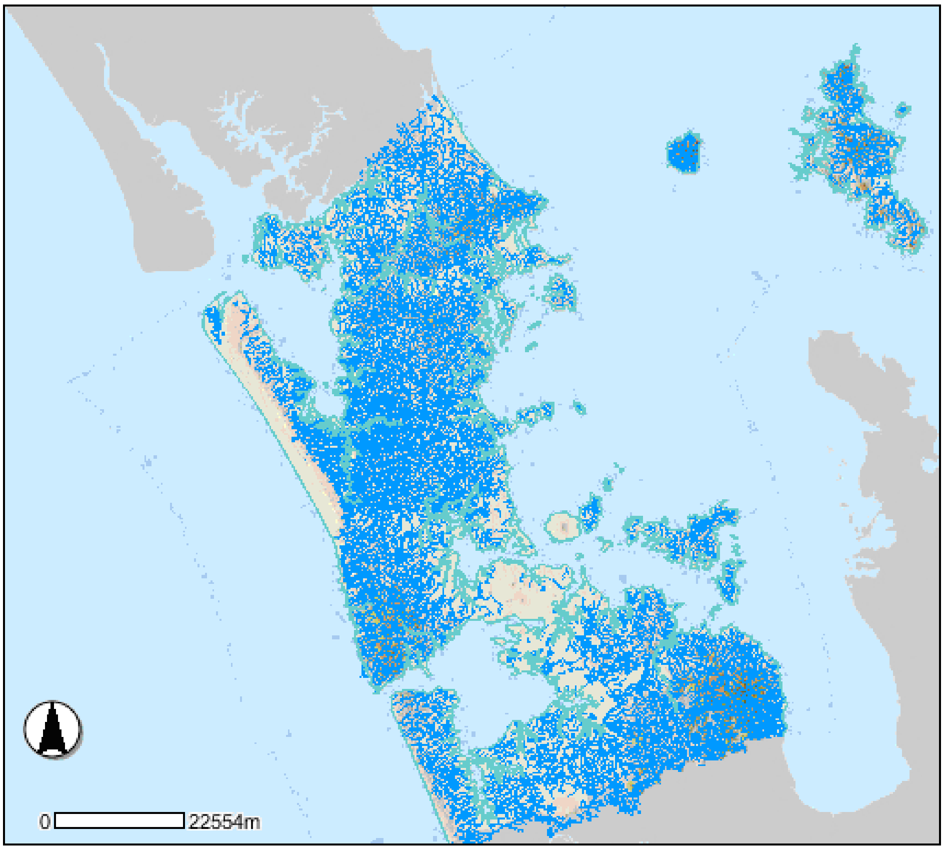
Figure 2.5 Landforms in the Auckland region. A) Faulting and folding of East Coast Bays sedimentary rocks. B) The Te Tokoroa lava flow. C) The Hunua Ranges. D) Mt Mangere. *Source: GNS Science, 2008* [10].

Marine and fluvial (river) derived sediments (sands and silts) form lowlands (e.g. the Manukau lowlands), extensive sand barriers (e.g. Kaipara Spit) and many of the beaches around Manukau and Waitemata Harbours. The unconsolidated nature of these soft sediment formations means they are form areas highly susceptible to change from both environmental and anthropogenic processes. These features give rise to various coastal and land instability hazards.

2.1.3 Hydrology

Auckland's surface and groundwater resources are principally fed by rainfall. During drier months groundwater may be the only source replenishing surface water bodies as soil moisture deficits absorb rainfall as storage rather than released as runoff. Surface water bodies predominantly consist of lakes and small 1st and 2nd order streams (90%) located in the upper catchments (Figure 2.6). Catchment geology is an important control on rainfall runoff and infiltration rates which determine base flows (normal river levels) and flood flows in the region. Low permeability soils (e.g. Onerahi Chaos) are linked to high runoff particularly in areas with steeper slopes. Urbanised catchments with a large amount of roading, paving and stormwater drainage networks also create high runoff rates resulting in quick and high flood peaks in river channels.

Figure 2.6 Stream and river network of the Auckland region. *Source: Auckland Regional Council, 2008.*

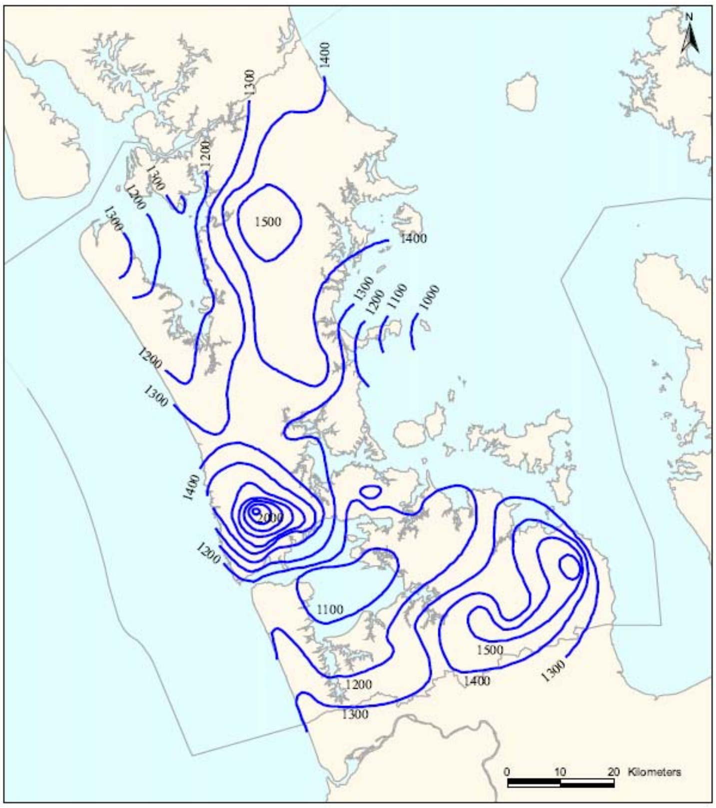


Groundwater aquifers are found in varying geology throughout the region. The best conditions for high yielding aquifers are the fractured basalts of the South Auckland Volcanic Field (See Chapter 14.1). Two well-developed geothermal fields produce low temperature (under 60°C) geothermal waters in Waiwera and Parakai. Other groundwater aquifers in the region are low-yielding by national standards but an important local water source for some rural areas and municipal industry (ARC, 2002).

2.2 Weather and Climate

Auckland region's climate is influenced by its topography and location between the Pacific Ocean and Tasman Sea (Salinger, 1996[12]; Fowler, 1999[13]). The region has a subtropical climate dominated by irregular atmospheric features (often hazardous) such as mid-latitude depressions and anti-cyclones. For instance, during summer months ex-tropical cyclones can develop from the northeast, bringing strong winds and intense rainfall. The region's exposure to westerly (Tasman) and northeasterly (Pacifc) climatic features interact with topography to form distinct rainfall patterns. Rainfall averages annually between 1200mm and 2200mm, and is largely controlled by topography as higher volumes occur near the highest elevations (Figure 2.7). Precipitation comprises almost entirely as rainfall although hail storms occur infrequently.

Figure 2.7 Rainfall distribution of the Auckland region –higher elevation areas are the North Auckland hills, the Waitakere ranges and the Hunua Ranges. *Source: Fowler, 1999*.



Seasonal climate trends appear similar for different parts of the region although local effects create variable temperatures and rainfall (Figure 2.8). Salinger (1996) determined nine distinct geoclimatic regions which differ due to their elevation, aspects, exposures and land uses (Figure 2.9). The frequency, magnitude and type of meteorological hazards (wind, high intensity rainstorms, drought, and hail) impacting on these geoclimatic regions vary due to their physical characteristics and influence of regional climate processes. Planning for meteorological hazards can be implemented at a local scale in the Auckland region.

Figure 2.8 Monthly average rainfall and temperature at Auckland Airport and Pukekohe between 1951 and1980. Source: Fowler, 1999.

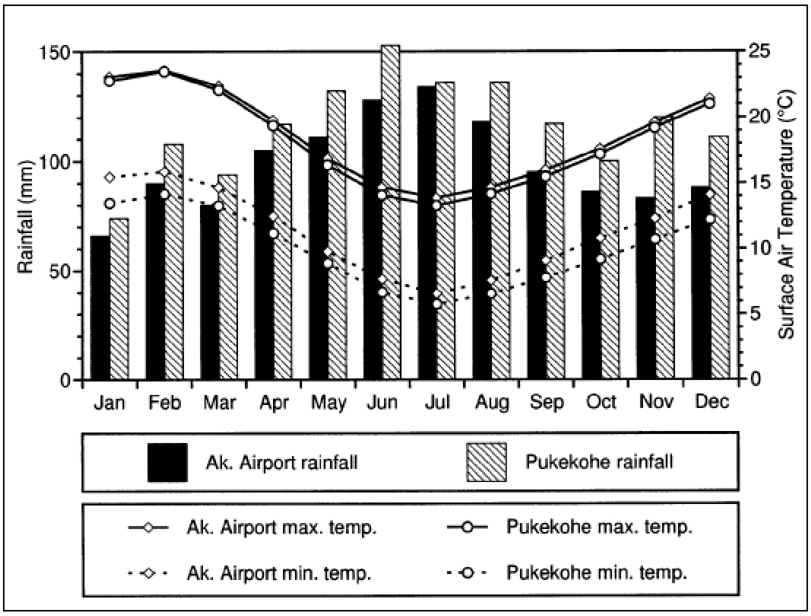
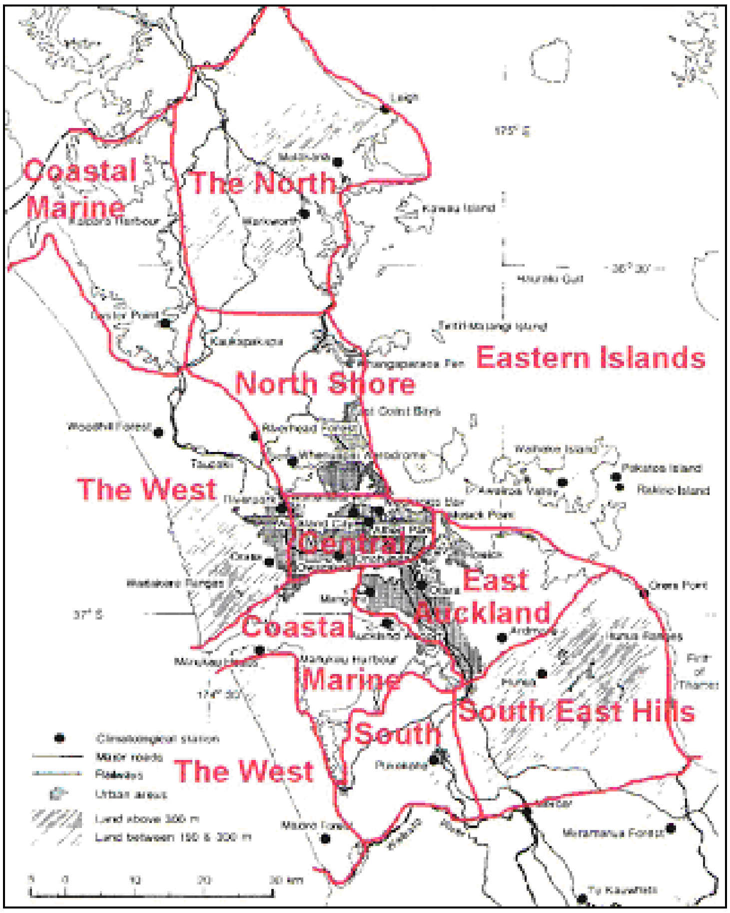


Figure 2.1 Auckland's climatic regions. *Source: Salinger, 1996*.

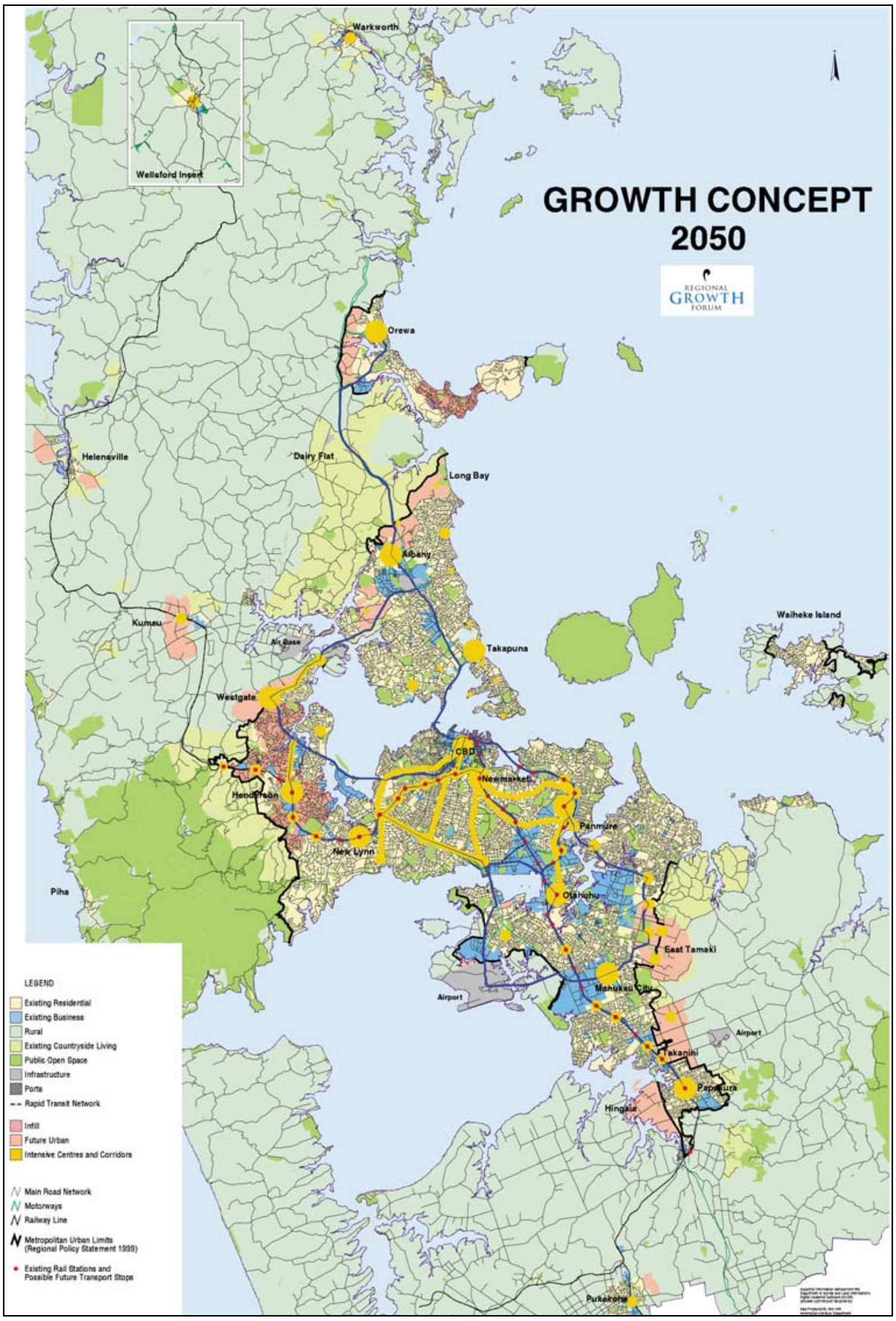


2.3 Population and Land Use

Auckland is the most populated region in New Zealand. On Census night 2006 the region's population was 1,303,068 or 32.4% of New Zealand's total population. Auckland experiences the fastest regional population growth and trends suggest this may exceed 2,000,000 by 2041 (ARGF, 2007[14]). The majority (81%) of the population lives within the metropolitan urban limits though rural populations are increasing due to the popularity of 'lifestyle block' living (Figure 2.10).

Auckland's population is ethnically diverse with 37% of the population originating from overseas. The main ethnic groups are NZ European 56.5%; Maori 11.1%; Pacific Island 14.4%; Asian 18.9% with the remaining Auckland region residents spread amongst less well represented groups or classed as "other" (Auckland Regional Council, 2007 [15]). Auckland region has a greater percentage of the population under 15 years old relative to the rest of New Zealand and is under-represented in the proportion of elderly residents (ARGF, 2007).

Figure 2.10 Growth concept map for the Auckland region: Yellow areas denote residential; pink is future residential growth; blue business land; grey is infrastructure, green is open space; and gold is major transport corridors. Source: Auckland Regional Growth Forum, 2007.



Population statistics and land use trends provide essential data for hazard and risk assessments, and hazards and emergency planning. Understanding trends in population factors that affect vulnerabilities to hazards such as age, level of education, access to information, ethnicity, income, mobility, etc, are important for hazards and land use planning and emergency management planning. Trends in land use can reduce hazard exposure through hazard avoidance or allow increased development and activity in hazardous areas if risk is considered acceptable.

Summary

The Auckland region is geologically and geomorphically diverse, bordered by the Pacific Ocean and Tasman Sea, contains a potentially active volcanic field, and is subject to a variety of geological and meteorological hazards. Coupled with a large and growing population, including considerable proportions of potentially vulnerable citizens and groups; the Auckland hazardscape presents challenges to policy planners, hazard analysts and emergency managers. Understanding and planning for the natural hazards that may impact the region; the people, businesses, environment and environment of the region contributes to a more sustainable future for the region.

4.4 References and Additional Reading

References

1. Press, F., Siever, R. 2001: Understanding Earth. 3rd edition. New York: W.H. Freeman and Company. p573.
2. Kenny, J. A., Hayward, B. W. 1993: Inventory of Important Geological Sites and Landforms in the Auckland Region. Geological Society of New Zealand Miscellaneous Publication. p67.
3. Edbrooke, S. W. 2001: Geology of the Auckland Area. Institute of Geological and Nuclear Sciences 1:250 000 geological map.
4. Mortimer, N., Smith Lyttle, B. 2001: New Zealand's Geological Foundations. Gondwana Research. 7. 261-272
5. Smith, I. E. M., Allen, S. R. 1993: Volcanic hazards at the Auckland volcanic field. Volcanic Hazards Information Series. p34.
6. Neall, V., 2001: Volcanic Landforms. In, Sturman, A., Spronken-Smith, R. (eds): The Physical Environment: A New Zealand Perspective. Oxford University Press: New York. p39-60.
7. Lugowski, A., Ogg, J. 2007: Timescale Creator Programme.
8. Auckland Regional Council. 2002: Auckland Regional Council, Auckland Water Resource Quantity Statement 2002. Auckland Regional Council Technical Report 171.
9. Edbrooke, S. W., Mazengarb, C., Stephenson, W. 2003: Geology and geological hazards of the Auckland urban area, New Zealand. Quaternary International. 103. 3-21.
10. GNS Science. 2008: GNS Image Library.
11. Auckland Regional Council. 2008: Hydrotel map of the Auckland Region. [cited from: http://maps.arc.govt.nz/website/maps/map_hydrotel.htm.]
12. Salinger, M. J. 1996: Meteorological Hazards in the Auckland Region: A Preliminary Response. Auckland Regional Council Technical Publication. p94.
13. Fowler, A. 1999: Potential climate change impacts on water resources in the Auckland region (New Zealand). Climate Research. 11. 221-245.
14. Auckland Regional Growth Forum. 2007: Growing Smarter: Auckland in the 21st Century. An evaluation of the Auckland Regional Growth Strategy. Auckland Regional Growth Forum Technical Report.

15. Auckland Regional Council. 2007: 2006 Census of Population and Dwellings: Report on initial results for Auckland region.

Additional Reading

Goff, J., Nichol, S., Rouse, H. (eds) 2003: The New Zealand Coast: Te Tai o Aotearoa, Dunmore Press, Palmerston North. p320

Soons, J. M., M. J. Selby, M. J. (Eds). 1992: Landforms of New Zealand 2nd Edition. Longman Paul. p392

3. Climate Change

3.1 Hazard Characteristics

Global warming is almost certain[1] to continue during the 21st century and enhance already observed changes in Auckland's regional climate (IPCC, 2007[1]). Global scale projections until 2100 that were presented in the IPCC 4th Assessment Report published in 2007 include: a global average surface warming of 1.1°C to 6.4°C, increases in mean annual rainfall in some regions and decreases in others and increase global mean sea-level from 0.18 to 0.59 m. Developing an understanding on how these changes will affect existing climate conditions of the Auckland region is essential for safeguarding people and property from climate related hazards.

New Zealand climate varies with two key natural cycles that operate over timescales of years (El Niño-Southern Oscillation, ENSO) and decades (Interdecadal Pacific Oscillation, IPO). Trends and variations in local climate over the coming century will be a combination of these natural climate variations and those resulting from increases in global greenhouse gas emissions.

The El Niño/Southern Oscillation (ENSO) is a natural feature of the global climate system, based in the tropical Pacific. El Niño events irregularly occur about 3 to 7 years apart, typically becoming established around April or May and persisting for about a year thereafter. In El Niño years, New Zealand tends on average to experience stronger and/or more frequent west to southwest winds, enhancing rainfall in western areas. La Niña events bring roughly the opposite changes on average with weaker westerly winds in summer with more northerly quarter winds at other times, and enhanced rainfall in the north and east.

The Interdecadal Pacific Oscillation (IPO) is a Pacific-wide natural fluctuation in the climate that persists for decades. There are two phases, positive and negative. The positive phase produces more westerly winds over the country with wetter conditions in the west and south. In the negative phase, westerly's weaken and more easterlies and north easterlies occur over northern New Zealand with an increased frequency of tropical disturbances (i.e. cyclones).

Phase changes of the IPO since 1900 are shown in Figure 3.3. The IPO exhibits phase reversals once every 20-30 years. Previous phase reversals of the IPO occurred around 1922, 1945, and 1977. The latest diagnosis of the IPO index from global sea surface temperatures indicates a recent reversal in 1999/2000 (Figure 3.3). This current negative phase would be expected to encourage more La Niña activity in the tropical Pacific, and a higher frequency of northeasterlies over the Auckland region.

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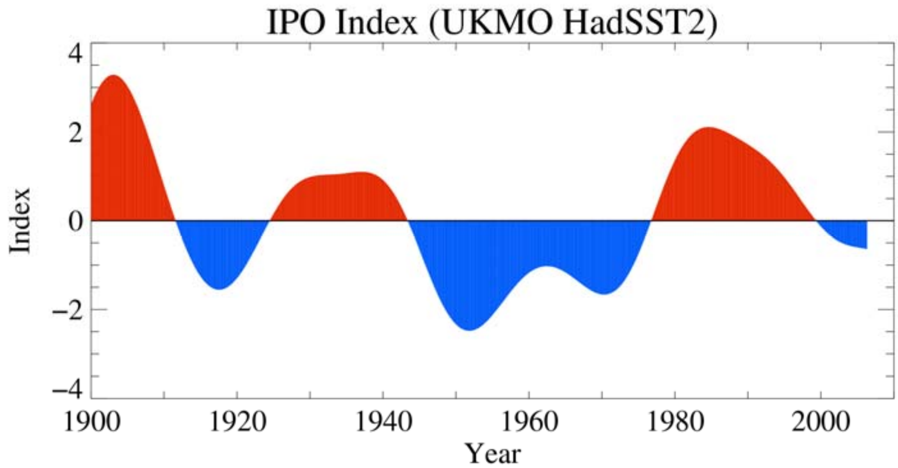
[1] At least 99% probability.

Figure 3.1 Phases of the Interdecadal Pacific Oscillation. Positive values indicate periods when stronger westerlies occur over New Zealand, and more anticyclones over the northern New Zealand. Negative values indicate periods with more north-easterli es over northern regions. *Source: Hadley Centre, UK Meteorological Office*.



Global warming effects are expected to accumulate during the 21st century, and enhance already observed changes in regional climate that have affected many physical and biological systems. Based upon global climate model output as used in the IPCC 4th Assessment Report, a downscaling to New Zealand conditions[2] has been completed, based largely upon statistical models. The most likely changes out to 2100 for New Zealand include increases in average temperature of between 0.5 and 5.5°C. As temperature increases, the water holding capacity of the atmosphere increases. With this the intensities of design rainfall extremes are projected to increase for a particular duration. For a specific rainfall intensity, the recurrence interval (return period) reduces. The westerly wind circulation over New Zealand is expected to gradually increase, with an enhancement of rainfall in many western regions, and decreases in the east, especially in winter and spring.

3.1 Location, Frequency and Magnitude

3.2.1 Auckland's climate

The Auckland region has a sub-tropical climate with warm humid summers and mild winters. Typical summer daytime maximum air temperatures range from 22°C to 26°C, but seldom exceed 30°C. Winter day-time maximum air temperatures range from 12°C to 17°C. Annual sunshine hours average about 2000 in many areas. Southwest winds prevail for much of the year. Sea breezes often occur on warm summer days. Winter usually has more rain and is the most unsettled time of year. In summer and autumn,

[2] The information about New Zealand and Auckland change in this chapter is primarily sourced from [2].

storms of tropical origin may bring high winds and heavy rainfall from the east or northeast.

3.2.2 Climate change and variability

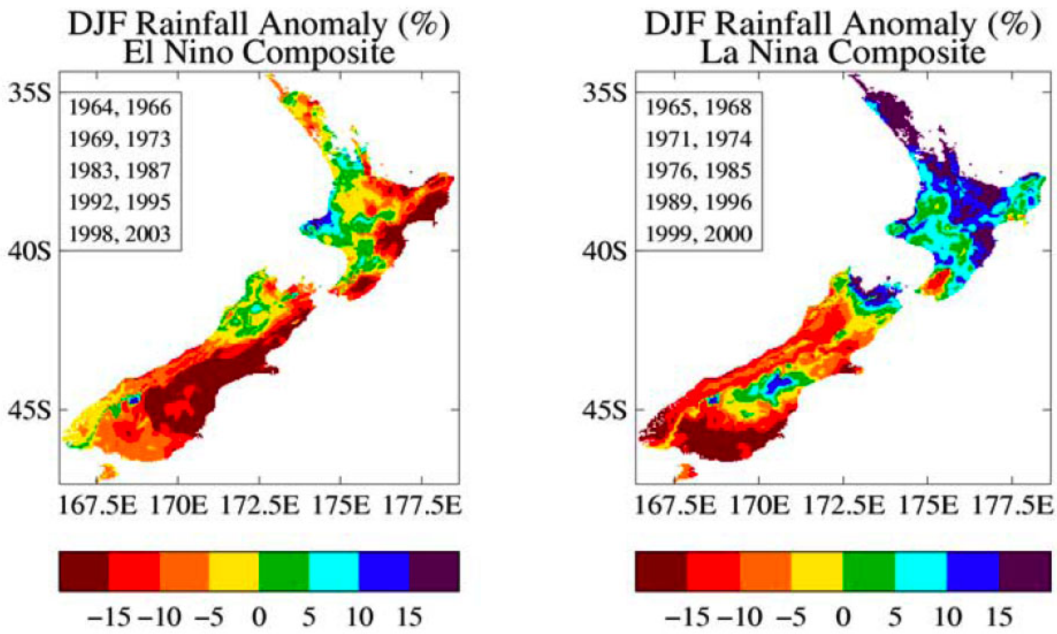
Since its inception, the IPCC has produced four assessment reports on Climate Change with the Fourth Assessment Reports released in 2007 (IPCC, 2007). There have been significant improvements in our understanding of climate change science in that time, with major improvements in detail from observations to modelling and downscaling projections of change to smaller areas such as New Zealand. At the same time the understanding of how sea level will rise during the 21st century have become more sophisticated. This, along with the continued development of supercomputers has provided climate scientists with enhanced tools for the evaluation of climate change scenarios. Also, there has been development of our understanding of how natural climate variability impacts on regional and local climate patterns around New Zealand. The future climate in New Zealand will arise from a combination of natural climate variation, and from anthropogenic origins as a result of increases in atmospheric greenhouse gas concentrations.

For the Auckland region, it is not feasible to make a single quantitative prediction of future climatic elements (e.g. rainfall volume and intensity). Rather rates of climate change depend on future global emissions of greenhouse gases which in turn depend on global social, economic and environmental policies and development. Incomplete scientific knowledge about some of the processes governing the climate system (e.g. natural year-to-year variability) also contributes to future uncertainty. It is necessary to consider a range of possible futures when assessing climate impacts and developing adaptation strategies.

3.2.3 The El Niño-Southern Oscillation (ENSO)

In El Niño years, Auckland tends to experience stronger and/or more frequent west to southwest winds. La Niña events bring roughly the opposite changes with weaker westerlies and more northerly quarter winds during summer, usually associated with enhanced rainfall in the region in all seasons. Annual maximum rainfalls during La Niña events are generally larger and more variable than are extremes during El Niño events, with differences in median annual maximum rainfalls not significantly different (Figure 3.2).

Figure 3.2 Differences between the long-term average rainfall and that in ENSO years (the rainfall anomaly), in percent, for summer (December, January, February). The ENSO rainfall is the average of the 10 strongest ENSO events between 1960–2007 (The insert box shows the ENSO years, where 1964 is December 1963 to February 1964, etc.).



3.2.4 Interdecadal Pacific Oscillation (IPO)

The Interdecadal Pacific Oscillation appears to accentuate or curtail the effects on El Niño and La Niña events depending on its phase (Bell, et al. 2000 [3]). The Positive IPO is associated with enhanced El Niño conditions, and Negative IPO is associated with normal fluctuation between El Niño and La Niña conditions. In the negative IPO phase, land and sea-surface temperatures in the Auckland region tend to be above average, and sea levels tend to be higher than average. Moreover, winds from the north and east, and storms of sub-tropical origin, tend to affect Auckland more frequently in the negative IPO. Hence, during the negative IPO, there tends to be a greater likelihood of coastal inundation from storm surge in the Auckland region, especially along eastern coastlines.

3.2.5 Projections for the Auckland Region

Many of the Auckland's natural hazards will be influenced in some way by climate changes. Reductions or increases in magnitude and changes to the location and frequency of hazards may be experienced. It is notable that information on projected changes in meteorological hazards is sparse at the regional level. Most information is provided at a global scale and is qualitative, providing relative increases or decreases. There are few regional assessments of climate change which provide quantitative predictions.

Recently, the IPCC Fourth Assessment provided climate projections based on scenario analysis for the period 2090–2099 relative to 1980–1999 (MfE, 2008 [2]). These global projections were "downscaled" with the purpose of having region-specific climate projections across New Zealand associated with the IPCC emission scenarios. Projected New Zealand climate changes are given for six greenhouse gas emission scenarios. Changes are specified for 2040 (2030–2049 average), and for 2090 (2080–2099 average), relative to the climate of 1990 (1980–1999 average). The main features of climate projections within the Auckland region can be summarised as follows:

- Increase in the mean temperature.
- Decrease of cold temperatures episodes and increase in number and intensity of high temperature episodes.
- Decrease in annual mean rainfall.
- Increased frequency and intensity of extreme rainfall events.
- Increased intensity of El Niño and a possible increase in El Niño frequency with an associated increase in the annual mean westerly component of wind flow.

3.2.5.1 Temperature

Table 3.1 indicates the range not only across the models analysed, and but also across the various emissions scenarios. The A1B projections were rescaled by the quoted IPCC global temperature changes to cover the other 5 illustrative scenarios. The values given in Tables 3.1 are averages over all grid-points within the regional council region. Averaging over all models and all 6 illustrative emissions scenarios gives an Auckland-average warming of around 1°C by 2040 and 2°C by 2090, with seasonal variations of a few tenths of a degree.

Table 3.1 Projected changes in seasonal and annual mean temperature (in °C) from 1990 to 2040 and to 2090, for the Auckland region. The average change, and the lower and upper limits (in brackets), over 6 illustrative scenarios are presented.

	Summer	Autumn	Winter	Spring	Annual
2040	1.1 [0.3, 2.6]	1.0 [0.2, 2.8]	0.9 [0.2, 2.4]	0.8 [0.1, 2.2]	0.9 [0.2, 2.5]
2090	2.3 [0.8, 6.5]	2.1 [0.6, 5.9]	2.0 [0.5, 5.5]	1.9 [0.4, 5.4]	2.1 [0.6, 5.8]

Note: This table covers the period from 1990 (1980-1999) to 2040 (2030–2049) and to 2090 (2080–2099), based on downscaled temperature changes for 12 global climate models, re-scaled to match the IPCC global warming range for 6 illustrative emission scenarios (B1, A1T, B2, A1B, A2, and A1FI).

Daily temperature extremes (overnight minimum and daily maximum) are expected to vary with regional warming, in addition to changes in mean temperature. A substantial increase is projected for the number of days above 25°C in Auckland Region. For example, under the B2 scenario, an additional 40 days or more per year are projected by the end of the century, while under the A2 scenario, this becomes more than 60 extra hot days. For comparison, Auckland currently experiences approximately 21 days per year with maximum temperatures exceeding 25°C.

3.1.1 3.2.5.2 Frost

Climate projections for New Zealand show a general decrease in the occurrence of frost days under all modelled scenarios. The least change is shown for Northland where frosts are already very rare. This scenario is likely to be similar in the Auckland region.

3.1.2 3.2.5.3 Rainfall

Table 3.2 gives the estimated range in seasonal and annual precipitation change over the 6 illustrative SRES scenarios, for selected sites within the Auckland region between two periods from 1990 to 2040 and from 1990 to 2090. The annual-average rainfall change has a pattern of decrease up to 3% by 2040 and 5% by 2090, in the mean. While summer and autumn show a small average increase by 2040, in winter and spring the pattern is reversed. A general decrease is expected by 2090, although the percentage changes are smaller than for the winter and spring seasons.

Table 3.2 Projected changes for selected stations within Auckland Regional Council area in seasonal and annual precipitation (in %) from 1990 to 2040 and to 2090. Lower and upper limits are shown in brackets.

	Location	Summer	Autumn	Winter	Spring	Annual
from 1990 to 2040	Warkworth	1 [-16, 20]	1 [-13, 22]	-4 [-22, 2]	-6 [-18, 6]	-3 [-13, 5]
	Mangere	1 [-17, 20]	1 [-14, 17]	-1 [-10, 5]	-5 [-15, 10]	-1 [-10, 6]
from 1990 to 2090	Warkworth	-2 [-31, 20]	-1 [-20, 12]	-4 [-24, 5]	-12 [-33, 6]	-5 [-19, 6]
	Mangere	-1 [-33, 20]	-2 [-21, 12]	-1 [-12, 9]	-9 [-30, 11]	-3 [-13, 9]

Note: This table covers the period from 1990 (1980-1999) to 2090 (2080–2099), based on downscaled precipitation changes for 12 global climate models, re-scaled to match the IPCC global warming range for 6 indicative emission scenarios.

3.2.5.4 Heavy rainfall

A warmer atmosphere can hold more moisture (about 8% more for every 1°C increase in temperature), so there is potential for heavier extreme rainfall under global warming. The IPCC (2007) declared that more intense rainfall events are "very likely over most areas" (Table SPM2). Recent climate model simulations confirm the likelihood that heavy rainfall events will become more frequent. Studies have suggested empirical adjustments (Table 3.3) to historical rainfall distributions (Semenov and Bengtsson, 2002 [4]) that can be applied to estimate a range of possible changes in extreme rainfall under global warming for a particular site. For example, for Auckland the worst case (most severe) end of the range for 2100 indicates that a rainfall amount with a return period of 50 years (AEP=0.02) under the current climate would have a return period of less than 10 years (AEP>0.10) by 2100. Design storm intensity rates increase by between 0.8 and 19.4 percent for the 2040s, 2 and 46 percent by the 2090s and 3 and 56 percent by the 2140s. Thus the intensity (mm/h) for the mid-range scenarios increases by 3.4 to 7.7 percent for the 2040s, 7.5 to 17.2 percent for the 2090s.

Table 3.3 Factors for use in deriving extreme rainfall information for preliminary scenario studies (screening assessments).

ARI (years) Duration	2	5	10	20	30	50	100
< 10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0
10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0
30 minutes	7.2	7.4	7.6	7.8	8.0	8.0	8.0
1 hour	6.7	7.1	7.4	7.7	8.0	8.0	8.0
2 hours	6.2	6.7	7.2	7.6	8.0	8.0	8.0
3 hours	5.9	6.5	7.0	7.5	8.0	8.0	8.0
6 hours	5.3	6.1	6.8	7.4	8.0	8.0	8.0
12 hours	4.8	5.8	6.5	7.3	8.0	8.0	8.0
24 hours	4.3	5.4	6.3	7.2	8.0	8.0	8.0
48 hours	3.8	5.0	6.1	7.1	7.8	8.0	8.0
72 hours	3.5	4.8	5.9	7.0	7.7	8.0	8.0

Note: This table recommends *percentage* adjustments to apply to extreme rainfall *per degree Celsius of warming*, for a range of average recurrence intervals (ARIs.). The percentage changes are mid-range estimates per degree Celsius and should only be used in a preliminary scenario study. The entries in this table for a duration of 24 hours are based on results from a regional climate model driven for the A2 SRES emissions scenario. The entries for 10-minute duration are based on the theoretical increase in the amount of water held in the atmosphere for a 1°C increase in temperature (8%). Entries for other durations are based on logarithmic (in time) interpolation between the 10-minute and 24-hour rates.

3.2.5.5 Tropical cyclones

Future changes in tropical cyclone behaviour remain uncertain. However, there are indications that tropical cyclones may intensify on average in a warmer climate while their overall number may decrease globally. Locally, a larger number of intense ex-tropical cyclones could impact on the Auckland region in terms of torrential rain, strong winds and storm surges.

3.2.5.6 Wind

The annual mean westerly wind component across New Zealand is expected to increase this century. MfE (2008) suggest a 10% increase in the annual mean westerly component wind speed over the next 50 years. In the recent Fourth Assessment

Report[3], a strong future seasonality in wind patterns is apparent with increased westerly winds in the winter and spring seasons. In spring the mean modelled westerly flow increases by about 10% by 2040 and 20% by 2090. Winter westerlies increase even more, while there are projected decreases of 5 to 20% in the summer and autumn.

An increase in the mean westerly component does not in itself imply an increase in total wind speed. However, strong[4] winds are associated with intense convection (expected to increase in a warmer climate) and with intense low-pressure systems, which might also become more common. Thus, an increase in severe wind risk could occur[5]. Since strong winds can cause damage to infrastructure and crops in Auckland, there is a demand to better understand how climate change might impact regional wind characteristics.

3.2.5.7 Drought

Drought hazard is expected to increase during this century in current drought-prone areas. Under a 'low-medium' scenario, by the 2080s severe droughts (defined in this report as the *current* one-in-twenty year drought) are projected to occur at least twice as often as currently in several regions including Auckland. Under the 'medium-high' scenario, results from (Mullan et al. 2005 [7]) suggest that the frequency of severe drought in these areas could increase even more (by up to four times in some parts of the Auckland Region by the 2080's).

3.2.5.8 Wildfire

The cumulative daily severity rating (CDSR) and very high and extreme (VH+E) Forest fire danger classes have previously been used as measures of fire season severity [8]. As might be expected, the increased temperatures and significantly decreased rainfalls under both the Hadley and CSIRO high extreme and mid-range scenarios produced significantly higher CDSR values and more days of VH+E Forest fire danger - the total number of days of VH+E Forest fire danger by more than 20 days per year in the Auckland region.

[3] With the Third Assessment models reported in [5], 6 models for the 2030s and 4 for the 2080s, there was a tendency for increased mean westerly flow over New Zealand in all seasons individually.

[4] We use the term "strong" here in a non-technical sense to cover the entire range in wind speed above about 10 m/s. A "strong" wind is formally defined on the Beaufort Wind Scale as Level 6 (in the range 22–27 knots, or 11–14 m/sec), one level above "fresh" and one level below "near gale".

[5] [6] identified an increasing number of strong wind events over the North Atlantic in their climate model simulation, which they relate to the increasing number of intense cyclones.

3.3 Key vulnerabilities and Potential Impacts

There is at present an incomplete understanding of how climate change from natural variability[6] and human induced trends will impact the Auckland region. Many planning decisions for settlements and infrastructure will need to account for new climatic conditions, but little work has been conducted on climate change vulnerability and impacts for the region. Despite the need for targeted research across multiple disciplines, there are a number of existing vulnerabilities that are expected to heighten current social, economic and environmental challenges.

3.3.1 Impacts from key climate drivers

3.3.1.1 Temperature

Extremely high and low temperatures have been linked with health problems across a variety of demographics in the Auckland region (e.g. the elderly). Adverse effects are typically related to the timing and duration of temperature episodes, as well as the degree of preparedness of the population to adapt to high or low temperature levels. Preparedness typically varies with respect to geographical and demographic factors, and needs to be taken into account when assessing the impact of extreme temperatures (McMichael et al. 2003 [9]).

Based on models of projected climate change, estimated deaths due to temperature in the Auckland region for people aged over 65yr is 4 deaths per year due to heat and 2 per year due to cold were identified for the base period 1989-1997 (McMichael et al. 2003). For a temperature increase of 2 - 3°C, the number of cold related deaths was predicted to diminish to zero. Meanwhile the number of heat deaths was predicted to increase to 53 (at +3°C). This represents a net increase in temperature related mortality of about eight fold and greatly outnumbers health gains.

Warm and cold temperature extremes also influence the cost and demand for electricity in association with heating and air conditioning. Moreover, temperature variability can adversely impact on agriculture production, animal stress, and growing seasons.

3.3.1.2 Rainfall

A range of hazards associated with high and low rainfall impact the Auckland region. Intense rainfall can result in floods and torrential rains are a major concern for urban stream health. At the same time irregular and scarce precipitation can significantly impact regional water supply and end-user activities (i.e. agriculture, horticulture and

[6] During El Niño years, there is a tendency over the northern North Island and the north-central South Island for flood frequency to be reduced below the long-term average. During La Niña events, weaker westerly winds in summer, and more northerly quarter winds, bring an increased likelihood of severe wind risk especially arising from ex-tropical cyclones during easterlies in the Auckland region.

various urban demands). Hazard risk will depend not only on exposure to different local geographic and demographic factors but also to changes in future Annual Return Periods (ARI's) for hazard events (Table 3.3).

Increased flood risk from high intensity rainfall has important implications for planning of major infrastructure that will need to cope with climatic conditions later in the 21st century. Frequency and magnitude increase of high intensity rainfall events would directly impact infrastructure across the Auckland region including stormwater drainage systems, development of low-lying land already subject to flood risk, roading and bridges. Indirect impacts would also arise, including financial costs involved with retirement of land use, extending current hazard zones and resource consent applications and processing.

3.3.1.2 Drought

The Auckland region is projected to become drier on average in the future, particularly in terms of moisture availability for pasture growth. This is likely to impact on Auckland's agricultural and horticultural industries, as well as place additional pressure on regional water supplies and river flows. Auckland's vulnerability to drought is affected by (among other things) population growth, urbanization, demographic characteristics, technology, water use trends, government policy, social behaviour, and environmental awareness. These factors are continually changing, and vulnerability to drought may rise or fall in response to these changes. Understanding and reducing these vulnerabilities is essential in preparing for and dealing with drought.

3.3.1.4 Wildfire

Results from the information reviewed here indicate that under future fire climate Auckland is likely to experience more severe fire weather and fire danger (Pearce et al. 2005 [10]). This is likely to result in increased fire risk including:

- longer fire seasons and increased drought frequency, and associated increases in fuel drying;
- easier ignition, and therefore a greater number of fires;
- drier and windier conditions, resulting in faster fire spread, greater areas burned, and increased fire suppression costs and damages; and
- greater fuel availability and increased fire intensities, increased resource requirements and more difficult fire suppression.

3.4 References and Additional Reading

References

1. Intergovernmental Panel for Climate Change, 2007: *Climate Change (2007). The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

2. Ministry for the Environment, 2008: *Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. 2nd Edition*. Mullan B; Wratt D; Dean S; Hollis M; Allan S; Williams T, Kenny G and MfE. Ministry for the Environment, Wellington. p149

3. Bell, R. G., Goring, D. G., de Lange, W. P. 2000: Sea level change and storm surges in the context of climate change. *IPENZ Transactions*. 27. No 1/Gen

4. Semenov, V. A., Bengtsson, L. 2002: Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM. *Climate Dynamics.* 19. 123-140.

5. Ministry for the Environment, 2004: Climate Change Effects and Impacts Assessment: *A Guidance Manual for Local Government in New Zealand*. Prepared by D. Wratt, B. Mullan and J. Salinger (NIWA), S. Allen and T. Morgan (MWH New Zealand Ltd), and G. Kenny (Earthwise Consulting). Ministry for the Environment Report ME 513, Wellington. p153.

6. Knippertz, P., Ulbrich, U., Speth, P. 2000: Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment. *Climatic Research.* 15. 109–122.

7. Mullan, B., Porteous, A., Wratt, D., Hollis, M. 2005: *Changes in drought risk with climate change*. National Institute of Water and Atmospheric Research (NIWA) Report WLG2005-23, Wellington. p22.

8. Pearce, H. G., Douglas, K. L., Moore, J. R. 2003: *A fire danger climatology for New Zealand*. Forest Research Contract Report No. 10052, prepared for the New Zealand Fire Service Commission Contestable Research Fund. New Zealand Fire Service Commission Research Report No. 39. p28.

9. McMichael, A. and Woodruff, R. Whetton, P., Hennessey, K., Nicholls, N., Hales, S. Woodward, A., Kjellstrom, T. 2003: *Human Health and climate change in Oceania; A risk assessment 2002*. Commonwealth Department of Health and Ageing. Canberra. p128.

10. Pearce, H. G., Mullan, A. B., Salinger, M. J., Opperman, D. R., Moore, J. R. 2005: *Impact of Climate Change on Long-term Fire Danger*. Prepared for the New Zealand Fire Service Commission Contestable Research Fund. New Zealand Fire Service Commission Research Report No. 50. p289.

Additional Reading

Allan, R., Lindesay, J., Parker, D. 1996: *El Nino Southern Oscillation and climatic variability*. Melbourne, CSIRO Publishing. p405.

Camilleri, M., Jaques, R., Isaacs, N. 2001: Impacts of climate change on building performance in New Zealand. *Building Research and Information*. 29. 440–450

Campbell, B. D. 2000: *Two-by-two: managing climate hazards for pastoral agriculture*. In: Managing the impacts of climatic variability: the Noah Paradigm. Proceedings of the New Zealand Institute of Agricultural Science and the New Zealand Society for Horticultural Science.

de Wet N, Ye W., Hales, S., Warrick, R., Woodward, A., Weinstein, P. 2001: Use of a computer model to identify potential hotspots for dengue fever in New Zealand. *New Zealand Medical Journal*. 114. 420-422

Intergovernmental Panel for Climate Change. 2007: *Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Parry M.L., Canziani O.F., Palutikof J.P., van der Linden P.J. and Hanson C.E. (eds.), Cambridge University Press, Cambridge, UK. 7-22.

Fowler, A. 1999: Potential climate change impacts on water resources in the Auckland Region (New Zealand). *Climate Research*. 11. 221-245

Fowler, A., Adams, K. 2004: Twentieth century droughts and wet periods in Auckland (New Zealand) and their relationship to ENSO. *International Journal of Climatology*. 24. 1947-1961.

Gordon, D. N. 1986: The southern oscillation and New Zealand weather. *Monthly Weather Review*. 114. 371-387

Kidson, J. W., Renwick J. A. 2002a: Patterns of convection in the tropical Pacific and their influence on New Zealand weather. *International Journal of Climatology*. 22. 151-174.

Kidson, J. W., Renwick J. A. 2002b: The Southern Hemisphere evolution of ENSO during 1981-1999. *Journal of Climate*. 15. 847-863.

McLeman, R., Smit, B. 2006: Vulnerability to climate change hazards and risks: crop and flood insurance. *Canadian Geographer-Geographe Canadian*. 50. 217-226

Pearce, G. 1996: *An initial assessment of fire danger in New Zealand's climatic regions*. New Zealand Forest Research Institute, Forest and Rural Fire Research Programme. Fire Technology Transfer Note 10 (October 1996). p28.

Power, S., Casey, T., Folland, C., Colman, A.; Mehta, V. 1999: Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics.* 15. 319-324.

Salinger, M. J., Mullan A. B. 1999: New Zealand Climate: Temperature and precipitation variations and their links with atmospheric circulation 1930-1994. *International Journal of Climatology*. 19. 1049-1071.

Salinger, M. J. , Renwick, J. A. , Mullan, A. B. 2001: Interdecadal Pacific Oscillation and South Pacific climate. *International Journal of Climatology*. 21. 1705-1721

Sturman, A., Tapper, N. 1996: *The weather and climate of Australia and New Zealand*. Melbourne, Oxford University Press. p476.

Thompson, C. S. 2007: Decadal climate variability of extreme rainfalls in New Zealand. *Weather and Climate*. 26. 3-20.

Wang, B. 1995: Interdecadal changes in El Nino onset in the last four decades. *Journal of Climate.* 8. 267- 285.

Wang, B., Wang, Y. 1996: Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. *Journal of Climate.* 9. 1586-1598.

White, W. B., Cherry, N. J. 1999: Influence of the Antarctic circumpolar wave upon New Zealand temperature and precipitation during autumn-winter. *Journal of Climate.* 12. 960-976.

Zhang, Y., Wallace, J. M., Battisti, D. S. 1997: ENSO like interdecadal variability: 1900-93. *Journal of Climate.* 10. 1004-1020.

4. Coastal Hazards: Soft Shoreline Erosion

4.1 Hazard Characteristics

Soft shoreline erosion is considered a significant issue in the Auckland region (ARC, 2000 [1]). Coastal erosion is described as "*The process of removal of material at the shoreline leading to loss of land as the shoreline retreats landward*" (Gibb, 1981[2]). The extensive urbanisation of the Auckland area, in a region with 1500 km of coastline has resulted in exposure of the Auckland population to hazardous coastal processes.

In this chapter, soft shorelines refer to sandy beaches and dunes comprised of unconsolidated or very weakly consolidated materials (Figure 4.1). Sandy beaches in the Auckland region broadly display dissipative (flatter profile), intermediate (flattish profile with a persistent sand bar) or reflective styles (steeper profile) (Figure 4.2). Beach profiles may contain features such as dunes, berms, and storm berms, troughs, terraces and sand bars. Sediments in the active wave zone are usually highly mobile so the beach profile and features constantly change as wind and storm patterns vary seasonally. Over yearly time scales beach profiles will also change in response to variations in sediment supply, wave conditions (orientation, frequency and magnitude), sea level rise and fall, and climate oscillations (See Chapters 3 and 6 for information on ENSO and IPO climate cycles). Dissipative and intermediate beaches (e.g. Orewa Beach, Piha Beach) are more likely to be composed of fine sandy or silty sediments and are often backed by sand dunes. These beaches are common on Auckland's exposed west and outer Hauraki Gulf coastlines. Reflective beaches are comprised of coarse sand and/or gravels and have a narrow zone of erosion typically a high tide berm and storm berm. Reflective beaches are not common in the Auckland region though some estuarine beaches (e.g. Mission Bay) show reflective qualities at high tide.

Figure 4.1 Components of a sandy beach profile. *Source: Daukas, 2008* [3].

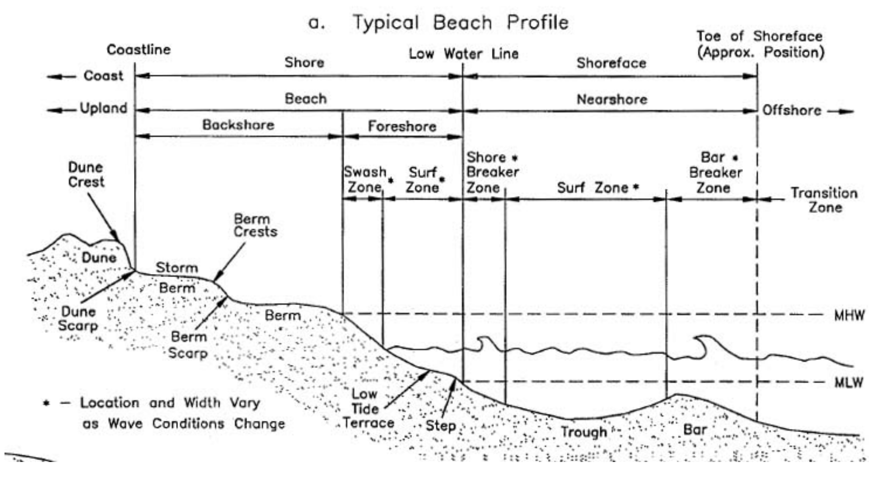
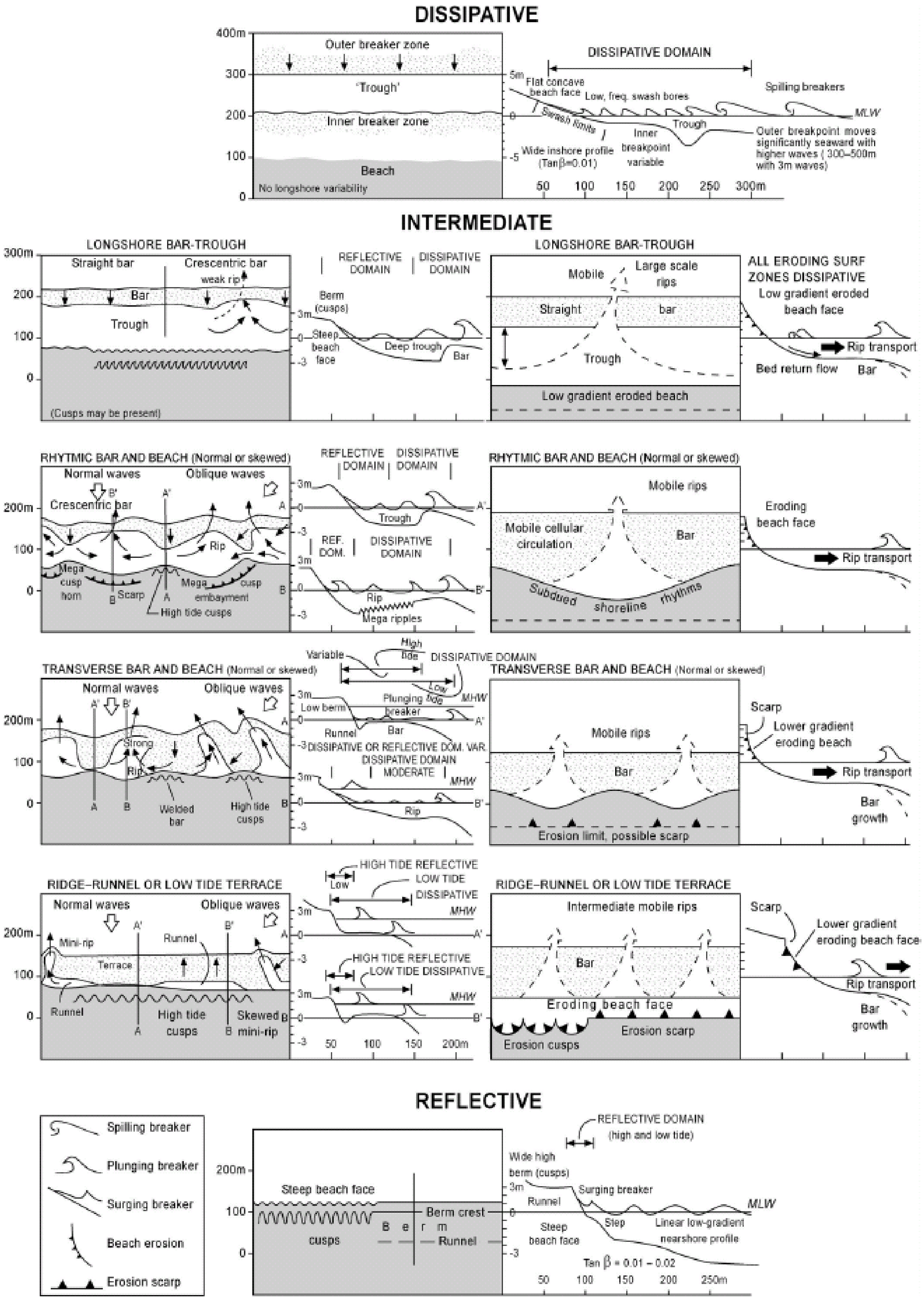
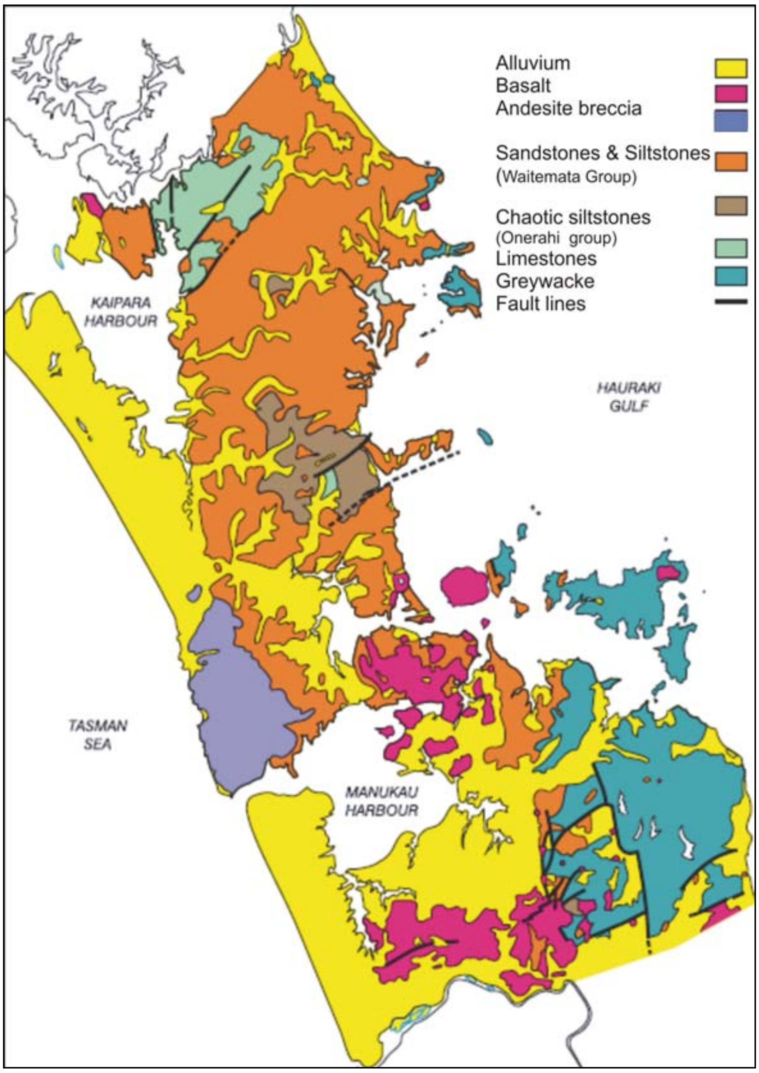


Figure 4.2 The types and features broadly representing sandy beach profiles on coastlines exposed moderate to high wave energy. The slope angle of the nearshore environment determines whether a beach is dissipative (larger tidal range with most wave energy lost on incoming waves) or more reflective (steeper beaches with smaller tidal range and wave energy reflecting back offshore after breaking). *Source: Short, 2006* [4].



Soft shorelines in the Auckland region are formed from mostly alluvial, pumiceous and marine sediments (Figure 4.3). Alluvial sediment shorelines are located along the inner Waitemata and Manukau Harbours. These are the region's oldest beaches (in terms of sediment age) and are composed of unconsolidated alluvial, pumice and sands of former estuaries. Behind the active beach profile, loose sediment deposits may be up to 20m thick. This areas land poorly compacted and vulnerable to subsidence when unsupported or overloaded by man-made structures. Erosion of the back beach slopes is also caused by non-marine processes (wind, rainfall), while erosion of the active beach is controlled by waves, tides and wind.

Figure 4.3 Geological map of the Auckland region. General locations of soft shorelines are coloured yellow on the map. Rocks labelled "Alluvium" include both marine and terrestrial sediments. *Source: Auckland Regional Council, 2002* [5].



The regions west coast features long stretches of sandy beaches which display a dissipative or intermediate form. Sediment is supplied to these beaches from rivers (e.g. Waikato river) and cliff erosion south of the region which is transported northward by waves and currents generated by persistent westerly swells. These beaches are often backed by foredunes recently developed by wind blowing sand from the beach face to the backshore area. Beyond foredunes, very old and large dune fields back west coast beaches and enclose the Manukau and Kaipara Harbours. These old dunes form poorly to moderated consolidated landscapes and are prone to wind erosion and failures on gentle slopes such as soil creep (See Chapter 12) (Edbrooke et al. 2003 [6]).

On the east coast, marine and terrestrial sands form sandspits at Omaha, Orewa, and Sandspit. These large features are fronted by dissipative or intermediate type beaches and are exposed to infrequent high energy wave's form during storm events often resulting in erosion of foredunes. Similar beaches can be found on the east coast of Great Barrier Island though development on the island is relatively sparse. Dry sand on dunes behind these beaches is extremely erosive during high winds, particular when dune vegetation is cleared. Beaches filling embayments in the inner Hauraki Gulf are less exposed to high waves and not as susceptible to extreme erosion events. Nevertheless, soft sands behind active beaches are still highly erosive even to small waves often prompting seawall construction to allow development and protect assets. Seawalls are known to exacerbate erosion local erosion problems in the inner Hauraki Gulf

Sandy beaches in the Auckland region experience cyclic periods of accretion (net sediment accumulation) or erosion (net sediment decrease) (Figure 4.4). Accretionary beaches can show a net gain in sand volume, though infrequent erosion events can be hazardous e.g. foredune scarping and dune blow-outs (Figure 4.5). On beaches experiencing a sustained period of erosion, sediment loss is caused by waves, currents and wind energy removing sediment from the active beach at a rate that is faster than it is replaced. Any change in this balance (i.e. a lowering of wave energy or increase in sediment available) will result in net shoreline accretion.

Figure 4.4 Schematic representations of eroding and accreting sandy beach profiles. *Source: Ministry for the Environment, 2004.*

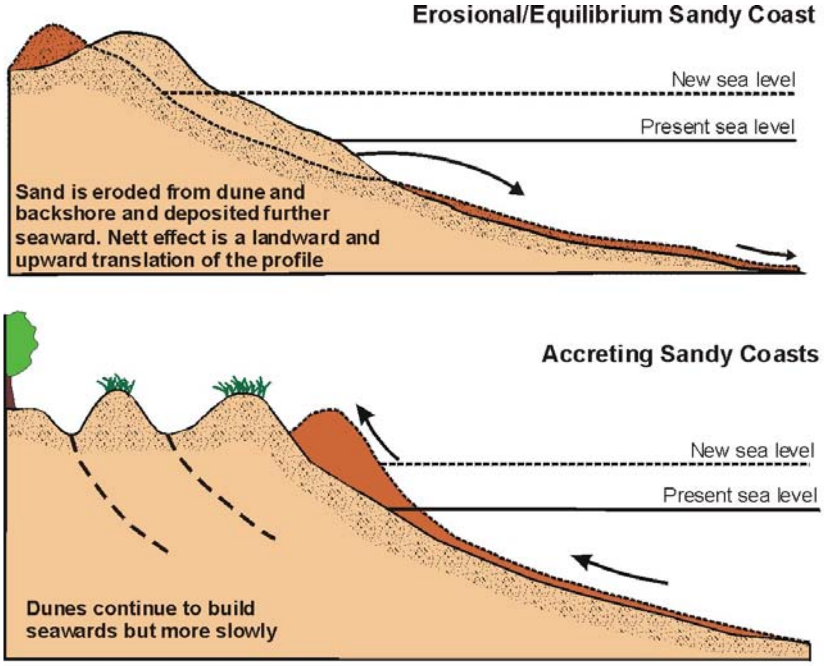
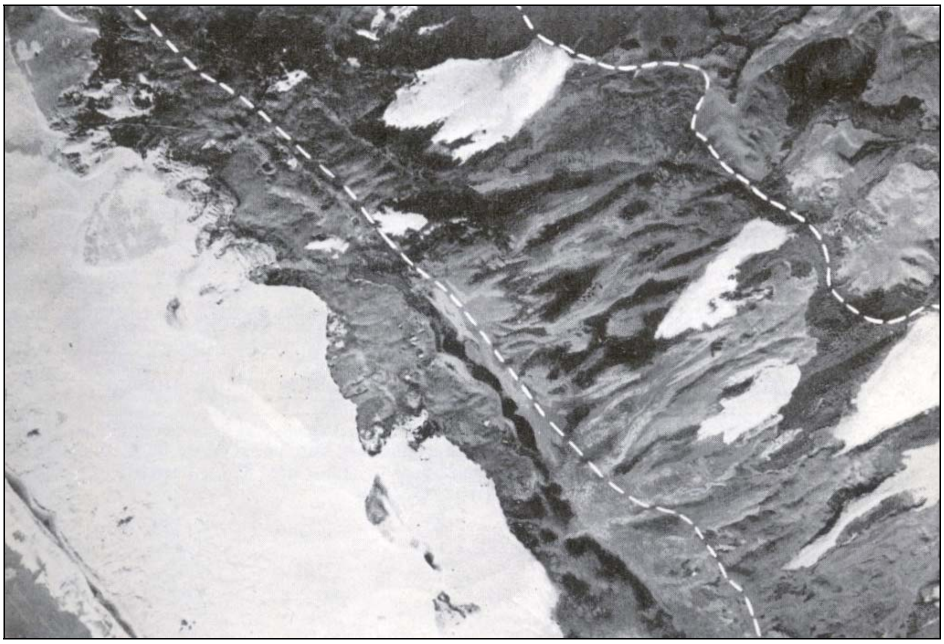
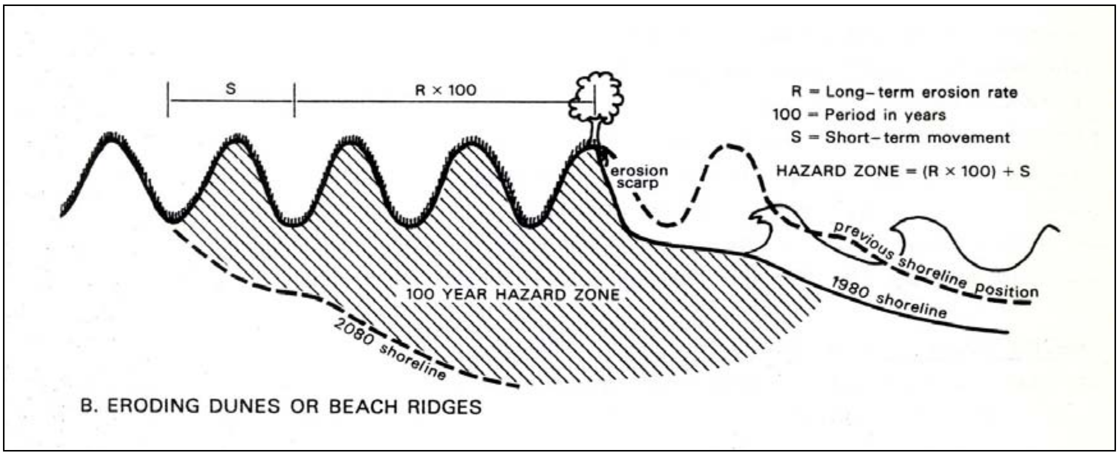


Figure 4.5 Parabolic dunes formed by blow-outs. The dotted lines mark changes in geomorphic units. From left to right, the geomorphic units are: the active beachfront and foredune system; the semi-stable established dune field and behind this an ancient dune field. *Source: Brothers, 1954* [7].



Beaches protect land by absorbing wave energy through a geotechnically weak mix of sand and water. The unconsolidated nature of beaches means they are forever changing environments. Sandy beaches have equilibrium forms (where sediment remains stable), depending on the wave and wind energy in that particular location as well as the size and amount of sediment available. Sandy beaches gradually adjust towards an equilibrium form whether it be a steep reflective or flat dissipative beach described earlier in this chapter (Kirk, 2001[8]). Beaches in accretionary or erosional phases are described as being in a state of dynamic equilibrium where they constantly adjust towards their natural form through events (e.g. storms) causing beach migration either landward (erosional) or seaward (accretionary). Subsequently one of the key concerns around soft shoreline erosion is a hazard zone for development does not remain static (Figure 4.6).

Figure 4.6 The process of dune or beach ridge migration on sandy beaches showing changes in shoreline over 100 years and calculation of a coastal hazard zone. Source: Gibb, 1981.



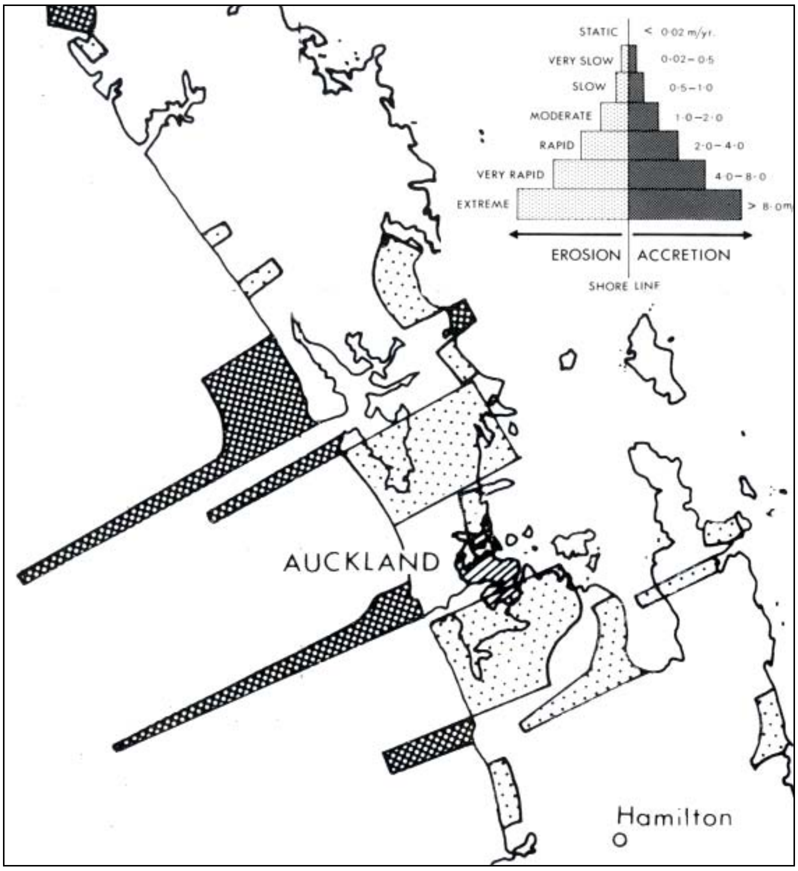
Beach erosion and accretion are a natural process. In the short term they are driven by wave and wind energy and in the long-term by sediment supply, sea-level and climate oscillations. Episodes of erosion are only of concern when threatening human habitation or development. Consideration of how the active beach changes over planning horizons (usually 100 years) is necessary due to the cyclic phases of erosion and accretion often experienced in response to coastal and climatic processes. Soft shoreline processes that may produce or exacerbate erosion hazards are:

- Wave energy available removes sediment at a greater rate than supply (non-equilibrium state resulting in net erosion),
- Landward retreat of the active beachface (including foredune),
- Blowouts or gradual erosion of sand dunes,
- Subsidence of the backshore area bringing the beaches backshore land into contact with waves and tides, and
- Elevated sea levels by climate change or tectonic subsidence allowing waves to erode further inland.

4.2 Location, Frequency and Magnitude

Auckland's soft sediment shorelines are shown in Figure 4.3. Gibb (1981) identified trends of sediment deposition and loss on Auckland's west coast beaches between 1880 and 1980 (Figure 4.7). Erosion and accretion rates where highly variable with beaches opposite Manukau Harbour experiencing localised erosion and accretion rates up to 19m/yr and 10m/yr respectively. Muriwai Beach experienced up to 12m/yr retreat though this was observed from only 5 years of measurement. Localised erosion and accretion on the exposed the west coast suggests that sediment moving northward along the coast has an important control on beach stability. In the long-term, erosion and accretion trends on west coast beaches will vary in response to changes in sea levels, near shore currents, wave energy, storm frequency and sediment supply.

Figure 4.7 Locations and average rates of erosion and accretion for the Auckland region, based on changes over the period 1880-1980. *Source: Gibb, 1981.*



On the east coast, Schofield (1985) [11] studied trends of erosion for Kaitoke and Palmers Beaches on Great Barrier Island and Omaha Beach. Beach profile data and sea level measurements from 1871 to 1980 were used to compare erosion and accretion rates from areas where coastal systems were anthropogenically altered (Omaha) to those with little or no development (Kaitoke and Palmers). Results from Omaha showed 30 to 40 m of beach accretion occurred between 1871 and 1934 followed by subsequent retreat of a similar distance. In addition, the northern end Omaha spit receded by a distance of 330 m during the erosional phase. This retreat matched a similar retreat period sometime prior to 1871. The author also measured the effects of individual storms on Omaha beach. For instance, the 1978 storm, average retreat rates north and south of the Omaha subdivision (constructed on the sand spit) were 12 m. Where the subdivision was sited, the storm-induced retreat was twice this rate. Higher erosion rates opposite the subdivision were attributed to the construction of a wooden seawall, removal of dune vegetation, levelling of sand dunes and lowering of the land behind the sea wall.

Greater Barrier Island beaches (east coast) are comparatively more exposed and have similar wave aspects and beach sediments to Omaha Beach though Schofield (1985) found sand loss from Omaha Beach was 4750m^3/per km of beach/per year greater than on Great Barrier Island beaches. As this is volume of sand loss the length of the beach is not relevant. The reasons for the greater sand loss at Omaha Beach are identified as attributable to anthropogenic activities associated with subdivision occupying the foredune and backshore are, groyne construction at the spit end and dredging of 'near shore' sediments for beach replenishment.

Anthropogenic attempts at reducing loss of beach material provide clear evidence of where past erosion has occurred in the Auckland region. Examples of seawalls constructed on alluvial beaches in Auckland's estuarine environments are shown in Figure 4.8. Seawalls provide an effective means of halting horizontal land loss from erosion however, beach sands in front of the structure are removed. This is because waves and currents are reflected back off the structure, taking sand with them back out into the estuary.

Figure 4.8 Seawall construction on alluvial beaches in the Auckland region. Left: Buckland's beach (specifically identified as susceptible to erosion by Edbrooke et al. 2003). Right: Taylor's Beach. Naturalness of beaches is sacrificed to protect assets; normally no beach sediments are visible and use of the beach is not possible at high tide.

4.3 Key Vulnerabilities and Potential Impacts

Assets at risk from soft shoreline erosion in the Auckland region are residential developments, roads, lifeline utilities and coastal structures. Soft shorelines bordering the Manukau and Waitemata Harbours have experienced or are vulnerable to erosion, though seawalls are constructed in many locations to protect assets. Seawall construction on these coasts mitigates shoreline erosion in the short to medium term but does not guarantee long-term protection where sea-levels are rising or other coastal hazards are exacerbated by existing seawalls. Seawalls alter local waves and currents causing scouring under walls or removal of sediment from the nearest unprotected coastline. Although seawalls are a quick solution to solving soft shoreline erosion problems they often exacerbate the erosion vulnerability of nearby shorelines to erosion.

The sandy beaches in the Rodney District, particularly on the Omaha and Orewa sandspits, have subdivision and development located on foredunes which are a component of the active beach profile. In these instances, coastal erosion risk is high as large storms may remove dune sand causing land loss and undermining of houses. As sea levels rise in response to global and local climate changes (i.e. ENSO, IPO), these areas will become more vulnerable as erosion rates increase on the upper beach face close to existing development (ARC, 1996[12]).

While erosion on dissipative and intermediate beaches is generally predictable and onset periods are often sufficient to remove at-risk assets from harm's way, there is increasing development pressure near these landforms due to their amenity values. Future long-term developments must recognise the cyclic processes of erosion and accretion on sandy beaches. Long-term sea level changes and climatic variability's driver erosion processes should be considerations for all planning near sandy beaches, particularly for long-term assets and infrastructure such as subdivision and lifeline utilities.

Some hazards and losses associated with soft shoreline erosion and coastal retreat are:

- Structural damage to privately owned buildings and infrastructure,
- Damage or destruction of lifeline infrastructure such as water, sewerage and gas pipes, or above ground features in the impacted zones such as roads, power transformers, network lines etc,
- Loss of land potentially resulting in an active hazard feature migrating closer to buildings/infrastructure,
- Loss of land resulting in a reduction in property value,
- Destabilisation of neighbouring slopes/properties,

- Psychological impacts for those affected economically,
- Clean-up costs for debris removal,
- Environmental impacts of the sedimentation of debris-receiving waterways,
- Costs of constructing and maintaining protection structures,
- Costs of running programmes such as dune re-planting or coastal care groups,
- Loss of beach amenity as there is no usable beach at high tide where sea walls are constructed,
- Aesthetic losses where hard structures replace natural landforms such as berms, ridges and dunes, and
- Secondary hazards such as leaking gas or water from broken pipes and pollution resulting from destruction of septic tanks and sewer lines.

In a planning context, whether erosion or instability should be considered for development of Auckland's soft shorelines can be determined by a series of factors both site-specific and on a larger scale:

1. Are the coastal processes of the location likely to result in increased risk? I.e. is this an area of net sediment gain or loss? What is the wave climate and current direction?
2. Is the geomorphology (slope angle, aspect, and existing features) of the location likely to result in increased risk (e.g. a narrow actively migrating beach)?
3. Has there been any human modification of the location? Is there evidence of vegetation removal, drainage modification, removal of dunes and construction of sea walls or other hard protection structures?
4. Is there a history of losses from large storm erosion events in this location?
5. What effects, both individual by site, and cumulative by area are likely? How do these effects relate to points 1-4 above?
6. If mitigation is undertaken, what is the residual risk?

4.4 References and Additional Reading

References

1. Auckland Regional Council. 2000: Coastal Hazard Strategy: Coastal Erosion Management Manual. Auckland Regional Council Technical Publication 130. p125.

2. Gibb, J. G. 1981: *Coastal hazards and urban planning*. In: Geomechanics in Urban Planning - Proceedings of Technical Groups. New Zealand Geomechanics Society and New Zealand Planning Institute. Palmerston North.

3. Daukas, S. 2008: *Geoscience: Ocean Science in Massachusetts*. [cited;June 2008 from: http://www.daukas.com/Geoscience/MAtour/CCC.html.

4. Short, A. D. 2006: Australian Beach Systems - Nature and Distribution. *Journal of Coastal Research*. 22. 11-27

5. Auckland Regional Council. 2002: *Auckland Regional Council, Auckland Water Resource Quantity Statement 2002*. Auckland Regional Council Technical Report 171.

6. Edbrooke, S. W., Mazengarb, C., Stephenson, W. 2003: Geology and geological hazards of the Auckland urban area, New Zealand*. Quaternary International*. 103. 3-21.

7. Brothers, R. N. 1954: A Physiographical Study of Recent Sand Dunes on the Auckland West Coast. *New Zealand Geographer*. 10. 47-59.

8. Kirk, B. 2001: *Marine Processes and Coastal Landforms*. In: Sturman, A., Spronken-Smith, R. (eds): *The Physical Environment; A New Zealand Perspective*. Oxford University Press: New York. p291-306.

9. Schofield, J. C. 1979: *Coastal erosion and coastal sand supplies from the Auckland-Northland region*. In: Tenth New Zealand geography Conference and Forty-ninth ANZAAS congress (geographical sciences). Christchurch.

10. Schofield, J. C. 1965 The Hinuera Formation and associated Quaternary events. *New Zealand Journal of Geology and Geophysics*. 8. 772-791.

11. Schofield, J. C. 1985: Coastal change at Omaha and Great Barrier Island. *New Zealand Journal of Geology and Geophysics*. 28. 313-322.

12. Auckland Regional Council, 1996: *The Environmental Impacts of Accelerated Erosion and Sedimentation*. Auckland Regional Council Technical Publication 69. 122.

Additonal Reading

Bruun, P. 1962: Sea-level rise as a cause of shore erosion. *Journal of Waterways Harbors Division, American Society of Civil Engineers.* 88. 117-130.

Bruun, P. 1988: The Bruun Rule of erosion by sea level rise: a discussion of large-scale two- and three-dimensional usages. *Journal of Coastal Research.* 4. 627-648.

Cooper, J. A. G, Pilkey O. H. 2004: Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change*. 43. 157-171

Crook, S. 2002: Aspects of low angle slope instability in Tauranga Group sediments. In: Proceedings of the 5th Australia-new Zealand young geotechnical professionals conference, Rotorua 2002.

Dean, R. G. 1991: Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research.* 7. 53-84.

Dean, R. G., Maurmeyer, E. M. 1983: *Models of beach profile response*. In: Komar, P. and Moore, J. (eds.), CRC Handbook of Coastal Processes and Erosion. Boca Raton, Florida: CRC Press. 151-165.

Eyles, G.O. 1985: The New Zealand Land Use Resource Inventory Erosion Classification. *Water & Soil Miscellaneous Publication*. 85. 1-60.

Goff, J Nichol, S and Rouse, H (eds) 2003: *The New Zealand Coast: Te Tai o Aotearoa*, Dunmore Press, Palmerston North. p320.

Kenny, J. A., Hayward, B. W. 1996: Inventory and Maps of Important Geological Sites and landforms in the Auckland Region and Kermedec Islands. Geological Society of New Zealand Miscellaneous Publication. p60.

Komar, P. D. 1998: *Beach Processes and Sedimentation, 2nd edition*. Upper Saddle River, New Jersey: Prentice Hall. p544.

Manning, P. A. 1983: Engineering geology of a section along the northern coast of the Manukau Harbour, Auckland. University of Auckland.

Masselink, G., Short, A. D. 1993: The effect of tide range on beach morphodynamics and morphology: a conceptual model. *Journal of Coastal Research.* 9. 785-800

Ministry for the Environment, 2004: *Coastal Hazards and Climate Change: A guidance manual for local government in New Zealand*. ISBN: 0-478-18933-8. p145

Pilkey, O. H., Cooper, J. A. 2004: Climate, society, and sea level rise. *Science.* 303. 1781-1782

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

Searle, E. J. 1956: Aspects of the Pleistocene and Recent history of the Auckland isthmus. *New Zealand Geographer*. 12. 75-88

Short, A. D. (ed.) 1999: *Beach and Shoreface Morphodynamics*. p379

U.S. Army Corps of Engineers, 2002: *Coastal Engineering Manual*. Washington, DC. p1200.

Woodroffe, C. D. 2000: *Coasts: Form, processes and evolution*. Cambridge University Press. p630.

Wright, L. D., Short, A. D. 1984: Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology.* 56. 93-118.

5. Coastal Hazards: Hard Shoreline Erosion and Cliff Instability

5.1 Hazard Characteristics

The erosion of hard shorelines is a serious hazard facing urban development in the Auckland region (ARC, 2000[1]). Developing an understanding of the environmental and anthropogenic processes contributing to erosion and cliff instability of hard shorelines combined with identifying hazardous areas will assist land use planning along Auckland's hard shorelines. This chapter will primarily focus on coastal cliff erosion and instability along soft to moderately hard sedimentary rock coastlines comprised of sandstones and siltstones. These coastal cliffs boarder much of the Auckland metropolitan area's eastern coast and are often in close vicinity to urban areas.

Coastal cliffs are essentially landforms created by erosion. A number of environmental and anthropogenic factors can contribute to the erosion and instability of coastal cliffs in the Auckland region. These include:

- Geology: rock type, hardness, strike and dip of bedding units and defects such as joints and faults.
- Cliff height and steepness
- Shore platform morphology and relief: width, gradient and elevation, ramparts, washboard relief, beaches, block falls.
- Marine processes: tides, sea level and wave climate (height, period, orientation).
- Subaerial weathering: salt erosion, wetting and drying.
- Biological: boring mollusc.
- Climate: rainfall intensity and volume, storm frequency and magnitude.
- Drainage: ground water seepage.
- Human modification: removal of vegetation, earthworks, weight loading of structures.

Geomorphic features provide evidence of past coastal cliff erosion along Auckland's sedimentary rock coasts. These may include 'freshly' exposed cliff faces, talus (cliff debris) deposits, beaches and shore platforms (Figure 5.1, Top Photo)). Shore platform width can provide an indication of cliff retreat rates that have occurred locally i.e. wider shore platforms can reflect higher rates of cliff retreat. Natural features can also indicate the future likelihood of erosion of cliff instability. For instance, rock defects such as faultlines (Figure 5.1 Bottom Photo) or bedding planes (see Figure 5.2), contacts between alternating sandstone and mudstone layers) and groundwater seepage are environmental factors that promote cliff failure. An example of how site specific factors contributing to cliff instability can be used to determine vulnerability is provided in Table 5.1.

Figure 5.1 Sedimentary rock shoreline features in the Auckland region. Top photo gently dipping sedimentary beds on a shore platform at a cliff base (photo by, L Homer). Bottom photo: Faults and joints in the cliff face and a talus slope at the cliff base indicating recent cliff failure. *Source: Jongens et al. 2007* [2].

Figure 5.2 Sandstone and mudstone greywacke cliff face in the Takapuna area. *Source: Paterson and Prebble, 2004* [3].

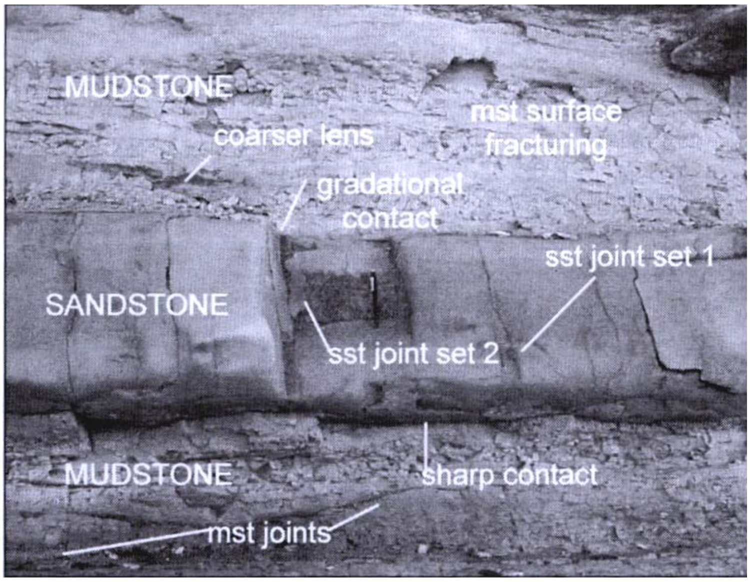
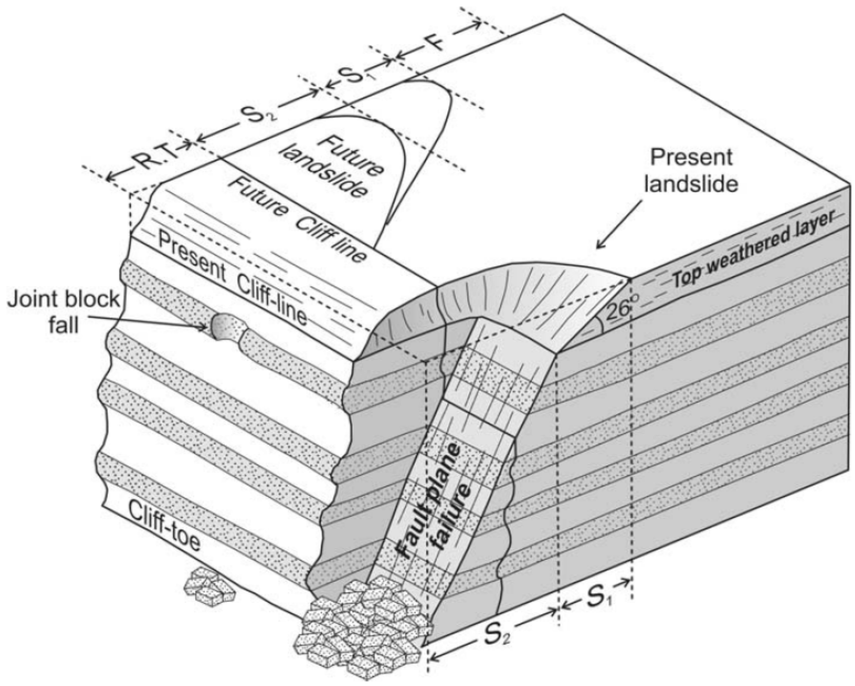


Table 5.1 Jongens et al. 2007 method for determining vulnerability of North Shore coastal cliffs based on geology, aspect, and groundwater conditions. Vegetation and human influences are not included as they can change considerably over a hundred year period and this method produces a 100 year vulnerability index.

Variable		Weight	Vulnerability class		
			Low (0)	Medium (1)	High (2)
(i)	Dip direction of bedding	2	Landward or sub-horizontal 0–1°	Seaward 2–10°	Seaward >10° or steeply folded
(ii)	Fault orientation	2	No faults	Cliff-line sub-normal	Cliff-line sub-parallel/oblique
(iii)	Sea-cliff aspect (degrees)	2	110–140	075–105	035–070
(iv)	Cliff height (m)	1	10–19	20–28	29–37
(v)	Cliff-toe lithology	3	Parnell Grit	Thick sandstone bed	Thin siltstone/ sandstone beds
(vi)	Cliff-face Si/Ss beds (above cliff-toe)	1	>50%Ss	50%Ss/50%Si	<50%Ss
(vii)	Groundwater seepage	2	Not present	–	Present

The development of Auckland's sedimentary coastal cliffs is controlled by marine processes (waves, tides, currents) destabilising the cliff by removing loose sediment deposits at the cliff toe, leading to gravitational slope failure as cliff angle adjusts to a more stable state. This is then followed by a renewed period of cliff toe erosion and subsequent slope failure and adjustment as the cycle continues. Due to these processes, coastal cliffs may exhibit short to medium-term stability but are inherently unstable in the long-term and experiencing gradual retreat. This is because rocks are weakened by ancient faultlines and ongoing weathering while infrequent mass failures triggered intense rainfall events (or large earthquakes) are also possible, especially on cliffs where drainage systems have been modified. The processes described above are observed in Figure 5.3, depicting elements of coastal cliff failure.

Figure 5.2 Elements of coastal cliff retreat and block failure. *Source: Jongens et al 2007.*



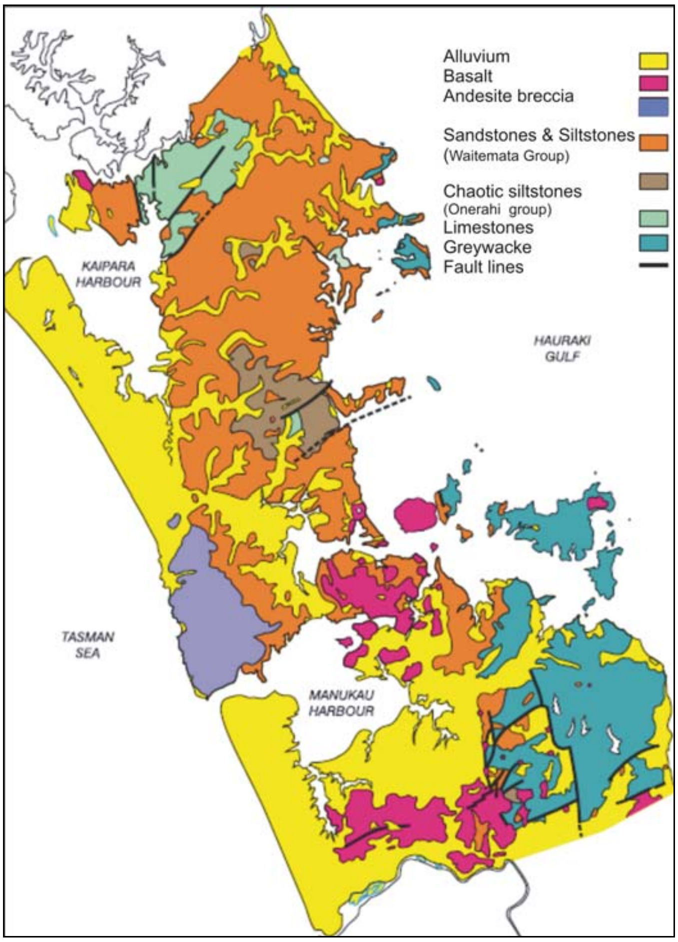
Jongens et al. 2007 studied sedimentary coastal cliffs along the North Shore City east coast and determined that a stable slope angle for these coasts is 26°. At steeper angles there is an inherent instability for these coastal cliffs. Long-term (>100 years) cliff retreat is shown in Figure 5.3 as the combined long-term averages of potential sudden failures along bedding planes or fault joints (*S1*), and the slumping of cliff faces as the slope evolves towards a stable slope angle of 26° (*S2*); *R* is the rate of retreat over a given time period *T* (in this diagram *T* = a time period of 100 years). The authors used data from 40 retreating coastal cliff locations on the North Shore to determine Coastal Landslide Hazard Zones (CLHZ) in metres (Equation 5.1). Hazard zone locations are described in Section 5.2.

Equation 5.1: $\text{CLHZ} = S + (RT) = F$

5.2 Location, Frequency and Magnitude

The locations of erosion and landslide–prone sedimentary coastal cliffs in the Auckland region are determined primarily by geology. Volcanic coasts (basaltic and andesitic) are formed of much harder rock than sedimentary coasts and less likely to form bedding, joint and plane failures. These coasts are considered to be relatively stable. Greywacke rocks exposed along the south east coastlines are softer and contain rock defects, suggesting cliffs are more vulnerable to instability than those of volcanic rock. From these generalisations a basic surface geological map can show Auckland coastlines that are most vulnerable to cliff failure and erosion (Figure 5.4).

Figure 5.2 Surface geology of Auckland region and surrounding area. Areas of sandstones and siltstones (Waitemata Group) are most vulnerable to cliff erosion. *Source: Auckland Regional Council, 2002* [7].

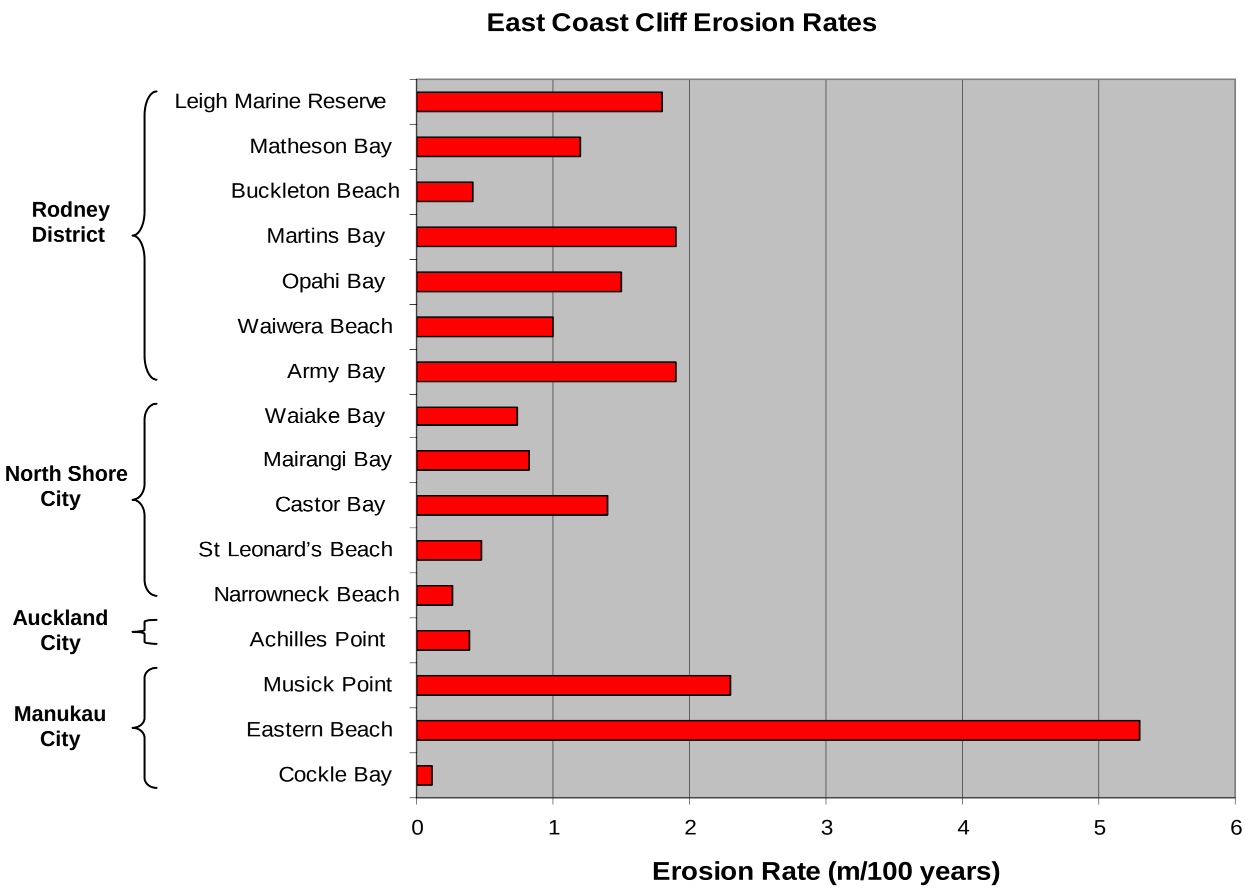


A regional slope stability map developed by Williams (1996) [8], shows indicative locations where coastal cliffs are susceptible to erosion and instability based on rock/soil type and slope angle (Figure 5.5). Comparing both Williams (1996) and geological maps (Figure 5.4) suggests basaltic (volcanic) coastal cliffs are most stable, greywacke cliffs are somewhat stable and sedimentary (sandstone and siltstone) coastal cliffs are most prone to instability and erosion. Sedimentary coastal cliffs comprised of sandstone and siltstone are generally located northern Auckland isthmus coast, northern Manukau Harbour, North Shore and Rodeny District.

Figure 5.1 Slope stability map for the Auckland region. Because the map considers slope angle as well as rock type, some areas of harder rock are classed in the areas of greatest instability. Orange =high hazard; yellow = moderate hazard and determined by local effects; cream = low hazard. Weathering effects around the coast of the Waipapa Terrane can also be seen as the inland areas of the Hunua ranges are ranked more stable than the coastal areas of the terrane. *Source: Williams, 1996*.

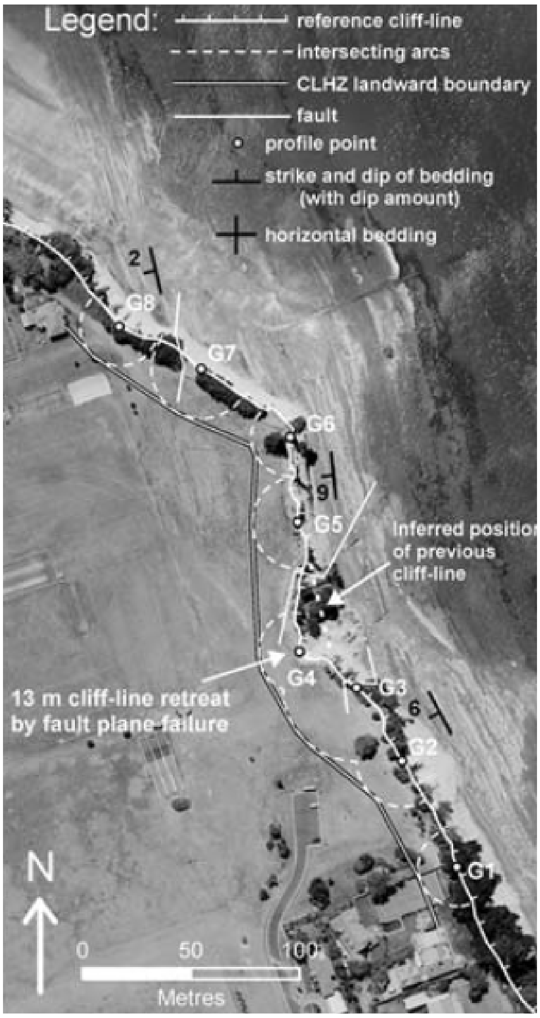
Sedimentary coastal cliff erosion rates have recently been investigated along East Coast Bays, North Shore (Glassey et al. 2003 [10]) and outer and inner Hauraki Gulf east coast (Bell, 2007 [11]). Over a 100 year period, Glassey et al. 2003 observed cliff retreat between 1 and 10m for 40 sites with an average of 3m. These are greater than those of Bell (2007) who determined longer-term (7100 years) retreat rates from measuring shore platform widths at the cliff toe (Figure 5.6). With respect to the cliff face, the measurement locations in these studies reflect the variation in erosion rates as cliffs often retreat more rapidly at the top edge than at the toe. Although cliff retreat rates appear minimal in comparison to those experienced by other coastal landforms (i.e. sandy beaches) they pose a significant hazard when rapid landslide failure occurs. As the magnitude of landslide events are hazardous to property and people near sedimentary coastal cliffs, Jongens et al. (2007) developed a 100 year Coastal Landslide Hazard Zone (CLHZ) for locations along North Shore's East Coast Bays from a combination of cliff profiles, historical erosion rates (from Glassey et al. 2003), faulting and bedding plane features and the slope angle of stable cliffs.

Figure 5.6 Sedimentary (sandstone and siltstone) coastal cliff erosion rates along Auckland's east coast for the last 7100 years. *Source: Bell, 2007.*



The CLHZ range covers a varying area of land between 13 and 34m landward from the cliff top, with an average of 23 m. These values may seem incongruous due to average erosion rates of 3m however, large block or wedge landslide failures often poorly represented by annual retreat rates are taken into account. A precautionary principle should be implemented where an erosion hazard may exist though magnitude, frequency or consequences are difficult to determine. To prevent further risk to property or people from cliff erosion along the North Shore this option is preferred to a cautious approach of siting assets in CLHZ's. Differences should be noted between a determined coastal hazard zone and a setback zone stated in council plans. Using the precautionary principle, a setback zone would include the coastal hazard zone but also allow for other considerations such as natural character, amenity, or cultural values (ARC, 2000).

Figure 5.5 An example of the CLHZ calculations In this case the CLHZ is 13 m from the current cliff edge. *Source: Jongens et al. 2007.*



5.3 Key Vulnerabilities and Potential Impacts

The major lifeline infrastructure locations identified in the *Assessment of Infrastructure Hotspots in the Auckland Region* (AELG, 2007) [12] report are not subject to erosion or instability hazards on hard shorelines. This report only focused on a few high priority locations, though some transport routes are potentially at risk to cliff erosion and instability along the northern Auckland City isthmus and southwest of North Shore City.

Urban (mostly residential) development and lifeline infrastructure facilities/networks situated within or adjacent to sedimentary coastal cliffs are most vulnerable to losses from cliff failure. In recent years, coastal cliff erosion and instability has affected residential properties in the North Shore City costing the community millions of dollars through damage to structures, loss of land and even the decommissioning of houses. Recent examples of coastal landsliding damage reported in Auckland region include the demolition of a house following a large coastal landslide on a cliffed coast with altered drainage, and the loss of half a hectare of farmland into the sea on Auckland's west coast (New Zealand Herald, 2008) [13].

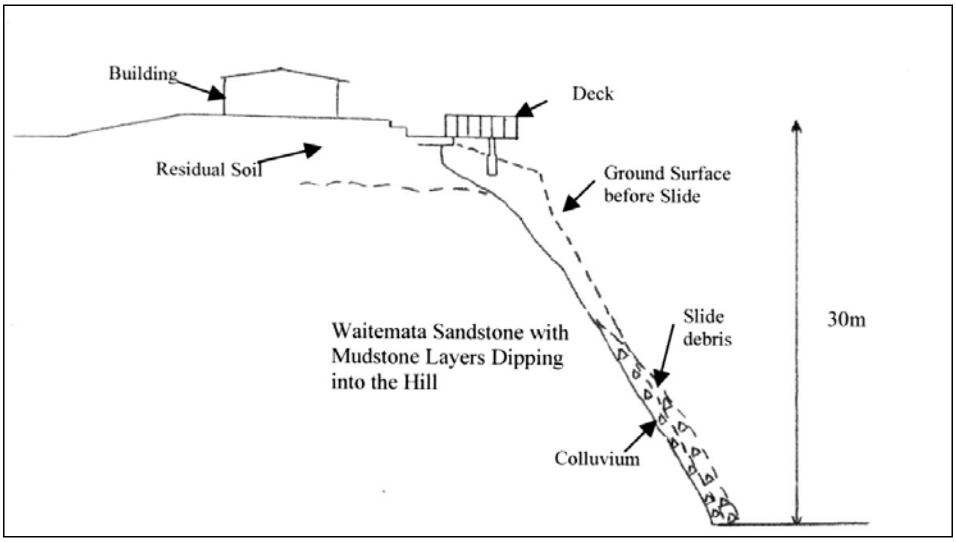
In general, long-term coastal hazard zones for land use planning adjacent coastal cliffs are developed without consideration anthropogenic activities. Over short to medium term timeframes (<50 years), changes in the natural state of a cliff from vegetation removal, slope loading and altering drainage patterns can contribute to lowering the strength of in situ material or increase loading forces acting on the slope to promote failure. Vegetation clearance can remove the structural reinforcement of established root networks while loss of rainfall interception causes a more rapid loss of soil and regolith strength through saturation (Paterson and Prebble, 2004). Modification to natural slope drainage patterns impacts on slope stability despite intentions to improve drainage and slope stability. An increase in runoff saturates slopes and reduces cliff stability as shear strength of cliff materials decreases. Water flowing through structural irregularities such as joints and faults observed along North Shore coastal cliffs can increase cleft pressures, promoting sudden failure of a cliff face. Increases in loading on cliff tops by large trees and buildings can also destabilise cliffs by altering forces acting upon cliff material (Figure 5.8). These activities are common place where urbanisation has encroached onto coastal cliff tops around the Auckland Metropolitan area and it is possible that long-term site stability for residential properties may not have considered the entire spectrum of physical and anthropogenic factors contributing to cliff stability.

Some hazards and losses associated with hard shoreline erosion and instability are:

- danger to life in the case of sudden onset landslide events (danger exists both at the head (active failure surface) and the toe (debris deposit area) of the landslide);
- damage or destruction of buildings and structures either in the head or toe area of the landslide;
- damage or destruction of lifeline infrastructure such as water, sewerage and gas pipes, or above ground features in the impacted zones such as roads, power transformers, network lines etc;
- loss of land potentially resulting in an active hazard feature migrating closer to buildings/infrastructure;
- loss of land resulting in a reduction in property value;
- destabilisation of neighbouring slopes/properties;

- psychological impacts for those affected either physically or economically;
- clean-up costs for debris removal;
- environmental impacts of sedimentation of debris-receiving waterways;
- pollution of land and water where toxic substances form part of landslide debris (e.g. paint, oil, garden chemicals);
- secondary hazards such as leaking gas or water from broken pipes;
- costs associated with mitigation or remedial works;
- litigation costs.

Figure 2.6 Example of loading on weathered material contributing to cliff instability. The engineering solution suggested to reduce further loss is to remove the deck and anchoring the building into bedrock (below residual soil layer). *Source: Adhikary, 2004* [6].



In a planning context, whether instability or erosion should be considered in the context of development of Auckland's hard coastlines can be determined by a series of site specific or regional scale factors:

1. Is the geology of the location likely to result in increased risk? Is the proposed location on Miocene age sandstones and mudstones? Do the beds dip towards the sea? Are there bedding plane weaknesses and faults present?
2. Is the geomorphology (slope angle, aspect, and existing features) of the location likely to result in increased risk?
3. Is the site undercut by wave action?
4. Has there been any human modification of the location, particularly near the cliff face? Is there evidence of vegetation removal, loading, drainage modification?

5. Have there been any sudden onset cliff failures in the neighbouring properties or nearby areas?
6. What effects, both individually by site, and cumulatively by area are likely? How do these effects relate to points 1-4 above?

5.4 References and Additional Reading

References

1. Auckland Regional Council. 2000: Coastal Hazard Strategy: Coastal Erosion Management Manual. Auckland Regional Council Technical Publication 130. p125.

2. Jongens, R., Gibb, J. G., Alloway, B. V. 2007: A new hazard zonation methodology applied to residentially developed sea-cliffs with very low erosion rates, East Coast Bays, Auckland, New Zealand. *Natural Hazards*. 40. 223-244.

3. Paterson, R.D., Prebble, W. M. 2004: Engineering geology and coastal cliff erosion at Takapuna, Auckland, New Zealand. In: To the eNZ of the Earth; proceedings of the 9th Australia New Zealand conference on geomechanics, Auckland 2004.

4. Edbrooke, S. W., Mazengarb, C., Stephenson, W. 2003: Geology and geological hazards of the Auckland urban area, New Zealand. *Quaternary International*. 103. 3-21.

5. Edbrooke, S. W. 2001: *Geology of the Auckland Area*. Institute of Geological and Nuclear Sciences 1:250 000 geological map.

6. Adhikary, T. P. 2004: *Coastal slope instability in Auckland and Northland*. In: To the eNZ of the Earth; proceedings of the 9th Australia New Zealand conference on geomechanics.

7. Auckland Regional Council. 2002: *Auckland Regional Council, Auckland Water Resource Quantity Statement 2002*. Auckland Regional Council Technical Report 171.

8. Williams, A. L. 1996: Slope Instability Hazards in the Auckland Region: a preliminary assessment. Auckland Regional Council Technical Publication 71. p29.

9. Gibb, J. G. 1981: *Coastal hazards and urban planning*. In: Geomechanics in Urban Planning - Proceedings of Technical Groups. New Zealand Geomechanics Society and New Zealand Planning Institute. Palmerston North.

10. Glassey, P., Gibb, J. G., Hovard, J., Jongens, R., Alloway, B., Coombes, K., Benson, A. 2003: Establishing a Methodology for Coastal Cliff Hazard Mapping: An East Coast Bays, Auckland Pilot Study, In: Proceedings of Coasts and Ports Australasian Conference, Auckland, New Zealand, Paper 49. p12

11. Bell, J. E. 2007: Towards a Better Understanding of Coastal Cliff Erosion in Waitemata Group Rock; Auckland, New Zealand. University of Waikato Thesis. p305.

12. Auckland Engineering Lifelines Group. 2007: *Assessment of Infrastructure Hotspots in the Auckland Region*. Auckland Engineering Lifelines Group Report. p59.

13. New Zealand Herald. *Various reports of landslide events in the Auckland region*. [cited; June 10th, 2008. Available from:

http://www.nzherald.co.nz/column/story.cfm?c_id=1500914&objectid=10405794

http://www.nzherald.co.nz/topic/story.cfm?c_id=228&objectid=10404803

http://www.nzherald.co.nz/topic/story.cfm?c_id=195&objectid=10119806.

Additional Reading

Bartrum, J. A. 1924: The shore platform of the west coast near Auckland: its storm wave origin. *Australian and New Zealand Association for the Advancement of Science.* 16. 493–495.

Bartrum, J. A. 1941: The problem of the occurrence of beach-limestone at Auckland, New Zealand. New Zealand Journal of Science and Technology. 23. 92-96.

Crook, S. 2002: Aspects of low angle slope instability in Tauranga Group sediments. In: Proceedings of the 5th Australia-new Zealand young geotechnical professionals conference.

Davies, P., Sunamura, T., Takeda, I., Tsujimoto, H., Williams, A. T. 2006: Controls of shore platform width: The role of rock resistance factors at selected sites in Japan and Wales, UK. *Journal of Coastal Research*. Special Issue 39. 160-164

de Lange, W. P., Moon, V. G. 2005: Estimating long-term cliff recession rates from shore platform widths. *Engineering Geology*. 80. 292-301.

Dickson, M. E. 2007: Shore platform development around Lord Howe Island, southwest Pacific. *Geomorphology*. 76. 295-315

Eyles, G.O. 1985: The New Zealand Land Use Resource Inventory Erosion Classification. Water & Soil Miscellaneous Publication. 85. 1-60.

Gibb, J. G. 1979: A coastal landslide. *Soil & Water*. 15. 20-21.

Gulyaev, S. A., Buckeridge, J. S. 2004: Terrestrial methods for monitoring cliff erosion in an urban environment. *Journal of Coastal Research*. 20. 871-878.

Healy, T. R. 1968: Bioerosion on shore platforms developed in the Waitemata Formation, Auckland. *Earth Science Journal*. 2. 26-37.

Kennedy, D. M., Dickson, M. E. 2007: Cliffed coasts of New Zealand: perspectives and future directions. *Journal of the Royal Society of New Zealand*. 37. 41-57.

Kenny, J. A., Hayward, B. W. 1996: *Inventory and Maps of Important Geological Sites and landforms in the Auckland Region and Kermedec Islands*. Geological Society of New Zealand Miscellaneous Publication. p60.

Manning, P. A. 1983: Engineering geology of a section along the northern coast of the Manukau Harbour, Auckland. University of Auckland Thesis.

Moon, V.G., Healy, T. 1994: Mechanisms of coastal cliff retreat and hazard zone delineation in soft flysch deposits. *Journal of Coastal Research*. 10. 663-680.

Stephenson, W. J. 2001: Shore platform width - A fundamental problem. *Zeitschrift fur Geomorphologie*. 45. 511-527

Stephenson, W. J., Kirk, R. M. 2000: Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: Part I. The role of waves. *Geomorphology*. 32. 21-41

Stephenson, W. J., Kirk, R. M. 2000: The development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: Part II. The Role of Subaerial Weathering. *Geomorphology*. 32. 43-56

Sunamura, T. 1983: *Processes of sea cliff and platform erosion*. In: Komar, P.D. (ed.) CRC Handbook of Coastal Processes and Erosion. CRC Press, Boca Raton, Florida. 223–265.

Sunamura, T. 1991: The elevation of shore platforms: a laboratory approach to the unsolved problem. J*ournal of Geology*. 99. 761–766.

Sunamura, T. 1992: *Geomorphology of Rocky Coasts*. Wiley, New York. p302 .

Trenhaile, A.S. 1987: *The Geomorphology of Rock Coasts*. Oxford University Press, Oxford. p388.

Trenhaile, A. S. 2002: Rock coasts, with particular emphasis on shore platforms. *Geomorphology*. 48. 7-22

Trenhaile, A. S. 2008: The development of subhorizontal shore platforms by waves and weathering in microtidal environments. *Zeitschrift fur Geomorphologie*. 52. 105-124

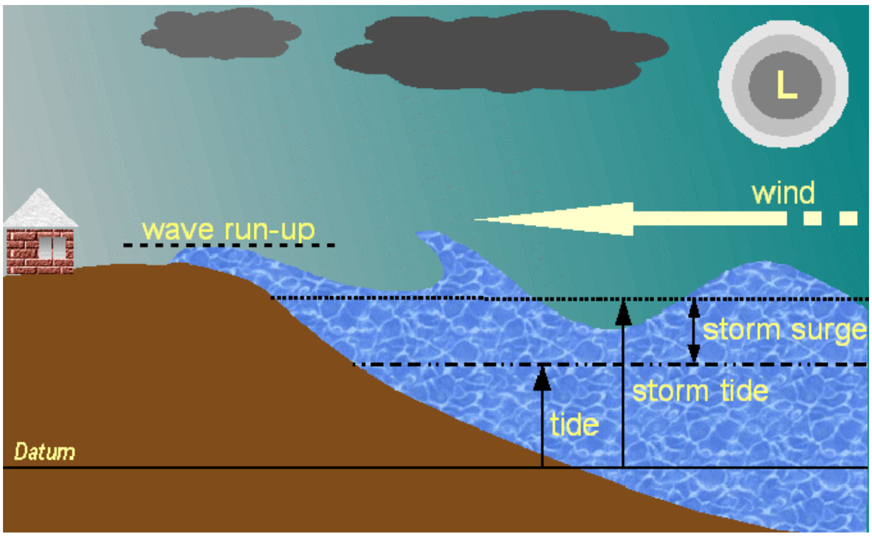
Tsujimoto, H. 1987: *Dynamic conditions for shore platform initiation*. Science Reports of the Institute of Geoscience, University of Tsukuba A8. 45–93

6. Coastal Hazards: Sea Level Rise and Coastal Flooding

6.1 Hazard Characteristics

Sea-level rise has the potential to exacerbate common coastal hazards affecting Auckland, such as flooding and erosion. Sea level is the position or elevation where the sea's surface (at still water level) intersects land. This position known as a 'datum', varies due to the influence of tides, weather conditions (i.e. winds and low pressure that lead to the generation of waves and storm surge), large scale oceanic-atmospheric interactions such as El Niño Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO), and longer-term climate-induced changes (Figure 6.1). The release or storage of sea-water in glaciers and polar ice-sheets (IPCC, 2007 [1]) also influences sea level position as too does land movement (uplift or subsidence) from tectonic processes. Growing concern about human-induced climate change has raised the profile of sea level rise and its contribution to coastal hazards.

Figure 6.1 Components of sea level.



Sea levels across the Auckland region are important because:

- tidal elevation governs the likelihood of coastal inundation, especially when combined with waves, storm surge or where a stormwater, river or stream network levels back up during high intensity rainfall;

- sea-level determines how close to a coastline wave breaking occurs. This is an important factor in determining factors such as the magnitude of wave run-up and overtopping of natural and man-made coastal defences and infrastructure.

Actual or mean sea level can be elevated (or lowered) due to a number of climatic, oceanic and geophysical (i.e. tectonic) factors including:

- Seasonal to annual climatic variability, El Niño-Southern Oscillation (ENSO), and Interdecadal Pacific Oscillation (IPO) (See Chapter 3). According to Bell et al. (2000) [2] annual ocean heating around northern New Zealand can elevate mean sea level by between 0.03 and 0.08m. ENSO (2-7 years) cycles may elevate mean sea level by up to 0.12m during La Niña phases while IPO phases (20 – 30 year cycles) can add another 0.05m (see Figure 6.1). In total these climatic factors can periodically elevate mean sea level up to 0.25m. Furthermore, a recent IPO shift to a negative phase could increase the frequency La Niña events and storm surge events impacting the Auckland region over the next 20 to 30 years from a greater predominance of easterly storms and ex-tropical cyclones (NIWA, 2007 [3]).
- Storm surge: the temporary (hours to days) increase in sea level above the predicted high tide due to a combination of strong winds and low barometric pressure. In New Zealand, maximum storm surge levels on the open coasts are generally <1m but can be enhanced in estuarine and harbour settings. The combination of astronomic tide[1] (including climate variability effects on mean sea level) and storm surge is frequently referred to as the storm tide.
- Waves: wave conditions affect localised water levels. For instance, shoreward of any wave breaking zone, water levels are set-up as water piles up against the shoreface before being transported back off shore (via rip currents on a sandy beach).
- Long-term Climate Change: Global sea-levels have risen over the last 100 – 150 years due to a net loss of ice sheets and glaciers on land, and thermal expansion (heating) of the oceans due to global temperature increases (IPCC, 2007). This trend is likely to continue into the future primarily due to continued thermal expansion of the oceans and loss of land based ices sheets and glaciers.

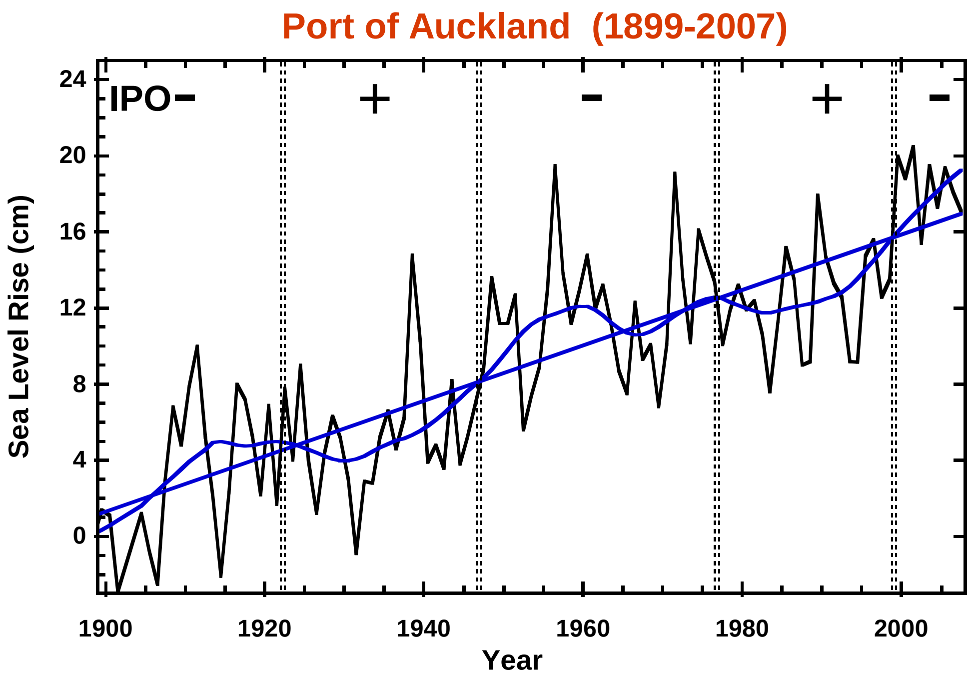
[1] The Highest Astronomical Tide levels will next be reached in August 2014 and February 2015, being the largest tides for the next 50 years (excluding sea level rise).

6.2 Location, Frequency and Magnitude

6.2.1 Historic Sea Level Rise

In Auckland, tide gauge records between 1899 and 2007 show an average annual rise in mean sea level of 1.4 mm/yr (Hannah, 2004 [5]; Ramsay et al. 2008 [6]) (Figure 6.2). This is fairly consistent with the average global mean sea level increase over this period of 0.17 m ±0.05 m (IPCC, 2007). From 1963 to 2003, average global sea-level rise rate was 1.8 mm/yr increasing to 3.1 mm/yr between 1993 and 2003. It is unclear whether the more recent rate increase reflects decadal variability or an increase in the longer term trend (or both) as there is limited information available yet on whether acceleration in global mean sea-level rise has commenced. Using reconstructed global mean sea levels from 1870 to 2004 a small acceleration of sea-level rise of 0.013 ±0.006 mm/yr over the 20th century has been observed (IPCC, 2007). If this rate of acceleration remained constant this factor alone would result in a mean increase in mean sea level of 0.28m to 0.34m between 1990 and 2100 (compared with a rise of 0.12m to 0.22m if the observed linear rate over the 20th century continued without the acceleration). However, this rate of acceleration is expected to increase.

Figure 6.2 The rise in annual mean sea level (black line) at the Port of Auckland (1899 to 2007) relative to mean level around 1900. The curved (blue) line is a weighted running mean showing the influence of the IPO on the average rate of sea-level rise. The long term linear trend is shown by the straight blue line. *Source: Ramsay et al. 2008* [6].



6.2.2 Future Sea Level Rise

Sea levels will continue to rise over the 21st century and beyond primarily because of thermal expansion within the oceans and loss of ice sheets and glaciers on land (IPCC, 2007). The projected mean sea level rise range estimated by the IPCC is 0.18m to 0.59m by 2090-2099, relative to the average mean sea level over the period 1980 to 1999 (Figure 6.3). These projections include sea level contributions from Greenland and Antarctica ice sheet loss rates observed from 1993 to 2003 though rates are expected to expected increase in the future particularly if greenhouse gas emissions are not reduced. Consequently, an additional 0.10 to 0.20m rise in the upper ranges of the emission scenario projections (dark blue shading) would be expected if ice sheet contributions were to grow linearly with global temperature change. An even larger contribution from these ice sheets, especially from Greenland, over this century cannot be ruled out. The IPCC (2007) has observed that "because understanding of some important effects driving sea-level rise is too limited, this [Fourth] report does not assess the likelihood, nor provide a best estimate or an upper bound for sea-level rise".

Sea-level will not stop rising at 2100 but will continue to rise for many centuries into the future. Stabilisation of future emissions can play an important role in determining the magnitude of water contribution from the two major uncertainties of longer-term sea-level rise, the Greenland and West Antarctic Ice sheets. Catastrophic contributions to sea-level rise from a collapse of the West Antarctic Ice Sheet or the rapid loss of the Greenland Ice Sheet are not considered likely to occur in the 21st century, based on currently understanding. However, the occurrence of such catastrophic changes becomes more likely as greenhouse gas concentrations increase.

A revised guidance manual for local government on coastal hazards and climate change is in preparation by the Ministry for the Environment (MFE). This will include updated information on future mean sea level for local government use in planning and decisions. For the interim, provisional suggestions for future sea level rise are:

(1) For planning and decision timeframes out to the 2090's (2090-2099) use:

- a base mean sea-level rise of 0.50m relative to the 1980-1999 average along with,
- an assessment of the sensitivity of the activity under consideration to possible higher mean sea-levels taking account of possible additional contributions[2]. This level is currently under discussion by MFE, but is likely to be no less than 0.80m.

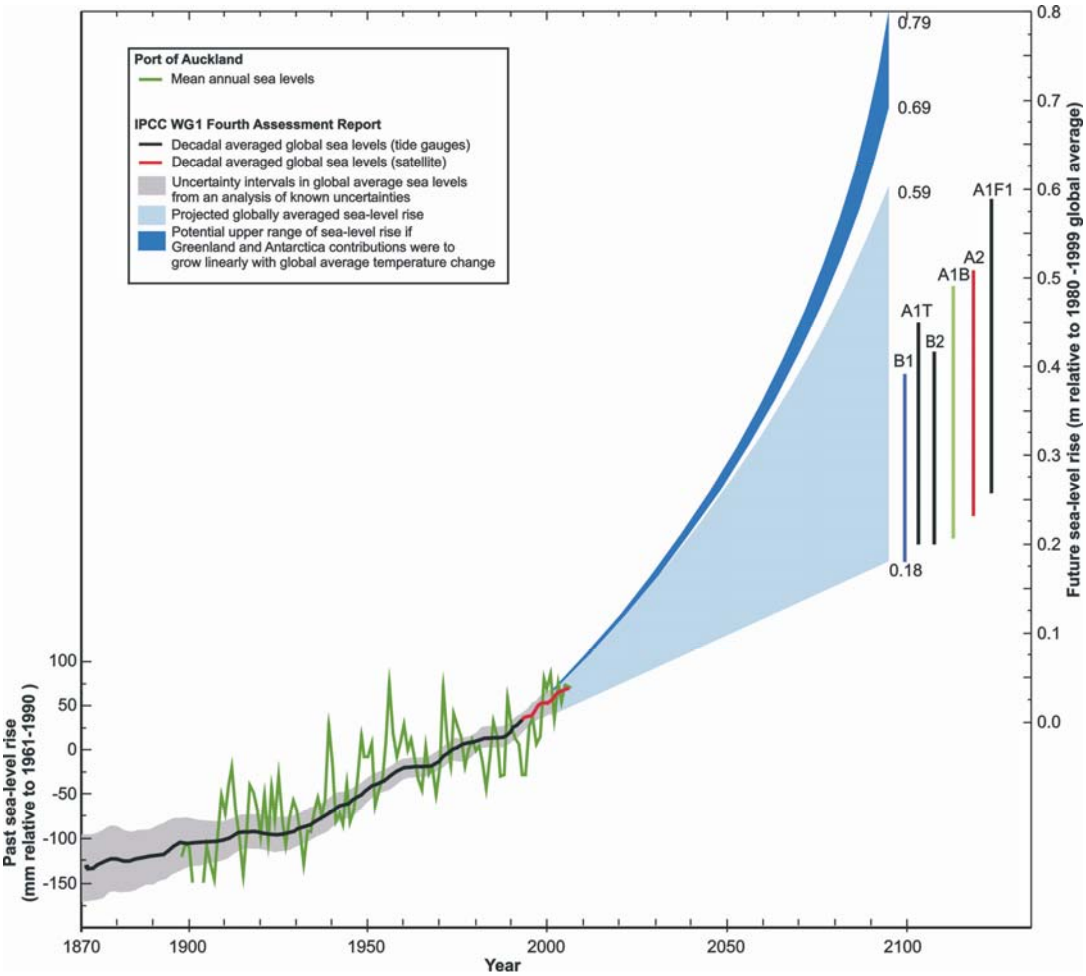
(2) For planning and decision timeframes beyond 2100 where as a result of the particular decision future adaptation options will be limited, an allowance for

[2] Possible extra contributions include higher emission profiles, and uncertainties associated with increased contributions from Greenland and Antarctica ice sheets, carbon cycle feedbacks, and possible differences in sea level from global averages in the New Zealand region.

mean sea-level rise of 0.01m per year beyond 2100 is suggested (in addition to the above suggestion).

These projections are for mean sea levels only. Less information is available on how storm surge frequency and magnitude will vary in the Auckland region with respect to climate change. This will largely depend on changes in frequency, intensity and/or tracking of cyclones and other low-pressure systems. As such it is assumed that any future increase in storm surge elevation will match the rise in mean sea-level until future projections of changes in storminess become more certain.

Figure 6.3 Global mean sea-level rise model results to the mid 2090s. The black line and grey shading on the left hand side show the decadal-averaged global sea levels and uncertainty respectively, as extracted from tide gauge records across the world. The red line is the decadal averaged sea levels as measured by satellites since 1993. The green line is the mean annual relative sea level as measured at the Port of Auckland since 1899. The light blue shading shows the range in mean global sea level out to the 2090s. The dark blue line shows the potential additional contribution from Greenland and West Antarctica Ice Sheets if contributions to sea-level rise were to grow linearly with global average temperature change. The vertical colour lines on the right-hand side show the range in model results from the various Global Circulation Model's for six different future emission scenarios. *Source: IPCC, 2007*.



6.3 Key Vulnerabilities and Potential Impacts

Climate change will not create any new coastal hazards in the Auckland region but will exacerbate existing coastal erosion and inundation problems (MfE, 2008 [7]). An increase in mean sea level will allow a gradual encroachment of seawater at high tides on low-lying coastal and estuarine land. If not constrained by coastal protection works, such low-lying areas will transform into coastal marsh and eventually become a permanent part of the coastal or estuarine system. Further, episodic inundation will still occur primarily due to storm events coinciding with reasonably high tides. Irrespective of any changes in storm surge frequency or magnitude, storminess or wave conditions, increasing mean levels of the sea will increase the chance of inundation during such storm events. Specifically:

- for existing areas prone to coastal inundation a higher likelihood that coastal inundation could occur during storms relative to the present day, given the same specific ground level or barrier height. Coasts with smaller tide ranges will be more vulnerable (e.g. Hauraki Gulf).

- the extent of land at risk from inundation may increase relative to the present day (although this will be specific site).
- higher sea-levels will back up water in rivers and streams, surface and storm water drainage, and sewer systems in low-lying coastal areas. This may exacerbate flood hazards on low lying flood plains and reduce the performance or drainage and sewage structures. Increased rainfall intensities may further exacerbate these problems (MfE, 2008).

In many locations sea level and storm surge will alter coastline position (and the jurisdictional Mean High Water Spring (MHWS) boundary). Coastal erosion is not only dependent on the hazard drivers (such as sea levels and wave conditions), and the changes to them, but also on the geomorphology and geological makeup of the coast, and the influences human activities have had in modifying the coast. Whilst these factors all influence the rate of coastal erosion, in general terms, the rate is predominantly driven by the natural drivers, i.e., waves and water levels. The following impacts on coastlines may be come evident on throughout the Auckland region from future sea level rise.

- Sandy coasts: Sandy coastlines that are relatively stable over time may show a bias towards erosion under a higher sea level unless sand supply to beaches can keep pace with erosion. Higher sea levels permit waves to attack the backshore and foredunes more readily, placing nearby infrastructure at risk to damage. Where the present width of the back or foreshore of the beach is not sufficient to accommodate erosion, erosion of any dunes backing the beach will occur (MfE, 2008).

- Cliff coasts: The effects of climate change on cliffs will be highly dependent on how resistant their geology is to erosion. Erosion of cliffs comprising soft sedimentary rocks (See Chapter 5) will continue at similar or slightly higher rates in response sea-level rise or changing in wave conditions (MfE, 2008).
- Estuarine coasts: Estuary and harbour shorelines will retreat as a result of both inundation and erosion but the rate and extent will be highly variable within any estuary. Once erosion or loss of land occurs, recovery (if it occurs) will be a much slower process than on open coasts. For low-lying land bordering estuaries, erosion may be relatively rapid due to regular then permanent high-tide inundation of areas that presently may experience only episodic inundation. Where the retreat is constrained (e.g. rock outcrop or coastal defence), intertidal areas and their associated ecosystems may be reduced and potentially 'squeezed out' (MfE, 2008).

A high proportion of residential and industrial development in the Auckland region has occurred close the coast. Some of these developments occupy low lying land vulnerable to coastal hazards at present. Investment in Auckland's coastal margins is likely to increase in future, with coastal hazard issues becoming more prevalent as sea level rises. Issues in Auckland Region with regard to sea level rise and coastal flooding would include:

- historical development increased population density in coastal areas.
- maintenance of existing protection works, including flood control schemes and coastal protection works, and their future effectiveness.
- understanding and recognising the effects of rising sea levels on future land use and subdivision activities along the coast.
- land-use activities (e.g. subdivision) have intensified or been located in high-risk areas.
- the threat to existing and future coastal communities from natural hazards.
- impact of salinization on coastal aquifers and the implications for water supply in coastal communities.
- identification of areas at high hazard risk from sea level rise and provision of information on avoidance measures to people.
- incorporation of comprehensive systems of hazard identification and analysis into the resource consent and building consent processes.

Rising sea levels and more frequent inundation events will likely lead to a reduction in the standard of coastal defence provided by existing structures. With higher water levels there is the potential for significantly higher wave run-up and overtopping of defences leading to increased inundation and damage to infrastructure and property located behind the defences. Climate change impacts on sea level and wave conditions will question the integrity and performance of existing man-made coastal defences, due to a variety of reasons (MfE, 2008):

- higher sea levels will increase the frequency that defences are overtopped by waves or high tides, particularly for coasts with small tide ranges. This influences land inundation risk, but can also lead to erosion of the protected area behind the defence leading to failure of the defence itself.
- an increase in storm tide heights (due to sea-level rise and/or changes in storm surge) will produce greater water depths at the defence, increasing the magnitude of overtopping during storms and exacerbating erosion problems.
- greater water depths against the structure heightens its exposure to larger waves, increasing damage and failure potential. For example with rock structures, the size of rock required for stability is directly proportional to the cube of the significant wave height. Hence even a small increase in wave conditions at the defence can result in a large increase in the size of rock armour (and financial cost) required to achieve the same stability.
- larger waves hitting the defence structure will cause greater reflection and erode the adjacent beach. This can lead to undermining and failure of the defence along with loss of the beach's amenity values.

Given that many older coastal defences in Auckland may not have been engineered to provide a high standard of protection, the impacts of sea level rise could substantially increase damage to these defences and reduce protection to adjacent land. Similarly, if defences are designed for a particular 'design life', this is unlikely to be met if sea level rise considerations were not factored into the structure design.

6.4 References and Additional Reading

References

1. Intergovernmental Panel on Climate Change, 2007: *Climate Change 2001: The Scientific Basis*. Cambridge University Press. p944.

2. Bell, R.G., Goring, D.G. and de Lange, W.P. 2000: Sea level change and storm surges in the context of climate change. *IPENZ Transactions*. 27. No 1/Gen

3. National Institute of Water and Atmosphere, 1997: *Extreme sea levels on the Waitemata Harbour Shoreline*. Prepared for Auckland Regional Council. NIWA Client Report No 97/33. Project No. VRC70501

4. Church J. A., White, N. J. 2006: A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*. 33. 5. 1-4

5. Hannah, J. 2004: An updated analysis of long-term sea level change in New Zealand. *Geophysical Research Letters*. 31. 1-4.

6. Ramsay, D., Altenberger, A., Bell, R., Oldman, J., Stephens, S. 2008: *Review of rainfall intensity curves and sea levels in Manukau City*. Prepared for Manukau City Council. NIWA Client Report: HAM2007-168

7. Ministry for the Environment. 2008: *Coastal hazards and climate change. A guidance manual for local government in New Zealand. 2nd edition.* Revised by Ramsay, D., and Bell, R. (NIWA). Ministry for the Environment. Draft report dated June 2008. p137.

Additional Reading

Bell, R. G., Goring, D. G. 1998: Seasonal variability of sea level and sea-surface temperature on the northeast coast of New Zealand. *Estuarine, Coastal and Shelf Science.* 46. 307-318.

Bell, R. G.; Goring, D. G. 1999: Flow-on effects of El Nino-Southern Oscillation events on sea-level rise in Northern New Zealand. Proceedings of the Coasts and Ports '99, 14th Australasian Coastal & Ocean Engineering Conference, Perth. Canberra, Institution of Engineers.

de Lange, W. P. 1996: Storm surges on the New Zealand coast. *Tephra.* 15. 24-31.

de Lange, W. P., Gibb, J. G. 2000: Seasonal, interannual, and decadal variability of storm surges at Tauranga, New Zealand. *New Zealand Journal of Marine and Freshwater Research.* 34. 419-434.

Douglas, B.C. 1992: Global sea level acceleration. *Journal of Geophysical Research.* 97. 699-706.

Emery, K.O.; Aubrey, D.G. (eds) 1991: *Sea levels, land levels, and tide gauges*. Springer-Verlag, New York. p237.

Goff, J Nichol, S and Rouse, H (eds) (2003): *The New Zealand Coast: Te Tai o Aotearoa*, Dunmore Press, Palmerston North.

Goring, D. G. 1995: Short level variations in sea level (2-15 days) in the New Zealand region. *New Zealand Journal of Marine and Freshwater Research.* 29. 69-82.

Goring, D. G., Bell, R. G. 1999: El Nino and decadal effects on sea-level variability in northern New Zealand: a wavelet analysis. *New Zealand Journal of Marine and Freshwater Research.* 33. 587-590.

Goring, D. G., Pearson, C; Kingsland, S. 1997: Extreme sea levels on the Mt Maunganui shoreline (Moturiki Island). Unpublished report prepared for Environment Bay of Plenty, NIWA, 97/32.

Hannah, J. 1990: Analysis of mean sea level data from New Zealand for the period 1899–1988. *Journal of Geophysical Research 95(B8)*.12. 399-405.

Hay, D. N. 1991: Storm and oceanographic databases for the Western Bay of Plenty Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

Heath, R. A. 1979: Significance of storm surges on the New Zealand coast. *New Zealand Journal of Geology and Geophysics.* 22. 259-266.

Heath, R. A. 1985: Review of the physical oceanography of the seas around New Zealand—1982. *New Zealand Journal of Marine and Freshwater Research.* 19. 79-124.

McInnes, K. L., Walsh. K. J. E., Hubbert, G. D, Beer, T. 2003: Impact of sea-level rise and storm surges on a coastal community. *Natural Hazards*. 30. 187–207

Murty, T. S., Flather, R. A. 1994: *Impact of storm surges in the Bay of Bengal*. In: Finkl, C. W. J. (ed.) Coastal hazards: perception, susceptibility and mitigation, Special Issue No. 12. Charlottesville, Coastal Education and Research Foundation. 149-161.

Nerem, R. S., Chambers, D. P., Leulitte, E. W., Mitchum, G. T., Giese, B. S. 1999: Variations in global mean sea level associated with the 1997-1998 ENSO event: implications for measuring long term sea level change. *Geophysical Research Letters.* 26. 3005-3008.

Nichols, R. J., Lowe, J. A. 2005: Climate stabilisation and impacts of sea level rise. In: International Scientific Symposium: Avoiding Dangerous Climate Change, (Ed) H.J. Schellnhuber et al. Chapter 200. 195-202.

Nunn, P. D. 1998: Sea-level changes over the past 1000 years in the Pacific. *Journal of Coastal Research.* 14. 23–30.

Ota, Y., Yamaguchi, M. 2004: Holocene coastal uplift in the western Pacific Rim in the context of late Quaternary uplift. *Quaternary International*. 120. 105–117.

Pirazzoli, P.A. 1993: Global sea-level changes and their measurement. *Global and Planetary Change.* 8. 135–148.

Pirazzoli, P. A. (ed.) 1996: *Sea-Level Changes*. John Wiley & Sons, Chichester, UK.

Pugh, D. T. (ed.) 1987: *Tides, surges and mean sea-level*. Chichester, John Wiley and Sons. p472.

Ramsay, D., Stephens, S. 2006: *Double trouble: How often do large waves occur with high water levels?* New Zealand Coastal Society. Coastal news. 32. 4-5.

Ramsay, D., Stephens, S., Oldman, J., Altenberger, A. In preparation: *The influence of climate change on extreme sea levels around Auckland City*. Draft report prepared for Auckland City Council. NIWA Client Report: HAM 2008-093.

Sinclair, M. R. 2002: How often is New Zealand hit by tropical cyclones? NIWA Water & Atmosphere 10(1), http://www.niwa.co.nz/pubs/wa/10-1/

Titus, J.G., Narayanan, V. 1996: The risk of sea level rise. *Climatic Change.* 33. 151–212.

Tonkin & Taylor Ltd. 2004: North Shore City Sea Inundation Study. Report prepared for North Shore City Council, July 2004. Job no: 21595.

Tonkin and Taylor Ltd. 2005: Assessment of potential sea levels due to storms and climate change along Rodney's east coast. Report prepared for Rodney District Council, July 2005. Job no: 22239.

Walters, R. A., Goring, D. G., Bell, R. D. 2001: Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research.* 35. 567-579

Wang, B. 1995: Interdecadal changes in El Nino onset in the last four decades. *Journal of Climate.* 8. 267- 285.

Wang, B.; Wang, Y. 1996: Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. *Journal of Climate.* 9. 1586-1598.

Warrick, R. A., Sims, G., Gibb, J. G., de Lange, W. P. 1997: *The CHAMP Programme: development of an integrated model for coastal hazard assessment for management and planning in New Zealand*. Proceedings of the Global Change Science in the Coastal Zone, Third LOICZ Open Science Meeting, Noordwijkerhout, The Netherlands. p51.

Zhang, Y.; Wallace, J. M.; Battisti, D. S. 1997: ENSO like interdecadal variability: 1900-93. *Journal of Climate.* 10. 1004-1020.

7. Coastal Hazards: Tsunami

7.1 Hazard Characteristics

A tsunami[1] is a series of waves typically created by sudden movement or rupturing of the ocean floor, from earthquakes, underwater landslides and underwater volcanic eruptions (de Lange and Healy, 1986 [1]; Berryman, 2005 [2]). In deep water a tsunami can travel at speeds in excess of 500 km/hr with the potential to propagate great distances across oceans in a matter of hours (Bell et al. 2004 [3]). At sea, tsunami wave heights are typically small. However, as a tsunami enters shallow water the wave's interaction with the seabed causes it to travel more slowly and increase in height. Tsunamis are known to reach heights of ten metres or more. Typically, tsunamis have wave periods of 15 to 60 minutes, which is longer than wind waves or swell, but shorter than ocean tides. In New Zealand, tsunamis arriving at the shore are typically less than 1m in height and generally not observed. Yet, a short historical record (Downes and de Lange, 2007 [4]) combined with palaeo-tsunami work (Goff et al. 2001[5]; Nichol et al. 2003[6]; Nichol et al. 2004[7]; Nichol et al. 2007[8]), Maori oral traditions (King et al. 2007[9]), and numerical hazard assessment (Berryman, 2005; Power et al. 2007 [10]) suggest that tsunami are perhaps one of the most underrated natural hazards in New Zealand.

The effects of a local, regional or remotely generated tsunami are not expected to be uniform; rather they are likely to vary along a coastline depending on local physiography, water depth and complex amplification effects. For a given coastal location, local tsunamis are those that arrive from their source within less than 1 hour of generation. Regional tsunamis are those that arrive between 1 and 3 hours from generation time; and remotely source tsunamis are events with travel times >3 hours after generation. Thus, the same tsunami can be a local tsunami for one location and a regional or distant tsunami for other locations.

Tsunami waves decrease in amplitude with travel time though wave period remains constant so the velocity of the wave is largely undiminished with distance, until it reaches shallow water near the coast. This does not mean that distant source tsunamis are less of a threat to the Auckland region. The frequency and magnitude of tsunami hazard form various sources are discussed in Section 7.2 and Appendix 7.1. For distant source tsunami initial energy released and size of the waves created can be of sufficient magnitude to create significant waves on arrival in Auckland region. Likewise regional (or locally) generated tsunamis may be small in amplitude and pose little threat

[1] The term *Tsunami* is Japanese meaning 'great harbour wave'. Originally, the term included long period waves generated by extreme meteorological conditions.

other than unusual currents. It is the combination of wave size and velocity that controls the degree of hazard.

Figure 7.1 Tsunami generation and propagation form the Chilean coast. Initial time in Auckland is approximately 13 hours. The tsunami is local at the star (source), regional for much of the west coast of South America, and distant for all other locations. *Source: NOAA, 2008* [11].

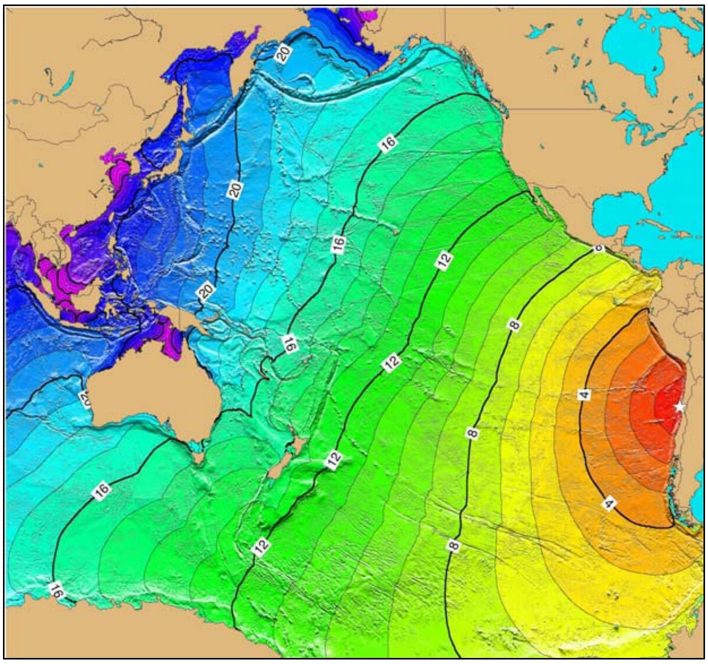
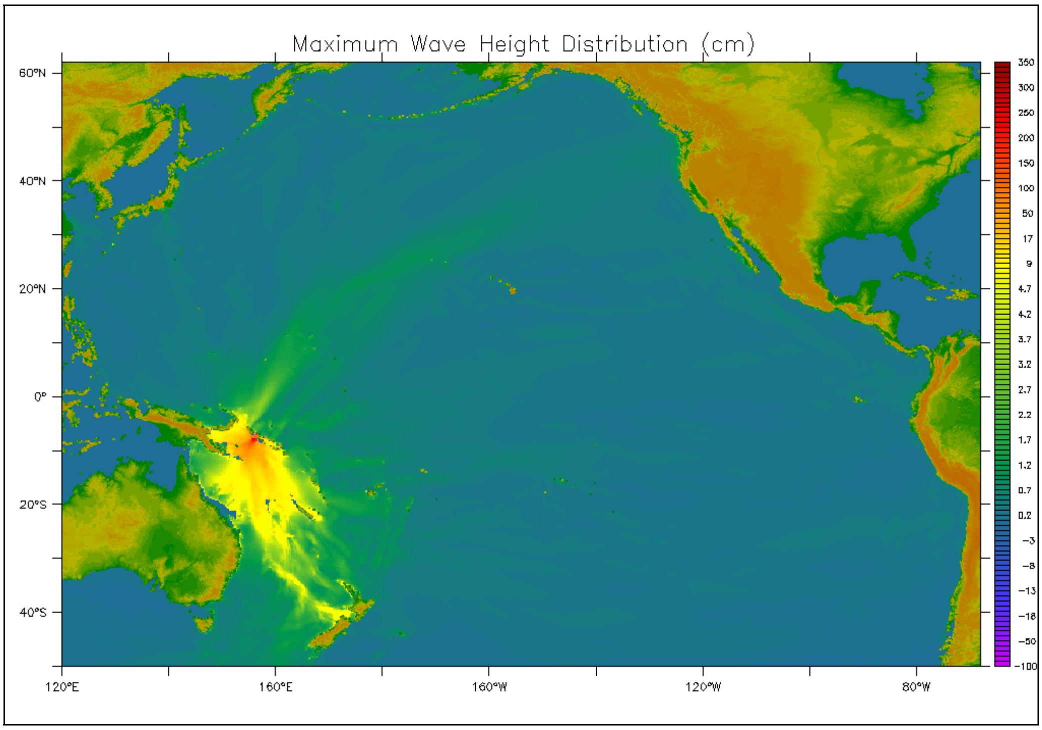


Figure 7.2 Decrease in tsunami wave amplitude (shown in cm) with distance from source in the Solomon Islands.



Tsunami waves that overtop natural coast beach ridges and barriers can surge considerable distances across inland low-lying areas. Large tsunami events are capable of causing widespread coastal flooding, erosion, damage to infrastructure and loss of life. On a devastating scale, this is what happened to coastal communities bordering the Indian Ocean following the Boxing Day Tsunami of 2004. An estimated 250,000 to 300,000 people perished as a result of this extreme event (Liu, 2005[12]).

Hazards associated with tsunami are:

- High velocity waves inundating coastal areas
- High amplitude waves inundating coastal areas
- Unusual and/or strong currents
- High velocity return waves (potentially carrying debris)

The consequences of these hazards are discussed in Section 7.3.

7.2 Location, Frequency and Magnitude

A number of studies investigate tsunami hazard for the Auckland Region. According to de Lange and Hull (1994) [13], since 1840, 11 tsunami have been recorded on Auckland mainland coasts with wave heights ranging from <0.1 to 1.8 m (Table 7.1) These tsunami events are understood to have been remotely generated from either west of South America, Alaska, Tonga-Kermadec Trench, or east of Japan and Kamchatka. This suggests future tsunami events are most likely to originate from these remote areas, which corresponds with the results for Auckland in the national tsunami hazard and risk review (Berryman, 2005). The risk that tsunamis pose to the Auckland region is also assessed in Goff et al. (2005) [14]. The report also includes an overview of tsunami sources, estimates of tsunami frequency and magnitude, and an identification of the uncertainties and gaps in current understanding of tsunami hazards. The authors acknowledged important advances in the palaeo-scientific research and cite two previously unknown events in the late 14th and early 15th centuries which reached estimated maximum run-up heights of 14m and 10m, respectively on the eastern coast of Great Barrier Island (Goff et al. 2001).

Local tsunami sources for the Auckland region are likely to have travel times of less than 1 hour to some part of the region[2]. These sources include:

1. active faults in the Firth of Thames (Kerepehi Fault), eastern Coromandel, and offshore volcanic zone of the Bay of Plenty.
2. submarine volcanism in the Tonga-Kermadec trench and offshore volcanic zone of the Bay of Plenty.

[2] Travel times may vary considerably across the region.

3. earthquake, volcanic and mass movement sources in the immediate Auckland region.

Table 7.1 Summary of historic tsunami observed in Auckland region. *Source: Goff et al. 2005.*

YEAR	DATE	LOCATION OBSERVED	WAVE HEIGHT(m)	Est. No. WAVES	SOURCE	CAUSE
1868	15-Aug	Gt. Barrier Is.	2.90	1	Chile	Quake
1868	15-Aug	Tamaki Est.	1.50	2-5	"	"
1868	15-Aug	Orewa	1.80	?	"	"
1868	15-Aug	Port Charles	1.80	1	"	"
1877	11-May	Auckland	0.20	?	Chile	Quake
1877	11-May	Thames	0.90	2-5	"	"
1877	11-May	Port Charles	3.60	20+	"	"
1883	29-Aug	Auckland	1.80	1	Krakatau Volcano	Rissaga
1883	29-Aug	Thames	1.50	1	"	"
1883	29-Aug	Coromandel	0.90	2-5	"	"
1952	5-Nov	Auckland	0.10	20+	Kamchatka, Russia	Quake
1960	23-May	Gt. Barrier Is.	1.50	>1	Chile	Quake
1960	23-May	Auckland	0.60	6-10	"	"
1964	29-Mar	Auckland	0.45	>1	Alaska, USA	Quake
1976	14-Jan	Auckland	0.10	?	Kermadec Islands	Quake
1977	22-Jun	Auckland	0.10	>1	Kermadec Ridge	Quake
1982	19-Dec	Auckland	0.10	?	Kermadec Islands	Quake
1986	20-Oct	Auckland	0.10	?	Kermadec Islands	Quake
1993	Jun	Auckland	0.10	?	Kermadec Islands	Quake
1994	6-Oct	Auckland	0.10	?	Kuril Islands	Quake

Locally generated tsunamis are most likely to be created by earthquakes along local faults and/or underwater landslides or volcanoes along plate subduction zones off eastern New Zealand. While volcanic activity may be capable of displacing the seafloor in the Auckland region, locally generated tsunamis are most likely to be associated with the Kerepehi Fault. This faultline runs through the Firth of Thames and is overlain by a considerable thickness of soft sediment that may amplify the seismic waves (de Lange and Healy, 2001[15]). The return period an earthquake along the faultine has been estimated to be between 4500 and 9000 years (Chick et al. 2001[16]). Areas most at risk from tsunami generated along this fault are the south eastern coastline of the region and Waiheke Island. Local tsunami sources west of Auckland are considered less important than those to the east though further research is needed to confirm this.

An eruption in the Hauraki Gulf or within the Waitemata or Manukau Harbours could potentially generate sufficient energy to form a tsunami. While there is no evidence of past tsunami from this source, the possibility of such an event should not be discounted. A scenario of this kind would place low-lying coastal land (<5m above mean sea level) at high risk including the shipping ports of Auckland and Onehunga (de Lange and Healy, 2001). There is little evidence at present to suggest that sources within the Hauraki Gulf would produce sizeable tsunamis.

Recent research into tsunami hazard and risk for Auckland identified that for tsunami events with return periods of up to 500 years the threat of locally generated tsunami is negligible (Berryman, 2005). On a longer timeframe, locally generated tsunamis increased slightly in likelihood, though the main threat to Auckland region is from distant tsunamis, followed by a lesser threat from regional tsunamis.

Regional tsunami sources for the Auckland region will likely have travel times of 1 to 3 hours. These sources include:

1. Subduction and upper plate earthquakes and submarine landslides associated with the Tonga-Kermadec Trench-Hikurangi Trough System.
2. The Fiji-Vanuatu arc (these sources require further investigation).

A regional tsunami event has not affected the region since records began (c.1840) though preliminary modelling results suggest a subduction earthquake along the Tonga–Kermadec Trench–Hikurangi Trough system, east and north-east of New Zealand, could be a source capable of producing a damaging tsunami in the Auckland region. A tsunami generated by a subduction earthquake could produce waves up to 4m above mean sea level and affect 30km to 100km of coastline. Such an event could cause waves to break on Great Barrier Island about 70 minutes after the earthquake. These estimates are based on a maximum possible event scenario.

Beyond the Hauraki Gulf there are numerous possible sources for tsunami generation, although in a similar manner, gaps exist in our understanding of the timing and frequency of larger events. This is an area that requires greater research support to help establish more robust chronologies of tsunami occurrence and magnitude.

Remote/distant tsunami sources for the Auckland region will likely have travel times of 3 to 15 hours. These sources include:

1. The west coast of South America is recognised as the most common distant source of tsunamis affecting Auckland. Waves from there would likely take between 12 to 15 hours or so to arrive and depending on the size of the event would affect both coasts, although historical evidence suggests the east coast response would be twice that of the west coast [Berryman, 2005; NIWA, 2008[17]).
2. Pacific North West and Alaska.
3. Southern Ocean (e.g. earthquake in the region of the Balleny Islands near Antarctica in March 1998).
4. The Solomon Islands subduction zone (this source requires more investigation).

Remote tsunami events can be created long distances away from the Auckland region. Two of the largest recorded tsunami events to affect Auckland originated from earthquakes along South America’s west coast. The larger of the two occurred in

August 1868 following a fault movement off the Chilean coast. This tsunami took approximately 15 hours to travel to New Zealand and had a wave height that reached up to 2.9m on Great Barrier Island's east coast (Goff et al. 2005). The other tsunami also had its genesis in a Chilean earthquake on May 22nd 1960 leading to a tsunami that affected much of the regions east coast with an observed wave height reaching 1.5m on Great Barrier Island. It is widely acknowledged that tsunamis from South American sources probably pose the greatest "external" tsunami threat to Auckland's eastern coastlines (Berryman, 2005; Power et al. 2007; Goff et al. 2005; de Lange and Healy, 2001).

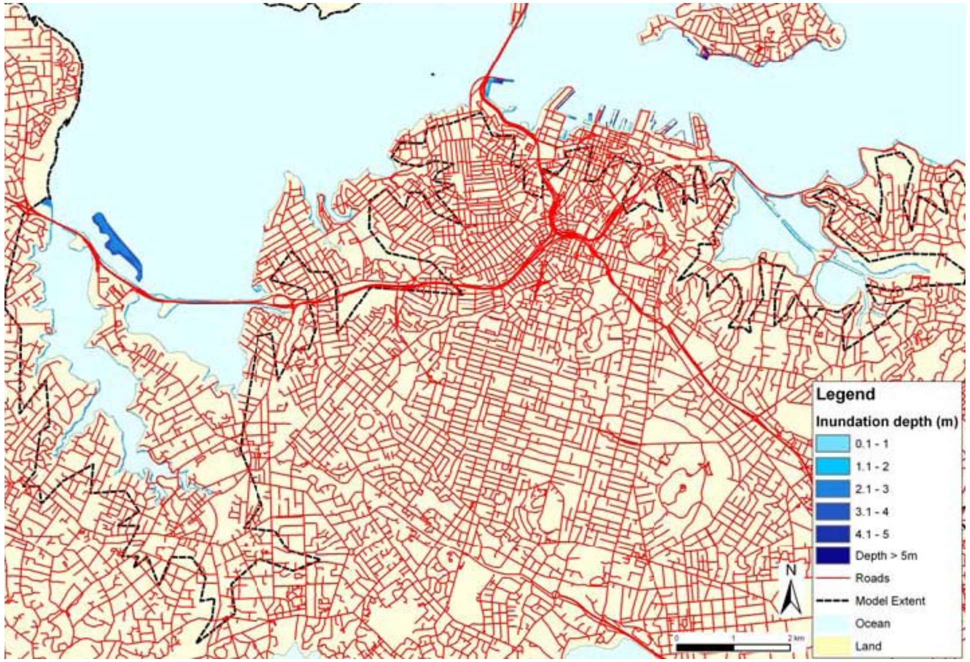
Given the higher frequency of tsunami events generated from distant sources, tsunami inundation modelling has been undertaken for Auckland's east coast (Lane et al. 2007[18]). A tsunami generated by an earthquake off South America was modelled as historical records suggest this is the most probable tsunami to affect the Auckland region in the next 50 to 100 years. To provide for possible sea level variations over this period the tsunami event was modelled for three sea levels heights. The sea levels were current Mean High Water Spring (representing the 'worst-case' for the tsunami where its maximum wave coincides with high tide) and MHWS with sea level rises of 0.3m and 0.5m representing 50 and 100 year projections for sea level as assessed by the IPCC Fourth Assessment Report (2007) [19].

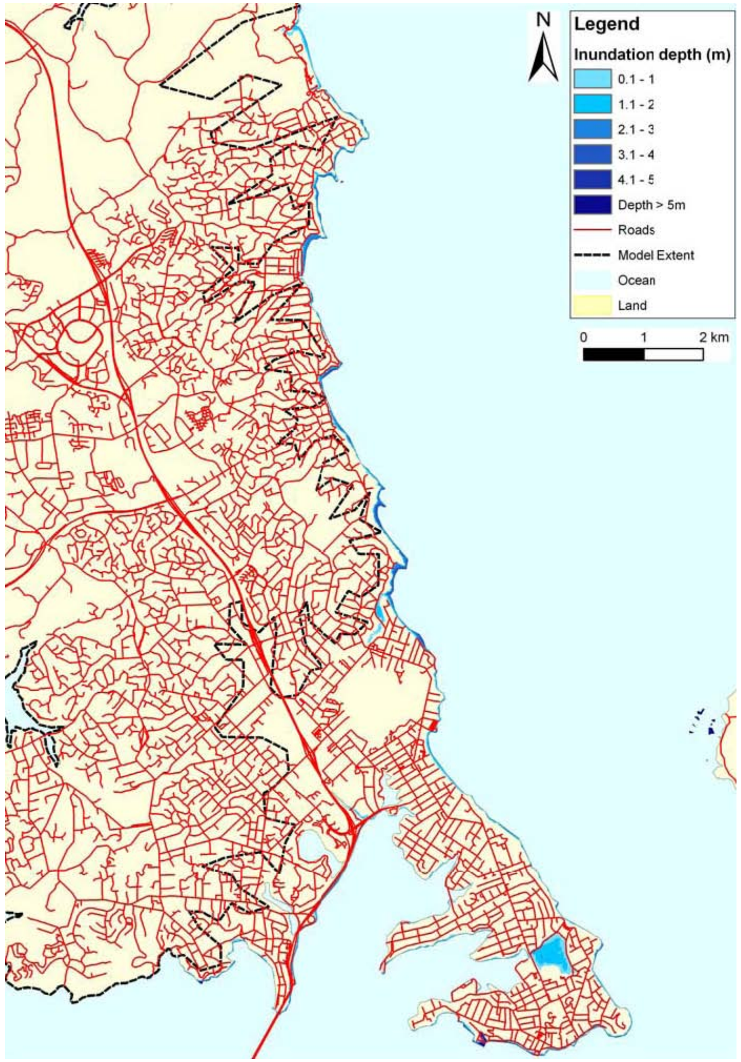
For the MHWS scenario, modelling demonstrated the tsunami event causes maximum water elevations of around 2 to 3m above Mean Sea Level and up to 3.5m in some east coast bays. Most of the inundation around Auckland is confined to fairly narrow coastal strips, although in some low-lying places the tsunami could cause significant inundation. Several low-lying coastal roads including the Northern motorway just north of the Harbour Bridge, the Northwestern motorway over the causeway between Point Chevalier and Te Atatu, and Tamaki Drive near Hobsons Bay are also at risk of inundation (Figure 7.3). Risk of inundation to the aforementioned areas increases considerably under higher sea level scenarios.

Based on historic records and palaeo-tsunami data, Goff et al. (2005) suggest the following tsunami magnitudes and frequencies are most likely for the Auckland region (See Table 7.2):

- Small tsunami (<1m): 1 in 13 years
- Medium tsunami (1-5m): 1 in 42 years
- Large tsunami (>5m): 1 in 870 years

Evidence further suggests that low lying land (<5m) along the region's eastern coasts are at highest risk to tsunami. Estimates of tsunami hazard based on numerical studies can be found in Berryman (2005). The results for the Auckland City East Coast are reproduced in Appendix 7.1.





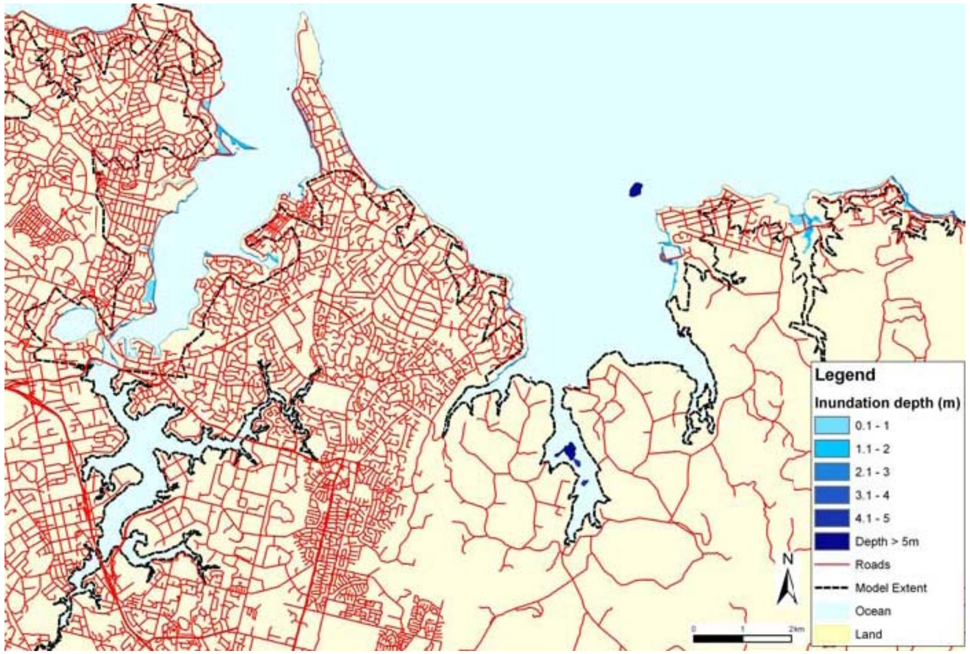


Figure 7.3 Modelled tsunami inundation depths and area extents for (from top left clockwise) Auckland CBD to Te Atatu, North Shore and Mission Bay to Maraetai based on a South American sourced tsunami reaching the shoreline at MHWS.

Table 2 Summary of tsunami data for the Auckland region.

TSUNAMI WAVE HEIGHT & GENERATION LOCATION SUMMARY FOR AUCKLAND

DISTANT

WAVE HEIGHT (m)	SIZE	LOCATION
0.45	Small	Alaska
2.90 (1.50 at Tamaki East)	Medium	Chile
0.20 (0.90 at Thames)	Small	?
1.50 (0.60 at Auckland)	Medium	Fiji/Solomon
14.00	Large	Kamchatka
0.10	Small	Krakatau Volcano
1.80	Medium	Kuril Islands
0.10	Small	?

SUMMARY

- 8 distant events in 700 years = 1 in 88 years
- 4 over 1.0 m high (1 over 10.0 m high - in prehistoric record)
- Small (4 in 117 years) = 1 in 30 years
- Medium (3 in 126 years) = 1 in 42 years
- Large (1 in 700 years) = 1 in 700 years

REGIONAL

WAVE HEIGHT (m)	SIZE	LOCATION
0.10	Small	Kermadec Islands area
0.10	Small	
0.10	Small	
0.10	Small	
0.10	Small	
<10.00	Large	
~5.00	Large	

SUMMARY

- 7 events in 2600 years = 1 in 370 years
- 2 at 5.0m or higher
- Small (5 in 18 years) = 1 in 4 years
- Medium (none) = 0
- Large (2 in 2600 years) = 1 in 1300 years

LOCAL (inside the Hauraki Gulf)

WAVE HEIGHT (m)	SIZE	LOCATION
<1.00	Small	Hauraki graben
2.00	Medium	Rangitoto Volcano

SUMMARY

- 2 events in 600 years = 1 in 300 years
- 1 over 1.0 m high
- Small (1 in 400 years) = 1 in 400 years
- Medium (1 in 600 years) = 1 in 600 years
- Large (none): 0

SUMMARY (ALL SOURCES)

- Small (1 prehistoric event ignored): 9 in 117 years = 1 in 13 years
- Medium (1 prehistoric event ignored): (3 in 126 years) = 1 in 42 years
- Large: 3 in 2600 years = 1 in 870 years

There is at present an incomplete understanding of how tsunamis from different source areas impact along the Auckland coastline including; wave propagation, current generation and inundation characteristics. Although a historic record of tsunami occurrence exists, it is not regarded as comprehensive. A better understanding of the tsunami landscape of this region requires further work. This must include the integration of findings from international data and local palaeo-tsunami research (particularly for tsunami sources north of New Zealand), as well as high resolution modelling to ascertain the vulnerability of harbours, estuaries and river mouths to local, regional and distant tsunami sources (Bell et al. 2004; Goff et al. 2005).

7.3 Key Vulnerabilities and Potential Impacts

Auckland region is identified as at risk from tsunamis. Risk is based on the close proximity of a large city and population close to the sea. Historically, no deaths of injuries to any human have been reported from tsunami affecting the Auckland region. Various international tsunami events have caused injury and death from drowning and impact by floating debris. Similar consequences are possible in the Auckland regional should an event cause considerable inundation of low lying coastal land.

Probabilistic risk modelling undertaken by Berryman (2005) suggests a 'worst case' scenario 1 in 100 year return period tsunami event (all sources) could cause as many as 44 deaths and 666 injuries along eastern coasts of Auckland's cities (Table 7.2). These figures increase considerably to 501 deaths and 3500 injuries for a 1 in 500 year return tsunami event (Table 7.3). Fewer deaths and injuries are likely on the west coasts of these cities (including the inner Waitakere Harbour of Auckland City) due to sparse development on low lying coastal land. East coast cities are more vulnerable to tsunami due to their exposure to a number of Pacific Ocean sources. The modelled consequences to Auckland's population assume no effective warning prior to the tsunami and night time populations are present at time of inundation. Warning systems will significantly reduce the vulnerability of coastal communities, particularly for remotely source tsunami events. The most likely source of a tsunami (remote, regional or local) will strongly influence human vulnerability and the precautions a community implements to lower its risk to tsunami. The ability to warn and evacuate coastal communities in a tsunami event varies widely across space and requires extensive pre-event planning to reduce vulnerability.

Auckland region Civil Defence Emergency Management currently receives alerts of distant source tsunami from the Pacific Tsunami Warning Centre in Hawaii. However, the Pacific Tsunami Warning Centre has limited ability to produce alerts of tsunami generated from the South West Pacific, the Southern Ocean or close to Auckland that are sufficiently timely and accurate to enable effective warnings. Capacity to receive alerts and communicate a warning for regional source tsunami is also largely undeveloped. Recent work targeted at responding to this challenge includes establishing a tsunami monitoring network for New Zealand's EEZ. The network would provide information on incoming remote and regional tsunami events as well as to detect (as near as possible) the first landfall of a wave on the main islands of New Zealand. In full operation, the network will be used to alert the Ministry of Civil Defence and Emergency Management of a tsunami threat. It will then be the Ministry's responsibility to issue civil defence warnings to the regions expected to be impacted and for those regions along with guidance form the Ministry to organise an appropriate response.

Table 7.3 Deaths and Injuries for Auckland Cities from a 'worst case' 1 in 100 year return period tsunami event. See Appendix 7.1 for wave heights. *Source: Berryman, 2005.*

		City						
	Percentile	Auckland City: East Coast	Auckland City: West Coast	Manukau City: East Coast	Manukau City: West Coast	North Shore City: East Coast	Waitakere City: East Coast	Waitakere City: West Coast
Deaths	84%	8	0	11	1	8	13	2
	50	1	0	3	0	2	2	0
	16	0	0	0	0	0	0	0
Injuries	84%	180	4	140	21	150	140	31
	50	69	0	58	0	55	35	11
	16	23	0	15	0	11	0	5

Table 7.4: Deaths and Injuries for Auckland Cities from a 'worst case' 1 in 500 year return period tsunami event. See Appendix 7.1 for wave heights. *Source: Berryman, 2005.*

		City						
	Percentile	Auckland City: East Coast	Auckland City: West Coast	Manukau City: East Coast	Manukau City: West Coast	North Shore City: East Coast	Waitakere City: East Coast	Waitakere City: West Coast
Deaths	84%	170	1	120	6	130	81	9
	50	36	0	34	0	28	22	2
	16	6	0	10	0	4	3	1
Injuries	84%	1200	25	1000	72	1000	380	110
	50	400	1	340	7	300	190	33
	16	130	0	160	0	76	51	25

For a remotely sourced tsunami the timeframe available is generally sufficient to provide an emergency response. This means the vulnerability of coastal populations in the Auckland region is dependant on developing a robust warning system and evacuation plans. Public vulnerabilities to remote events may arise from issues such as:

- Having gaps in plans and procedures

- Gaps in knowledge of where vulnerable populations might be located
- Communication difficulties with disabled or ethnic populations
- Lack of public awareness of high consequence/low probability hazards and tsunami in particular
- Physical evacuation difficulties (no transport, traffic jams, etc)

It is important to acknowledge that warning networks can only alert the public of tsunami threats from remote events. Waves generated by seafloor movements or undersea landslides near the Auckland coast would reach shorelines before any useful warning could be issued. In any case, not all undersea earthquakes generate tsunami.

Considerable infrastructure located near to the sea and the adjacent Manukau and Waitemata Harbours including the country's principal international airport and general cargo port. Future investment in the coastal zone is expected to increase and simultaneously coastal hazards issues are expected to become more acute. Some general hazard consequences associated with tsunami impact are:

- injury or drowning of people in low-lying coastal areas due to inundation and impact by floating debris
- inundation of coastal infrastructure such as roads, airport and ports resulting in vehicle damage, accidents, temporary obstruction or failure of roads
- damage to moorings and coastal structures
- coastal erosion and potential loss of support to structures in the coastal marine area
- short and long term economic losses due to damage, clean-up, and repair/ construction and remedial structures
- Pollution of land and coastal marine area from oil/petrol release, rubbish/debris and damage sewage infrastructure
- major social and psychological
- disruption to water networks

Regional costs from damage to property and infrastructure could potentially exceed millions of dollars when tsunami wave heights are >1m. Similar to deaths and injuries, damage will be higher for cities with eastern coastlines as these areas are more densely developed than the west coast and wave heights are likely to be greater. This is reflected by probabilistic models which suggest damage on Auckland City's east coast alone could reach as much as $2, 400, 000, 000 for 1 in 100 year and 1 in 500 year return period tsunami event (Berryman, 2005). These models only consider building damage (commercial, industrial and residential) and do not take into account losses from damage to coastal structures, utilities, remediation/clean up, personal property and indirect costs such as loss of income and production from business and work closure. These consequences would greatly increase the potential financial cost of tsunami impact in the Auckland region.

Table 7.5 Costs for Auckland Cities from a 'worst case' 1 in 100 year return period tsunami event. See Appendix 7.1 for wave heights. *Source: Berryman, 2005.*

		City						
	Percentile	Auckland City: East Coast	Auckland City: West Coast	Manukau City: East Coast	Manukau City: West Coast	North Shore City: East Coast	Waitakere City: East Coast	Waitakere City: West Coast
Cost ($m)	84%	910	36	130	20	250	120	31
	50	480	0	53	0	97	43	11
	16	130	0	18	0	16	0	5

Table 7.6 Costs for Auckland Cities from a 'worst case' 1 in 500 year return period tsunami event. See Appendix 7.1 for wave heights. *Source: Berryman, 2005.*

		City						
	Percentile	Auckland City: East Coast	Auckland City: West Coast	Manukau City: East Coast	Manukau City: West Coast	North Shore City: East Coast	Waitakere City: East Coast	Waitakere City: West Coast
Cost ($m)	84%	2400	120	930	68	1100	320	110
	50	1300	0	300	1	430	130	34
	16	600	0	130	0	91	57	29

7.4 References and Additional Reading

References

1. de Lange, W., Healy, T. R. 1986: New Zealand Tsunamis: 1840-1982. *New Zealand Jounal of Geology and Geophysics*. 29. 115-134.

2. Berryman, K. R. (ed) 2005: *Review of Tsunami Hazard and Risk in New Zealand*. GNS Client Report 2005/104. Institute of Geological and Nuclear Sciences.

3. Bell, R.G; Downes, G.; Berryman, K.R.; Walters, R.A.; Chague-Goff, C.; Barnes, P.; and Wright, I. 2004: Tsunami hazard for the Bay of Plenty and eastern Coromandel Peninsula: Environment Waikato Technical Report 2004/32 stage 2.

4. Downes, G., de Lange, W. 2007: *Revision and update of the tsunami database for New Zealand*. In: Earth: Our Changing Planet. Proceedings of IUGG XXIV General Assembly 2007. Perugia, Italy.

5. Goff, J., Chague-Goff, C., Nichol, S. L. 2001: Palaeotsunami deposits: A New Zealand perspective. *Sedimentary Geology*. 143. 1-6.

6. Nichol, S. L., Lian O. B., Carter, C. H. 2003: Sheet gravel evidence for a late Holocene tsunami run-upon sand dunes, Great Barrier Island, New Zealand. *Sedimentary Geology*. 155. 129-145.

7. Nichol, S. L., Goff, J., Regnauld, H. 2004: Sedimentary evidence for a regional tsunami on the NE coast of New Zealand. *Geomorphologie:. Relief, Processus, Environment*. 1. 35-44.

8. Nichol, S.L., Lian, O.; Horrocks, M.; and Goff, J. 2007: Holocene record of gradual, catastrophic, and human influenced sedimentation from a back barrier wetland, northern New Zealand. *Journal of Coastal Research*. 23. 3. 605-617.

9. King, D., Goff, J., Skipper, A. 2007: Maori Environmental Knowledge and natural hazards in Aotearoa - New Zealand. *Journal of the Royal Society of New Zealand*. 37. 59-67.

10. Power, W., Downes, G., Stirling, M. W. 2007: Estimation of tsunami hazard in New Zealand due to South American earthquakes. *Pure and Applied Geophysics*. 164. 547-564.

11. National Oceanic and Atmospheric Administration, 2008: *NOAA Tsunami webpages*. [Available from: http://www.tsunami.noaa.gov/].

12. Liu, P., 2005: South Asia Tsunami, Sri Lanka Field Survey. [cited from: (http://ceeserver.cee.cornell.edu/pll-group/tsunamis_data.htm).

13. de Lange, W., Hull, A. G. 1994: *Tsunami Hazard for the Auckland Region*. Auckland Regional Council Technical Publication 50. p41.

14. Goff, J., Walters, R., Lamarche, G., Wright, I., Chague-Goff, C. 2005: *Tsunami Overview Study*. Auckland Regional Council Technical Publication 280. p47.

15. de Lange, W., Healy, T. R. 2001: Tsunami Hazard for the Auckland Region and Hauraki Gulf, New Zealand. *Natural Hazards*. 24. 267-284.

16. Chick, L. M., de Lange W., Healy T. R. 2001: Potential Tsunami hazard associated with the Kerepehi Fault, firth of thames, New Zealand. *Natural Hazards*. 24. 309-318.

17. National Institute of Water and Atmosphere, 2008: Physical Hazards Affecting Coastal Margins and the Continental Shelf. [cited from: http://www.niwa.cri.nz/rc/prog/chaz/news/tsunami].

18. Lane, E, Walters, R., Arnold, J., Enright, M., Roulston, H. 2007: Auckland Regional Council Tsunami Inundation Study. NIWA Client Report: CHC2007-126. p55.

19. Intergovernmental Panel for Climate Change. 2007: *Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Parry M.L., Canziani O.F., Palutikof J.P., van der Linden P.J. and Hanson C.E. (eds.), Cambridge University Press, Cambridge, UK. 7-22.

Additional Reading

Bryant, E. 2001: *Tsunami: The Underrated Hazard*. Cambridge University Press. p350

Chague-Goff, C., Dawson, S., Goff, J. R., Zachariasen, J., Berryman, K., Garnet, D. L., Waldron, H. M., Mildenhall, D. C. 2002: A tsunami (c. 6300 years BP) and other environmental changes, northern Hawke's Bay, New Zealand. *Sedimentary Geology*, 150. 89-102.

de Lange, W. 1997: Tsunami in the Hauraki Gulf. *New Zealand Science Monthly.* 8. 4-5

de Lange, W., Bell, R. G. 1998: Tsunami risk from the southern flank: Balleny Islands earthquake. *Water & Atmosphere.* 6. 13–15.

de Lange, W. 2003: *Tsunami and storm surge hazard in New Zealand*. Chapter 4. In: Goff, J. R., Nichol, S. L., Rouse, H. L. (eds). The coast of New Zealand: Te Tai O Aotearoa. Dunmore Press, New Zealand. 79-95

de Lange, W., Moon, V. G. 2007: Tsunami wash-over deposits, Tawharanui, New Zealand. *Sedimentary Geology,* 200. 232-247.

Goring, D. G. Bell, R. G. 1998: Canterbury shelf waves and the PNG tsunami. *Water & Atmosphere.* 6. 15–16.

Hull, A. G., Mansergh, G. D., Townsend, T. D., Stagpoole, V. M., 1995: *Earthquake hazards in the Auckland region: a report prepared for the Auckland Regional Council*. Auckland Regional Council Technical Publication 57.

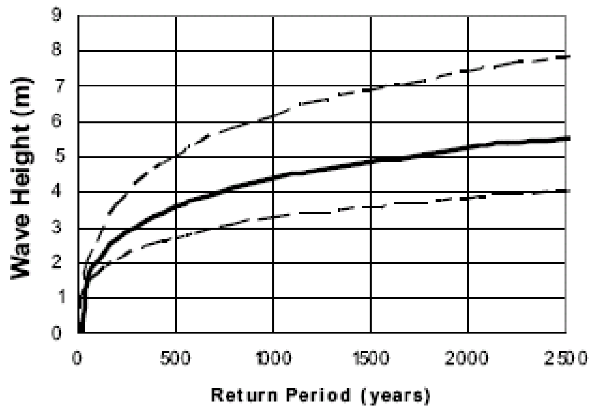
Lowe, D. L., de Lange, W. P. 2000: Volcano-meteorological tsunamis, the c. AD 200 Taupo eruption (New Zealand) and the possibility of a global tsunami. *The Holocene*. 10. 401-407.

Walters, R., Goff, J. R., McFadgen, B. G. 2003: Assessing tsunami hazard in the New Zealand coast. *Science of Tsunami Hazards*. 21. 137-153

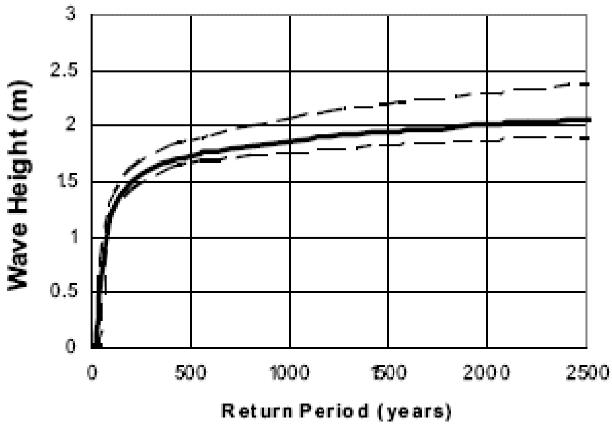
Appendix 7.1

Probabilistic Tsunami Wave Heights (*Source: Berryman, 2005*).

Auckland City: East



Auckland City: West



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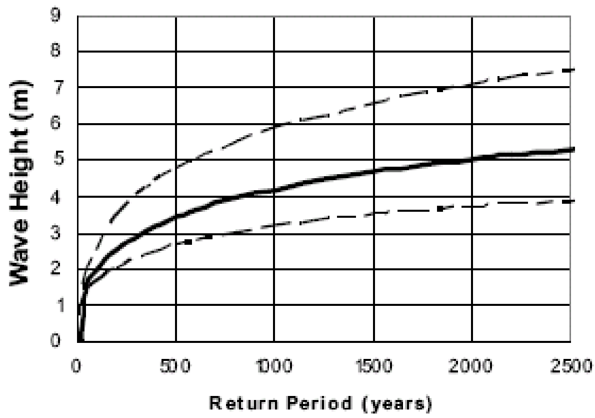

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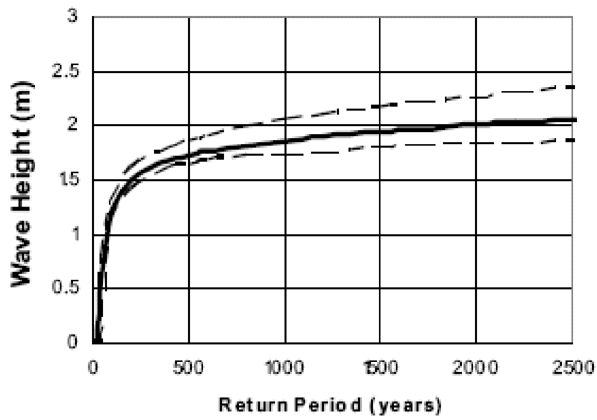

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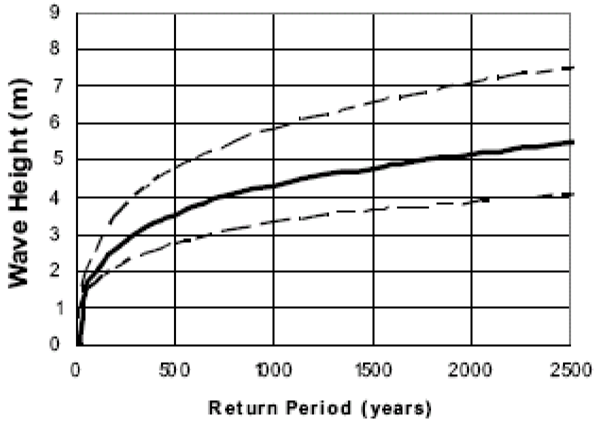

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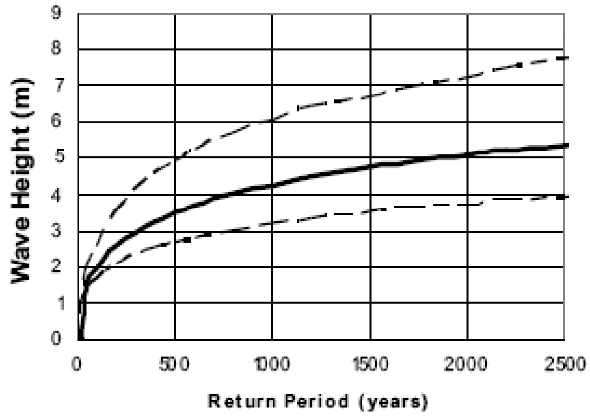

Waitakere City: West