Auckland Engineering

Life Lines

AUCKLAND ENGINEERING LIFELINES PROJECT

STAGE ONE REPORT
JULY 1997

PART 1: HAZARD INFORMATION
PART 2: NETWORK UTILITY INFORMATION

AUCKLAND REGIONAL COUNCIL
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Auckland Regional Council

Auckland Engineering Life Lines

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PART 2: UTILITY NETWORK INFORMATION

PREFACE

The Auckland Engineering Lifelines Project (AELP) was initiated by the Auckland Regional Council in late 1995. The primary objective of the AELP is to reduce the impact of all know hazards on the Lifeline services of the Auckland Region. The project is based on, and follows on from the successful Lifelines Projects in Wellington and Christchurch. The AELP joins a growing list of regional lifeline projects throughout New Zealand.

The cooperation and participation in the AELP to date is recognition by the Auckland community of the need to address the vulnerability, response and recovery of the region to a variety of hazards. The importance of the efficiency of response of lifelines, both in economic and social terms is well accepted by those participating. This acceptance is demonstrated by the many and varied organisations participating in the project. Without the ongoing support and involvement of these organisations, the project could not hope to achieve its objectives.

The AELP is a unique opportunity for participating organisations to identify the extent of co-dependence of their organisation on other Lifelines Services. The identification of these service interdependencies is arguably the most important deliverable of the AELP. The identification of the interdependencies not only allows the individual organisations to better prepare themselves for a disaster, but may also enable them to *influence* and prioritise the response of other organisations Lifelines to their own, and ultimately the whole lifeline network's advantage. An integrated and prioritised 'whole system' response is therefore the objective rather than isolated organisation reactive responses.

The AELP is being overseen by a Steering Committee made up from eighteen representatives of the participating organisations. The majority of the work is being performed by five task Groups, responsible for Hazard analysis, Transportation, Civil, Communication and Energy Services. The project methodology, programme and communications is managed by an appointed Project Manager.

This report, Stage I Report - Hazards and Network Utility Information - is the first report produced by the AELP. The primary purpose of this report is to communicate to the AELP organisations the extent of the hazards investigated, the likely effect of these hazards on engineering lifelines, and also the extent of the Engineering Lifelines service network throughout the Auckland Region. The utility network maps has been produced to enable the vulnerability of the network to be evaluated and quantified. This report is therefore a reference document, intended for use in assessing the vulnerability of components of the lifelines network, and the network as a whole to various hazards.

The AELP has adopted an "All Hazards" approach: Natural hazards (earthquake, volcano, cyclone etc), Human hazards (hazardous substance spills, vandalism etc) and Biological hazards (algal blooms, disease out breaks etc) have been considered and described in Part 1 of this report.

Part 2 identifies the Engineering Lifeline services network components and facilities: those parts that are important to the ongoing operation and effectiveness of the Auckland Region. Principal supply routes of energy, water, transport and communications are included on the maps.

The focus of the AELP has been, and will continue to be, on the efficient recovery and response of Engineering Lifeline Services from hazards. The integration of this project with Civil Defence is presently limited to CD representation on the Steering Committee and Task Groups. In addition, a large number of important Civil Defence Emergency facilities have been identified and entered on to the Auckland Regional Councils GIS mapping database. In time, maps of these facilities will be produced to supplement the network information herein.

The cooperation of all the organisations involved in the project to date has been both willingly given and gratefully received. Special mention of the valued contributions by the Chairs of each task group must be made, the enthusiasm and dedication of these individuals has been essential to the success of this project thus far.

The next phases of the project; the analysis of network vulnerability and interdependence, and the all important stages of response and recovery planning will follow from the initial workshop on 25th July 1997.

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7 July 1997

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PART 1

HAZARDS INFORMATION

SECTION 1

INTRODUCTION

1.0 INTRODUCTION

The following hazards have been considered by the Auckland Engineering Lifelines Project:

- earthquake,
- volcanic eruption,
- tropical cyclone,
- tsunami,
- biological hazards,
- fire and hazardous substance spill,
- vandalism / terrorism.

Both geographic (maps) and scenario based approaches have been used to present the hazard information. Hazards such as earthquake- and rain- induced instability, can be mapped over the region using GIS (*geographical information system*) based on a scenario event as a trigger. For hazards such as tsunami, where the effects are more localised (i.e. along the coast), scenarios have been used to illustrate the effects. Vulnerable stretches of coastline have been identified, but not mapped. For hazards such as fire and algal blooms, the effects are discussed in more general terms.

In selecting the various hazard scenarios, the emphasis has been on developing credible events that would test the region's infrastructure should they occur. This approach has produced scenarios with different return periods.

The perceived magnitude of the consequences of a hazard event and its return period will determine the acceptance or non-acceptance of the risk of that event. Risk is a function of the probability (or return period) of an event, the existence of something of value that is under threat by the event, and the sensitivity, or vulnerability of that value to damage or destruction. Risk is not discussed as part of this hazard information stage of the Project, but will be considered further in Stage 2 once network vulnerability and interdependencies have been assessed.

Where a geographic approach has been used, data has been analysed using GIS at two scales:
Region A (areas of medium to high population and services density): 1: 100 000
Region B (areas of low population and services density): 1: 250 000

For ease of presentation and reproduction, maps accompanying this report are produced at scales of 1:250 000 and 1:500 000 for Regions A and B respectively.

The following is a summary of the hazards investigated as part of the project, and the level of information that has been provided.

EARTHQUAKE

The region's geology was assessed in terms of it's ground shaking and liquefaction potential. An earthquake scenario (2 000 year return period) was then developed and hazard maps produced of *ground shaking* (peak horizontal ground accelerations and modified Mercalli intensity), *earthquake-induced instability*, and *liquefaction* for the scenario. In addition, maps of uniform hazard (for a 2 000 year return period event) were prepared for earthquake-induced instability and liquefaction.

Earthquake motions were selected to be around, or slightly in excess of earthquake code standards. Based on the current level of understanding of the earthquake hazard in Auckland, this was an earthquake with a return period of 2000 years.

Earthquake-induced damage to Lifelines (with respect to the scenario) has been qualitatively assessed and included as a matrix (section 2.5).

VOLCANIC ERUPTION

Auckland is situated on a potentially active volcanic field. However, the region faces an additional volcanic threat from several large central North Island volcanic centres.

Three volcanic scenarios and their effects on Lifelines are discussed in this report. The first is an eruption from the Auckland Volcanic Field. This scenario is one of five recently developed for the Auckland Regional Council's *Volcanic Impact Assessment for the Auckland Field* (ARC Technical Publication No.79, April 1997). The second and third scenarios are eruptions at Egmont volcano and the Okataina Volcanic Centre respectively.

For the Auckland Volcanic Field, meaningful probabilities of eruption occurrence in any century cannot be calculated. However, for the purposes of the Lifelines Project, a return period of 1:1000 years has been assumed. Return periods for Egmont and Okataina are taken as 1:300 and 1:2000 respectively.

TROPICAL CYCLONE

An extreme cyclone scenario has been developed with a 1:100 year return period. It is based on a number of 'near-miss' (for Auckland) events such as Cyclone Bola. The cyclone has been tracked such that its highest impact is on the Auckland metropolitan area.

Wind and *rainfall* profiles have been developed, and the latter used to prepare a *rain-induced instability* hazard map. Barometric pressure associated with the cyclone has been used to develop a *storm surge* scenario and areas prone to resulting *coastal flooding* have been identified.

Damage to Lifelines from wind, rain, flooding, slope failure, surges and wave action (with respect to the cyclone and storm surge scenarios) has been qualitatively assessed and included as a matrix (section 4.4).

TSUNAMI

The most likely damaging tsunami event for Auckland is a teletsunami originating from South America. A scenario has been developed based on a tsunami caused by a Magnitude 9 earthquake off Northern Chile. This has an estimated return period of 1:75.

Two other scenarios are presented for completeness, based on local sources: an earthquake on the Kerepehi Fault (1:4,500 to 9,000 year return period), and a local volcanic eruption in the inner Hauraki Gulf (1:1,000 year return period).

Areas along the coast susceptible to *coastal erosion* and other effects have been identified.

DROUGHT

Drought is discussed in terms of it's contribution to a regional water supply shortage. Other factors such as demand and reservoir storage also contribute to a water supply shortage. The current water supply system has been guaranteed to meet water requirements for a 1:200 year return period drought.

BIOLOGICAL HAZARDS

The direct and indirect effects of disease outbreaks and algal blooms on the region's infrastructure are considered. These are remote hazards (with respect to Lifelines), and the likelihood of their occurrence can be controlled through appropriate health and reservoir catchment management practices.

FIRE AND HAZARDOUS SUBSTANCE SPILLS

The effects of fire, explosions and hazardous substance spills on Lifelines are discussed. These events have the potential to occur reasonably frequently in the Auckland region (compared to some of the other hazards), however the effects are much more localised. A hazardous substance spill scenario is presented to illustrate the sorts of effects that might occur.

VANDALISM / TERRORISM

Vandalism and terrorism at a scale which would seriously affect Lifelines has a low probability. The risk of these hazards can be minimised through good security measures.

The Auckland Regional Council has commissioned the hazard information contained in this report. Information on each hazard is presented in the form of a stand-alone report, and consequently there is a degree of repetition between reports and between sections.

The hazard information has been prepared for the purposes of the Auckland Engineering Lifelines Project. It's use for any other purpose is limited. The hazard maps have been prepared at a regional scale and do not replace any requirement for detailed site specific geological or geotechnical investigation. Readers of the report are advised to consult with the Auckland Regional Council or the authors of the reports as to the suitability of the information for other applications.

SECTION 2

EARTHQUAKE

REPORT 2.1

GROUND SHAKING HAZARD MAP (Accompanying Notes)

Prepared for

AUCKLAND REGIONAL COUNCIL

By

BECA CARTER HOLLINGS & FERNER LTD

And

INSTITUTE OF GEOLOGICAL & NUCLEAR SCIENCES LTD

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1.0 INTRODUCTION

The Resource Management Act (1991) designates responsibility for integrated management of the land, natural and physical resources and avoidance or mitigation of natural hazards to Central, Regional and Local Government. As part of the Auckland Regional Council's responsibilities under the Act, a series of studies are being undertaken to assess the potential risks and impacts of seismic hazard to the Auckland Region. These studies build on the fault hazard and ground shaking maps presented in ARC Technical Publication No.57 and the preliminary slope instability hazard map presented in ARC Technical Publication No.71, and include assessments of:

- Ground Shaking Hazard (reported herein);
- Liquefaction Susceptibility Hazard; and
- Earthquake Induced Slope Instability Hazard.

Based on the results of this work and a desire among the many agencies in the Auckland Region to understand better the likely effects of future earthquakes in Auckland, the Auckland Engineering Lifelines Project was developed. Part of this project is to identify a scenario earthquake and its ground shaking effects. An Earthquake Hazard Task Group was established within the Lifelines Project. One aim of the Group was to modify, where necessary, the preliminary ground shaking hazard map produced in the earlier study.

The objectives of the Ground Shaking Hazard assessment are to:

(i) Identify those areas of the Auckland Region that are potentially susceptible to ground failure as a result of ground shaking associated with earthquake and/or fault displacement (potentially active faults are reviewed in ARC Technical Publication No.57);

(ii) Identify the degree of shaking amplification expected for different foundation conditions; and

(iii) Provide a basis for development of models for Peak Horizontal Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) likely to be generated by a 2000 year return period event in the Auckland Region.

The maps will also be used to assist identification of services vulnerability as part of the next stage of the Auckland Engineering Lifelines Project. The Ground Shaking Hazard Map is produced at the following scales:

- Region A, areas of medium to high population and services density, 1:100,000;
- Region B, areas of low population and services density, 1:250,000.

This report accompanies the maps and provides background earthquake hazard information, and the methodology for classification of different soil types and their description.

Notice to Reader/User of this Document:

This report is the property of our Client, the Auckland Regional Council, the Institute of Geological and Nuclear Sciences and Beca Carter Hollings & Ferner Ltd. This document discusses ground instability at a regional scale. It is not suitable for a site investigation database and should not be used as such.

Should you be in any doubt as to the applicability of this report or its recommendations and/or encounter materials that differ from those described herein, it is essential that you discuss these issues with the authors before proceeding with any work based on this document.

2.0 SEISMICITY OF THE AUCKLAND REGION

2.1 HISTORICAL RECORDS

Earthquakes

The Auckland Region occurs within one of the least historically (last 150 years) seismically active regions of New Zealand. This is in part because Auckland is located some 300km from the major northeast-southwest oriented seismically active zone which lies beneath the east coast of the North Island and marks the boundary between the Australian and Pacific tectonic plates. This zone is judged to be capable of producing large (magnitude, $M \geq 8$) earthquakes.

Historical earthquakes and their effects are described together with known faults of the Auckland Region in the ARC Technical Publication No.57 dated April 1995.

2.2 GROUND SHAKING

Strong ground shaking is one of the principal effects of earthquakes. A larger magnitude earthquake produces stronger shaking than a smaller earthquake at the same focal depth. In general, locations more distant from the source receive a lower level of shaking than locations near the epicentre. However, because ground conditions are locally variable, the level of shaking felt from the same earthquake at a similar distance from the epicentre will vary from site to site. This occurs because different geological materials and conditions at different sites amplify earthquake shaking by different amounts.

Strong ground shaking and associated ground failure may cause damage to man-made structures during earthquakes.

3.0 SOILS AND ROCKS OF THE AUCKLAND REGION

3.1 SOIL AND ROCK TYPES

Much of the Auckland urban area is built on Miocene, Pliocene and Quaternary sedimentary rocks and soils. Younger basaltic volcanoes have erupted through these rocks, resulting in a wide range of volcanic landforms such as scoria cones, lava fields, explosion craters and tuff rings. The majority of these volcanic deposits rest upon residual and transported soil masses, rather than rock.

To the west, the hills of the Waitakere Ranges are underlain by volcanic and volcaniclastic rocks (sedimentary rocks derived from eroded Miocene-age volcanoes), and to the east, the hills of the Whitford-Brookby area and the islands of Motutapu, Motuihe, and in part, Waiheke, Kawau, Little Barrier and Great Barrier are underlain by weathered Mesozoic greywacke rocks. To the north, soft sedimentary rocks and hard volcanic rocks support gentle to moderately sloping lowlands and upstanding ranges respectively. Weathering has produced a thick regolith of soil and slope debris up to 20m to 30m thick.

The Quaternary deposits (Pleistocene and Holocene age, ie <1.6 million years) comprise soils which have been transported into place. Because the Pleistocene deposits (10,000 to 1.6 million years) are considerably older than the Holocene deposits (<10,000 years), and generally occur on higher ground, these materials tend to be stronger and are often less saturated than the Holocene deposits. However, they are soils (not rock) and do contain some loose sands and sensitive silts.

In general, the Holocene age deposits comprise both sandy coastal deposits and soft clayey estuarine deposits. These are generally the weakest materials encountered in the Auckland Region and, because of their location, typically in low lying areas adjacent to swamps and water courses, they also tend to be saturated.

3.2 SUSCEPTIBILITY TO EARTHQUAKE SHAKING

The soil type and soil profile, the geotechnical properties of the soil/rock sequence and the degree of saturation are of particular importance when considering susceptibility of soils and rocks to ground shaking. The weaker, water-saturated Quaternary deposits and man-made ground (including reclamations) have characteristically lower densities than other soil/rock types encountered in the Auckland Region, and are therefore likely to be most susceptible to ground shaking.

3.3 SOIL/ROCK CATEGORY

The soil and rock mass types (detailed in ARC Technical Publication No.71, June 1996) have been grouped according to their expected response to ground shaking from earthquakes. The groupings are based on the characteristic physical properties (SPT, weathering profile etcetera) and known behaviour of the soil and rock types both in the Auckland Region and in other parts of New Zealand. In Auckland, weathering has produced a mantle of residual clayey soils on all rock units. This soil cover is up to 20m to 30m thick and is an important factor in assessing the response of the ground to shaking.

(i) **Residual Soil Overlying Rock**

Residual and colluvial soils, ash and weathered tuff:

- up to 30m thick, overlying greywacke;
- up to 20m thick overlying interbedded sandstone and mudstone; and
- associated with conglomerate and basalt.

(ii) **Firm to Stiff Sediment of Pleistocene Age**

- Alluvium; and
- Basalt, ash and tuff overlying alluvium.

(iii) **Coastal Deposits**

- Beach and dune sands;
- Man-made fills overlying zone (i) or (ii) deposits.

(iv) **Estuarine Deposits of Holocene Age**

- Stream alluvium and swamp deposits; and
- Man-made fills overlying zone (iii) or (iv) deposits.

4.0 GROUND SHAKING HAZARD ASSESSMENT

4.1 SOIL CLASSIFICATION TABLE

The soils in, or on which lifelines are located, vary widely. Engineering properties and behaviour range from those of rock to very soft soil, including engineered and non-engineered fill and reclaimed land, some of which comprises hydraulically placed sand and harbour mud.

The soil groupings developed in Section 3.3 have been allocated Hazard Zones, numbered 1 to 4, with Hazard Zone 1 indicating the least potential susceptibility of a site to amplification of ground shaking, and Hazard Zone 4 indicating the highest potential susceptibility of a site to amplification of ground shaking. The characteristic physical properties and expected behaviour in response to earthquake shaking are summarised in the Soil Classification Table, Table 1.

4.2 GROUND SHAKING MAP

The Ground Shaking Hazard Map shows the distribution of the Soil/Rock Mass categories identified as Zones 1 to 4 in Table 1. The map is produced at scales of 1:100,000 for areas of medium to high population and services density (Region A), and 1:250,000 for areas of low population and services density (Region B).

4.2.1 Areas of Medium to High Population and Service Density (Region A)

Ground shaking hazard mapping in Region A indicates that much of Auckland City lies within the zone of least shaking amplification, while Manukau City and a large part of the eastern Waitakere City contain a significant area of moderate ground shaking amplification. Significantly higher ground shaking amplification may occur in the following areas (major lifelines services in these areas are indicated in brackets):

- Reclaimed land surrounding the Ports of Auckland, the eastern part of the northern Central Business District and reclaimed land at Auckland International Airport (Auckland's main port and airport facilities; Auckland's wastewater treatment facilities);
- A large area of Holocene-age, saturated fine sediments in Manukau City near Takanini and Ardmore (SH1; Ardmore aerodrome);
- An area of similar materials in West Auckland, extending from Green Bay to Henderson, Kumeu and Riverhead (Northwestern Motorway, main electric power line);

- South Onehunga light industrial area;
- Isolated areas of locally thick, unconsolidated materials within the Auckland Isthmus, North Shore City and Manukau City.

4.2.2 Areas of Low Population and Service Density (Zone B)

The primary higher ground shaking amplification hazard areas identified are located adjacent to stream valleys and tidal embayments in the Rodney and Papakura Districts. The main areas likely to be affected by higher amplification of earthquake shaking are indicated below. Major lifelines services in these areas as shown on topographic maps (NZMS 260), are indicated in brackets.

Rodney District:

- Parakai - Helensville - Kaukapakapa (SH16, north Auckland Railway) - Waitoki;
- Omaha and Kaipara flats (North Auckland Railway);
- Low-lying sections of the Whangaparaoa Peninsula;
- Low-lying ground behind Orewa Beach (medium population density) ; and
- Small coastal settlements between Kaukapakapa and Tauhoa;

Waitakere City:

- Pipelines from the Waitakere Reservoir may locally cross zone 2 and 4 deposits.

Papakura District:

- Wairoa River valley, extending northeast from Papakura (Ardmore Aerodrome), through Clevedon, to the coast;
- Paparimu - Hunua - Ardmore (extension of pipelines/tunnels carrying water from the Cossey's, Mangatangi, upper Mangatawhiri and Wairoa reservoirs; main electric power line); and
- Happy Valley - Ararimu - Hunua (main electric power line).

Great Barrier Island:

- Kaitoke Creek - Claris (Aerodrome).

Table 1: Ground shaking hazard zones and soil classification table

Hazard Zone	Soil Foundation Condition	Soil Category	Engineering Description of Soils/Rock	SPT Blows/300mm (N)	Shear Wave Velocity (m/s)[1]	Typical Ground Failures Resulting From Earthquakes
1	*Residual Soil Overlying Rock*	Residual and colluvial soils, ash and weathered tuff: • up to 30m, overlying greywacke; • up to 20m overlying interbedded sandstone and mudstone; conglomerate and basalt	• CW:[2] sand/silt/clay • HW: gravel in a silty sand/clay matrix • MW: very weak rock • SW-UW: weak to moderately strong rock	5 - 25+ 15 - 50+ 30 - 100+ 50 - 200+	100 - 300 200 - 500 300 - 1000 500 - 2000	• Generally minor to nil damage to gentle slopes; • Movements on critically steep slopes, and on gentle slopes in sandstone and mudstone with clay seams, undercut by streams and coastal erosion.
2	*Firm to Stiff Sediment of Pleistocene age*	• Alluvium; • Basalt, ash and tuff overlying alluvium	• Soft to very stiff alluvium; • Sensitive pumiceous silt; silt, peat and clay; • Loose to dense sand and breccia; • Ash, tuff and basalt overlying these deposits	5 - 25[3]	100 - 300	• Widespread failure of coastal cliffs and river banks; • Movement on moderate to steep slopes; • Localised liquefaction of saturated loose sand lenses in severe[4] shaking
3	*Coastal Deposits*	• Beach and dune sands; • Man-made fills overlying zone 1 or 2 deposits	• Medium dense fine sand and shell, saturated; • Loose fine sand, unsaturated	5 - 40	100 - 500	Localised liquefaction of saturated loose sand pockets
4	*Estuarine Deposits of Holocene age*	• Stream alluvium and swamp deposits; • Man-made fills overlying zone 3 or 4 deposits	Very soft to stiff mud, silt, peat, pumiceous clay; typically saturated	0 - 10	50 - 200	• Widespread sliding failures of moderate slopes; • Widespread liquefaction of saturated sand deposits in moderate shaking

(1) Values of shear wave velocity are assessed

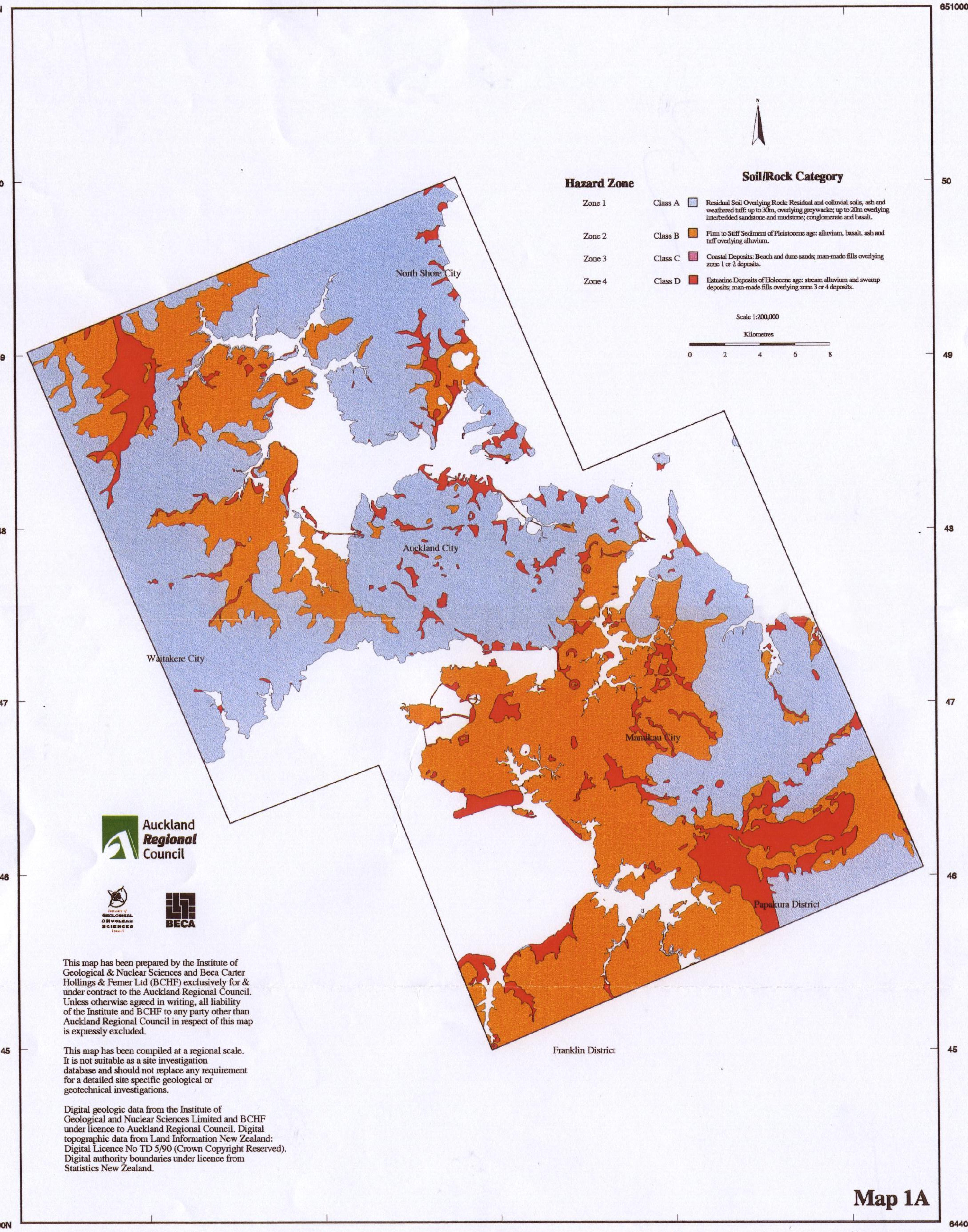
(3) Where basalt rock overlies deep alluvium, the rock stiffness does not significantly influence site behaviour

(4) Shaking levels:
Severe ≥ 0.40g ≥ Strong 0.20g ≥ Moderate 0.15g ≥ Moderate to Low 0.1g ≥ Low 0.05g

(2) Rock Weathering Grades:
CW completely weathered; HW highly weathered (soil)
MW moderately weathered (very weak rock)
SW slightly weathered; UW unweathered (rock)

Ground Shaking Hazard and Soil/Rock Mass Distribution

Region A



This map has been prepared by the Institute of Geological & Nuclear Sciences and Beca Carter Hollings & Ferner Ltd (BCHF) exclusively for & under contract to the Auckland Regional Council. Unless otherwise agreed in writing, all liability of the Institute and BCHF to any party other than Auckland Regional Council in respect of this map is expressly excluded.

This map has been compiled at a regional scale. It is not suitable as a site investigation database and should not replace any requirement for a detailed site specific geological or geotechnical investigations.

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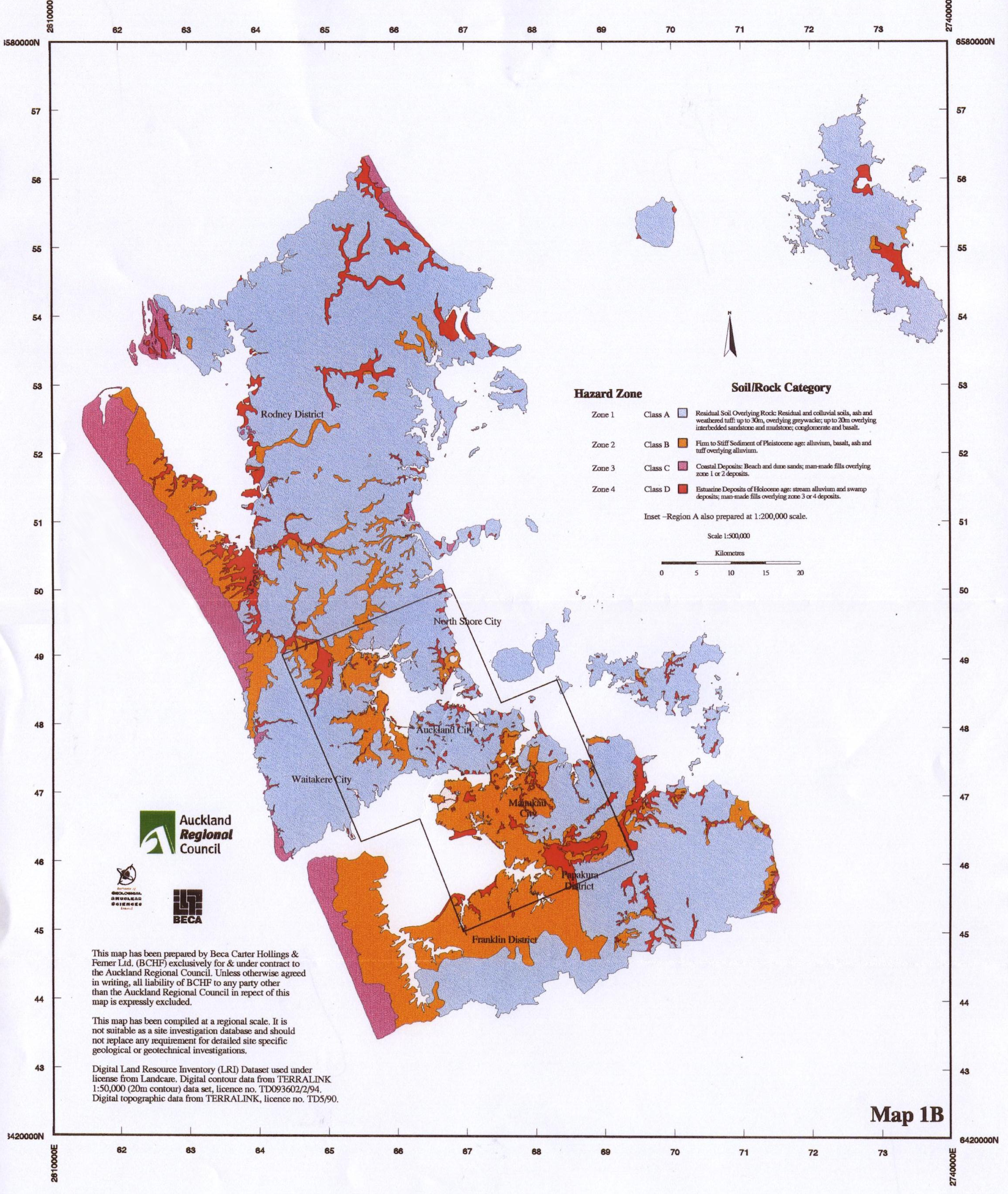
This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Ground Shaking Hazard and Soil/Rock Mass Distribution

Region B



Map 1B

Auckland Engineering Lifelines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

REPORT 2.2

PEAK HORIZONTAL GROUND ACCELERATIONS AND MODIFIED MERCALLI INTENSITIES FOR SCENARIO EARTHQUAKES IN THE AUCKLAND REGION: AUCKLAND ENGINEERING LIFELINES PROJECT (Notes to Accompany Maps)

Prepared for

AUCKLAND REGIONAL COUNCIL

By

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Institute of Geological & Nuclear Sciences Ltd

Client Report 43619D
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SUMMARY

This study has produced maps of the Auckland region and Auckland Engineering Lifelines Project study regions that show the distribution of earthquake shaking intensities for a magnitude 6.0 earthquake located 20 km east of the downtown area of Auckland city. Earthquake shaking is shown in terms of peak horizontal ground accelerations (PGA) and Modified Mercalli Intensities (MM)—measures useful for engineering performance and earthquake damage assessment. The accompanying report outlines the methods used to determine the scenario earthquake and assess the level of shaking for the ground conditions in the Auckland region.

Two possible scenario earthquakes were considered: (1) a magnitude 6.9 earthquake caused by 2.5 m of slip along a 25 km segment of the Kerepehi fault 43 km to the east of downtown Auckland, and (2) a magnitude 6.0 earthquake 20 km east of the downtown area of Auckland city. Only scenario (2) satisfied the brief for the project to produce earthquake motions that have a ca. 2,000 year return period in Auckland Engineering Lifelines Project study regions.

The distribution of PGA was determined for the scenario earthquake using an attenuation model developed recently by the Institute based on 461 records from 51 New Zealand earthquakes. PGA attenuation was modelled for three soil classes (Hazard Zones 1, 2+3, and 4) developed in a parallel study. For each soil class an appropriate PGA amplification factor was determined based on overseas models and available information on the engineering properties of the soils in the project area.

To generate maps for the Lifelines study regions, PGA values developed from the attenuation model were determined for a grid with spatial resolution of 100 m. Shaking intensity was determined by overlaying attenuation grids for each soil class grid and then selecting the shaking value from the attenuation grids based on the soil class grid. A scenario earthquake location 20 km due east of Auckland results in the highest accelerations offshore, with an area from downtown Auckland City and along the southern motorway having similar PGA values at about 0.15–0.25g.

A similar procedure was undertaken for determining the MM intensity distribution, using a New Zealand-based MM attenuation model and MM amplification factors based on overseas models and local soils information. Intensities of MM 7–8 are predicted for the scenario earthquake within an area from downtown Auckland City and along the southern motorway.

We believe that in this initial stage of the Auckland Engineering Lifelines Project involving response planning for networks or facilities at a number of locations, the scenario developed in this study is the most appropriate. The scenario approach recognises that levels of earthquake motion with a long return period are unlikely to be the same at a series of sites across a region in a single event. A limitation of this scenario approach is that there may be several scenarios that match the target motions at one locality, but give very different levels of motion elsewhere. The earthquake shaking intensities and uniform hazard model results developed for this study are suitable only for the Auckland Engineering Lifelines Project, and are not a substitute for site-specific earthquake hazard investigations.

1.0 INTRODUCTION

Many national and local agencies have expressed their need to understand better the likely effects of a range of natural and man-induced hazards in the Auckland region. This need has been recognised by the Auckland Regional Council and resulted in the formation of the Auckland Engineering Lifelines Project.

For the earthquake hazard section of the Lifelines Project a suitable scenario earthquake and its ground shaking effects was required for parts of the Auckland region with significant vulnerable infrastructure. An Earthquake Hazard Task Group was formed within the Lifelines Project to determine a suitable earthquake scenario and its shaking intensity within the Auckland region.

This report and accompanying appendices document the methods and models used to develop the maps for the Auckland Engineering Lifelines Project. Work has been undertaken in collaboration with the Earthquake Scenario Task Group of the Auckland Engineering Lifelines Project. The report has been reviewed by Mr David Dowrick and Mr Dick Beetham of the Institute. Tracey Townsend responded rapidly to many requests for extra information to be included in this report.

2.0 SCENARIO DEVELOPMENT AND SHAKING INTENSITY CALCULATION

2.1 DEVELOPMENT OF KEREPEHI FAULT EARTHQUAKE SCENARIO

An initial earthquake scenario for the Auckland region was developed in consultation with the task group based on a surface rupture event along the segment of the Kerepehi fault closest to Auckland city (Appendix II). Existing geological and geophysical information on the location, segmentation and timing of past surface fault ruptures were reviewed to determine the location and magnitude[1] of the scenario event.

For this study we have assumed that the unnamed fault mapped by Hochstein et al., (1986) in the Hauraki Gulf is an active segment of the Kerepehi fault, and that it has the same fault parameters as segments of the fault studied onshore further south. Based on the onshore segment length of 25 km, NW strike and 4 km easterly stepover distance between segments, we continued the Kerepehi fault offshore to a point where it was closest to the Auckland Engineering Lifelines Project study area. The parameters used to calculate the probable PGA and MM intensities from the Kerepehi fault scenario event are given below:

Fault segment length	25 km
Fault depth (h_C)	12 km
Average slip/event	2.5 m
Average recurrence interval	5,000 yrs
Fault type	Normal
Fault dip	60°SW
Magnitude	M_W 6.9
Closest distance from Auckland (downtown) (r)	43 km

[1]The magnitude is a measure of the energy released by an earthquake at its source and it is calculated from seismographic records. M, M_L, M_S and M_W are commonly used when describing earthquake magnitudes - M_L resulting from analysis of New Zealand seismograms, M_S from analysis of the surface waves appearing on distant, or overseas, seismograms, and M_W, the moment magnitude, obtained from the length of fault rupture and the amount of slip associated with the earthquake event. For pre-instrumental earthquakes, the magnitude, M, has been estimated by comparison with later instrumentally recorded events.

Once the Kerepehi fault scenario event was completed, maps were developed at scales of 1:100,000 and 1:250,000 showing contours at 0.05g intervals from 0.05g–0.5 g of the mean peak ground accelerations (PGAs) expected on surface deposits of soft rock, such as greywacke, in the study region. These maps were supplied to the Earthquake Hazard Task Group for comment and review.

2.2 REVIEW OF ADEQUACY OF KEREPEHI FAULT SCENARIO

Given the relatively great distance of Kerepehi fault from downtown Auckland, there is a possibility that more frequent smaller magnitude events closer to Auckland could produce more severe ground motions than the Kerepehi fault event in the areas of medium–high population density. To aid in the assessment of the adequacy of the Kerepehi fault event, Institute staff developed a probabilistic PGA hazard assessment to estimate the 500 and 2000 year return period accelerations for the Auckland region (Appendix II, III). Hazard calculations were performed using the SEISRISK software package with an existing seismicity model for the Auckland region and recently developed PGA attenuation models. Hazard was calculated using two source regions—Auckland and Coromandel—to represent the different character of earthquake occurrence to the east of Auckland city. The uniform hazard was calculated to include variability in the attenuation models and with and without the influence of the Kerepehi fault (Figures 1–8).

We calculated higher seismicity rate parameters for our hazard model than used in previous studies to recognise the proximity of Auckland to more active seismic areas to the east and south. We emphasise, however, that the computation of seismicity rate parameters for Auckland is based upon a very small dataset. The inclusion or removal of a few moderate magnitude earthquakes, or altering the area over which the earthquakes are gathered, can result in large changes in the calculated seismicity rate parameters and consequent estimates of average return times for shaking intensities.

The results from our uniform hazard model showed that the offshore Kerepehi fault event scenario produces lower accelerations than required to represent 1000–2000 year return period motions in central Auckland. To obtain contenders for alternative scenarios, we decided to analyse the mix of events contributing to the 1000 year and 2000 year motions. The outcome was that the magnitude range 5.8–6.4 at distances of less than 20 km was assessed as the primary contributor to the 2000 year motions. The analysis also showed that the contribution to the 2000 year motions from this combination of magnitude and distance ranges came at a level about 0.8σ above the mean level of the attenuation expression, an enhancement of about 50% over the mean PGA. As a candidate for a scenario event, magnitude 6.0 at a depth of 10 km at an epicentral distance of 20 km gives a mean PGA on standard soil of 0.17g, enhanced to 0.26g, approximately the target value for a 2000 year return period shaking in Auckland city, when account is taken of the variability in the attenuation.

We examined a number of possible locations for a magnitude 6 earthquake 20 km from downtown Auckland city (Figure 9), and judged that a location 20 km due east of Auckland is a reasonable scenario. The higher accelerations lie mainly offshore, with the 2000 year return period ground motion values being achieved in a band from central Auckland along the southern motorway.

One disadvantage of this scenario is that the Waitakere Ranges, which are important for the Lifelines study as the location of several water supply dams and pipelines, have PGAs of only ~0.1–0.05g for "standard soils", less than the target value. This shows a disadvantage of the scenario approach. Unless the hazard is governed by a single major source, the selected scenario event cannot satisfy the target ground motions everywhere. For an exercise that concentrates on the Waitakere facilities, it may be appropriate to develop another similar scenario in which the target PGAs are satisfied in the Waitakere region rather than in downtown Auckland.

3.0 RESULTS

3.1 MM INTENSITY AND PGA MAPS ACCOUNTING FOR SOIL CONDITIONS

Once the appropriate scenario earthquake was agreed upon, detailed PGA (Maps 1a, 1b) and MM intensity maps (Maps 2a, 2b) for the scenario event were developed. These maps include variations in ground motion based upon the soil characterisation zonation developed for the Auckland region (Appendix IV).

Modification factors developed from research in California have been used to assess appropriate PGA scaling factors for the Auckland soil characterisation zones. A GIS approach has been used to combine the modified Auckland Ground Shaking Hazard Map with the New Zealand attenuation model and these PGA scaling factors (Appendix IV).

To generate maps for the Lifelines study regions PGA values developed from the attenuation model were determined for a grid with spatial resolution of 100 m. Shaking intensity was determined by overlaying attenuation grids for each soil class grid and then selecting the shaking value from the attenuation grids based on the soil class grid. A scenario earthquake location 20 km due east of Auckland results in the highest accelerations offshore, with an area from downtown Auckland City and along the southern motorway having similar PGA values at about 0.15–0.25g.

A similar approach has been used for MM intensities. The distribution of MM intensities for "average" (firm to stiff) soil conditions was produced using the Dowrick (1992) MM intensity attenuation model that was developed from New Zealand data, and then modification factors derived from the Californian work of Borcherdt and others used to produce MM Intensities maps reflecting soil conditions in Auckland (Appendix IV).

PGA and MM Intensity maps have been developed at scales of 1:100,000 for Region A (Maps 1a, 2a) and 1:250,000 for Region B (Maps 1b, 2b).

Note that for the purposes of this report, these maps have been reproduced at scales of 1:200 000 (Region A) and 1:500 000 (Region B).

4.0 CONCLUSIONS

The Kerepehi fault about 45 km east of downtown Auckland city is the nearest known active fault capable of generating large earthquakes in the Auckland region (Figure 10). Calculation of earthquake shaking in terms of PGA and MM intensity indicates that the level of ground shaking from the Kerepehi fault earthquake in the Auckland Engineering Lifelines study regions is equivalent to that expected with about a 500 year return period, when all sources of earthquake shaking are considered. Thus, the Kerepehi fault earthquake scenario is not sufficient to represent accurately the earthquake ground motions expected at about a 2,000 year return period.

We have selected a scenario earthquake suitable for the Lifelines project based on a hazard model developed from two seismic source regions around the greater Auckland area, New Zealand-based PGA and MM intensity attenuation functions (with variability) and inclusion of large earthquakes from the Kerepehi fault. This hazard model indicates that PGA values of 0.15–0.25g and MM intensities of MM 7–8 can be expected at a 2000 year average return period in Lifelines Region A. Based on the contribution from different size earthquakes to this shaking hazard, a magnitude 6 earthquake 20 km east of downtown Auckland city provides the most reasonable scenario earthquake for the purposes of the lifelines study that focuses on infrastructural assets in Auckland city and along the southern motorway.

Only limited data are available to characterise the soil conditions with regard to their potential to amplify ground shaking at low to moderate accelerations. Overseas models have been used extensively in this study to allocate amplification factors for both PGA and MM intensity in the four soil types mapped in the Lifelines study regions. While more data would act as a useful check for our amplification factors, we believe comparisons to overseas models are adequate for this lifelines study.

We believe that in this initial stage of the Auckland Engineering Lifelines Project involving response planning for networks or facilities at a number of locations, we have developed a distribution of ground motions representative of those expected with an average return period of about 2000 years. The scenario approach recognises that similar levels of earthquake motion with a long average return period are unlikely to occur together at a series of sites across a region. The earthquake shaking intensities and uniform hazard model results developed for this study are suitable only for the Auckland Engineering Lifelines Project and its associated liquefaction and earthquake-induced slope instability hazard assessments;, and are not a substitute for site-specific earthquake hazard investigations.

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Table 1: Ground shaking hazard zones and soil classification table

Hazard Zone	Soil Foundation Condition	Soil Category	Engineering Description of Soils/Rock	SPT Blows/300mm (N)	Shear Wave Velocity (m/s)[1]	Typical Ground Failures Resulting From Earthquakes
1	*Residual Soil Overlying Rock*	Residual and colluvial soils, ash and weathered tuff: • up to 30m, overlying greywacke; • up to 20m overlying interbedded sandstone and mudstone; conglomerate and basalt	• CW:[2] sand/silt/clay • HW: gravel in a silty sand/clay matrix • MW: very weak rock • SW-UW: weak to moderately strong rock	5 - 25+ 15 - 50+ 30 - 100+ 50 - 200+	100 - 300 200 - 500 300 - 1000 500 - 2000	• Generally minor to nil damage to gentle slopes; • Movements on critically steep slopes, and on gentle slopes in sandstone and mudstone with clay seams, undercut by streams and coastal erosion.
2	*Firm to Stiff Sediment of Pleistocene age*	• Alluvium; • Basalt, ash and tuff overlying alluvium	• Soft to very stiff alluvium; • Sensitive pumiceous silt; silt, peat and clay; • Loose to dense sand and breccia; • Ash, tuff and basalt overlying these deposits	5 - 25[3]	100 - 300	• Widespread failure of coastal cliffs and river banks; • Movement on moderate to steep slopes; • Localised liquefaction of saturated loose sand lenses in severe[4] shaking
3	*Coastal Deposits*	• Beach and dune sands; • Man-made fills overlying zone 1 or 2 deposits	• Medium dense fine sand and shell, saturated; • Loose fine sand, unsaturated	5 - 40	100 - 500	Localised liquefaction of saturated loose sand pockets
4	*Estuarine Deposits of Holocene age*	• Stream alluvium and swamp deposits; • Man-made fills overlying zone 3 or 4 deposits	Very soft to stiff mud, silt, peat, pumiceous clay; typically saturated	0 - 10	50 - 200	• Widespread sliding failures of moderate slopes; • Widespread liquefaction of saturated sand deposits in moderate shaking

(1) Values of shear wave velocity are assessed
(3) Where basalt rock overlies deep alluvium, the rock stiffness does not significantly influence site behaviour
(4) Shaking levels:
Severe ≥ 0.40g ≥ Strong 0.20g ≥ Moderate 0.15g ≥ Moderate to Low 0.1g ≥ Low 0.05g

(2) Rock Weathering Grades:
CW completely weathered; HW highly weathered (soil)
MW moderately weathered (very weak rock)
SW slightly weathered; UW unweathered (rock)

APPENDIX I: GROUND SHAKING HAZARD ZONES

APPENDIX II: SEISMICITY AND ATTENUATION MODELS

II.1 Seismicity Models

In this section we outline in detail our procedure for developing models used in selecting an appropriate earthquake scenario for the Auckland Engineering Lifelines Project.

II.1.1 Distributed Seismicity

To develop an appropriate distributed seismicity model, the Institute's earthquake catalogue was searched for M_L 3.5 and greater earthquakes occurring from 1840 to the end of 1993 within approximately 100 km of Auckland (longitude 173.5° to 176°E, and latitude 36° to 38°S), and less than 40 km depth. The epicentres of 135 earthquakes were retrieved. The pattern of historical seismicity shows a distinct decrease in activity from east to west across the region, suggesting that the Coromandel and Kaimai areas are seismologically distinct from the Auckland area. The seismicity of the Coromandel region is also characterised by swarms of earthquakes typified by the temporal clusters of activity. While swarms like this have not been seen in the vicinity of Auckland, a swarm of earthquakes in Northland in 1956 (Eiby, 1964) is similar in character, and we assume earthquake swarms such as this could occur anywhere in the Auckland–Northland region. For example the Peria earthquake of 1963 was about M_L 4.9 (Eiby, 1964), and caused damage at MM 7 levels in a small area east of Kaitaia.

Seismicity rate parameters were calculated for the search area. These are approximately twice the rates obtained by Smith and Berryman (1992) for their Region A which includes all of the Northland Peninsula. Our assessment of the earthquake hazard in Auckland is influenced by the presence of M_L ³ 5 earthquakes in the catalogue from the offshore Coromandel area. Recent studies indicate that these events are deep earthquakes from near the Bay of Plenty region. As a sensitivity test we excluded the four M_L ³ 5 earthquakes from the catalogue and recalculated the seismicity rate parameters. Exclusion of these larger events results in few differences at small magnitudes, and larger differences in the M 5.5±0.3 and M 6.1±0.3 magnitude classes (the magnitude classes from which some earthquakes were excluded).

Our use of higher seismicity rate parameters than the average from the whole of the Northland Peninsula recognises that Auckland lies in the more active southern part of the zone, and the possible recurrence of earthquakes near M_L 6 such as the 1891, Waikato Heads earthquake. It must be emphasised, however, that the computation of seismicity rate parameters for Auckland is based upon a very small dataset. While we have not undertaken a formal sensitivity analysis, we have shown how accepting or rejecting just a few moderate magnitude events, or altering the area over which the calculations are made, can result in large changes in the calculated seismicity rate parameters and consequent estimates of average return times for shaking intensities.

Although there is considerable uncertainty in what seismicity rate parameters are appropriate for an earthquake hazard for this project, we emphasise that these rates are very low compared with Wellington, for example. The higher rates obtained for Auckland in this study are at most about 6% of Wellington seismicity rates.

II.1.2 Kerepehi Fault Earthquake

The Kerepehi fault is a NNW-striking normal fault that displaces basement greywacke rocks by about 2.5–3 km in the central part of the Hauraki lowlands (Hochstein et al., 1986). A surface scarp, often about 5 m high, displaces river alluvium deposited about 18,000 years ago. Unpublished paleoseismic studies of the Kerepehi fault indicate that the fault has several seismically active

segments, the southern most of which probably ruptured between 450 and 900 years ago. The central segment of the three that are mapped onshore ruptured more than 1800 years ago with at least 2 m of surface displacement, and on the two southern segments there is evidence for two surface rupture events in the past 18,000 years, resulting in an estimated average recurrence interval for each fault segment of 5,000 to 8,000 years.

We have assumed that the unnamed fault mapped by Hochstein et al., (1986) in the Hauraki Gulf is a northern active segment of the Kerepehi fault, and that it has the same fault parameters as segments of the fault studied onshore further south. Based on the onshore segment length of 25 km, NW strike and 4 km easterly stepover distance between segments, we continued the Kerepehi fault offshore to a point where it was closest to the Lifelines study area. The parameters used to calculate the probable PGA and MM intensities from the Kerepehi fault scenario event are given below.

Fault segment length	25 km
Fault depth (h_c)	12 km
Average slip/event	2.5 m
Average recurrence interval	5,000 yrs
Fault type	Normal
Fault dip	60°SW
Magnitude	M_W 6.9
Closest distance from Auckland (downtown) (r)	43 km

II.2 Attenuation Models

In this section we outline models for the attenuation of peak horizontal ground acceleration (PGA) and Modified Mercalli Intensities (MM) away from the earthquake source.

II.2.1 Peak Horizontal Ground Acceleration

Peak horizontal ground accelerations have been estimated in this study using an preliminary model developed recently (February 1997) by the Institute of Geological and Nuclear Sciences. The model is based on 461 acceleration records from 51 New Zealand earthquakes, supplemented by 66 overseas records at distances of 10 km or less from the source for which there are no New Zealand data. For the range of magnitudes and distances relevant to estimating the seismic hazard in central Auckland, where there are no major faults giving rise to large magnitudes at short distances, this model is recommended as more appropriate than those based purely on overseas data.
The peak horizontal ground acceleration expression is:

$$\log_{10}PGA = 0.326\, M_W - 1.57 \log_{10} (r^2 + 19^2)^{1/2} + 0.00593\, h_c - 0.488 + k\, \sigma \log10PGA \quad (1)$$

$$\sigma \log10PGA = 0.236$$

PGA is the stronger of two orthogonal horizontal components of peak ground acceleration, in units of g, M_W is moment magnitude, r is the shortest distance in kilometres from the source to the site of interest, h_c is the centroid depth of the rupture volume, $\sigma \log_{10}PGA$ is the standard deviation, and k is the number of standard deviations from the mean value for which the expression is evaluated.
The PGA study has now been completed (Zhao et al, 1997) resulting in an attenuation expression that is different from that used here, but which gives similar PGA values for shallow earthquakes.
In developing the model, the data were divided into that from "soil" sites, taken as those having soil deposits greater than 3m thick, and "rock" sites. The expression given above is for "soil" sites, and in this study has been used directly to estimate peak ground accelerations for Hazard Zone 2, Firm to Stiff Sediment of Pleistocene Age, and Hazard Zone 3, Coastal Deposits. These site conditions are

referred to as "standard soils". Peak horizontal accelerations for the other hazard zones have been estimated using modification factors based on studies in the Unites States (see Section IV.1.3).

II.2.2 Modified Mercalli Intensities

Modified Mercalli Intensities have been estimated using an attenuation model developed from New Zealand intensity maps by Dowrick (1991, 1992):

$$I = 2.18 + 1.411\, M_S - 0.00439\, r - 2.709\, \log_{10} r + k\, \sigma_I \qquad (2)$$

$$\sigma_I = 1.0$$

The MM intensity σI is given as a function of surface wave magnitude M_S, the shortest distance r in kilometres from the site to the rupture surface at centroid depth, σ_I is an assumed standard deviation of the attenuation expression, and k is the number of standard deviations from the mean value for which the expression is evaluated. The above expression applies for normal and strike-slip earthquakes, and is appropriate for the Auckland region.

The site conditions for which the model applies correspond to those for which isoseismals are mapped. In this study, it is assumed that Hazard Zones 2 and 3 correspond to these conditions. Modification factors derived in other Californian studies are used to estimate MM intensities for the other Hazard Zones (see Section IV.1.4)

APPENDIX III: DEVELOPMENT OF EARTHQUAKE SCENARIO

In this section we describe the steps by which the two possible earthquake scenarios — an offshore earthquake generated by movement along the Kerepehi fault and a local non-fault related earthquake — were evaluated.

III.1 Uniform Hazard Peak Ground Accelerations and Intensities

Peak ground accelerations (PGAs) and Modified Mercalli intensities (MM Intensities) were estimated for Auckland for return periods of 150 years (PGA only), 500 years, 1000 years and 2000 years. These values were estimated by combining the seismicity model discussed in Section II.1 with the attenuation models of Section II.2. The seismicity affecting Auckland was represented by two distributed seismicity source zones, for Auckland and Coromandel, and two fault source zones for offshore segments of the Kerepehi fault.

Results for central Auckland city, are summarised in Table III.2. The table lists "deterministic" and "probabilistic" estimates, that is neglecting and including the variability in the attenuation models respectively. The preferred estimates are the probabilistic results including variability. The results for deterministic attenuation (i.e. zero variability) are included because they are used below in selecting scenario events that produce PGAs in central Auckland that correspond approximately to the 2000 year values. The effect of the Kerepehi fault segment(s) is indicated by showing results with and without the fault taken into account.

The intensity results are given for two values of standard deviation for the attenuation model. Dowrick (1991) prefers a standard deviation of $\sigma_I = 0.5$. This value corresponds to that obtained when intensity is regressed against mean isoseismal radius. However, the distance from the source to a given isoseismal typically contains considerable scatter, and this contribution to the standard deviation from the scatter of individual values of radii about their mean value for a particular isoseismal map is neglected in the regression against mean isoseismal radius. For estimating individual intensity values at a given distance, this neglected part of the variability may be important. Seismic hazard estimates are often very sensitive to the standard deviation used, with this parameter sometimes having a greater effect on the results than the differences in the estimates of the mean values. Accordingly, a value of $\sigma_I = 1.0$ has been used for most of our results in this study. This value gives an amount of scatter generally consistent with that in the PGA models.

Table III.2a: PGA estimates for central Auckland

	Return Period 150 year		Return Period 500 years		Return Period 1000 years		Return Period 2000 years	
	Det.	Prob.	Det.	Prob.	Det.	Prob.	Det.	Prob.
With Kerepehi Fault	0.08	0.11	0.12	0.17	0.15	0.22	0.17	0.28
Without Kerepehi Fault			0.11	0.17	0.14	0.21	0.17	0.26

Table III.2b: MM intensities estimates for central Auckland

Return Period	500 years			1000 years			2000 years		
σ_I	0.0[1]	0.5	1.0[2]	0.0	0.5	1.0	0.0	0.5	1.0
with fault	6.7	–	7.4	7.1	–	7.8	7.4	–	8.2
no fault	6.5	6.7	7.3	6.9	7.1	7.7	7.3	7.5	8.1

Notes:

1. $\sigma_I = 0.0$ is the deterministic case
2. $\sigma_I = 1.0$ is the value used in this study for the mapped intensities

The 500 year return period PGA estimated for Auckland, including variability, is 0.17g. This is reasonably consistent with the results of a nationwide seismic hazard study (Matuschka et al., 1985) that was used to determine the zone factor in the current New Zealand Loadings Standard, NZS4203:1992. The results of Matuschka et al. gave a value of approximately 0.45g for the 450 year return period 5% damped spectral acceleration at 0.2s, $SA_{450\ yr}(0.2s)$. This corresponds to a PGA of about 0.18g, as there is a factor of approximately 0.4 to go from SA(0.2s) to PGA. The code zone factor Z nominally corresponds to $SA_{450\ yr}(0.2s)$, but at 0.6 is somewhat larger for Auckland than the value estimated by Matuschka et al., and corresponds to a PGA of about 0.24g.

The 2000 year return period PGA estimated for Auckland, including variability and the contribution of the fault, is 0.28g. This is the target PGA for the scenario event, for which a 2000 year return period value has been selected, as discussed in Section III.3

The effect of the Kerepehi fault on the estimated 500 year and 2000 year return period PGAs for central Auckland is slight. Without the fault taken into account, the 500 year PGA reduces from 0.174g to 0.166g, and the 2000 year value from 0.276g to 0.261g. The fault is too distant from central Auckland to have a significant effect in terms of PGA according to the attenuation model used in this study.

Modified Mercalli intensities for central Auckland are estimated as 7.4 and 8.2 for 500 year and 2000 year return periods respectively, taking account of variability in the attenuation model and the effect of the fault. Ignoring the contribution of the faults reduces the two intensity estimates by only about 0.1 unit.

Maps of the MM Intensities and PGA distributions for "standard soils" for return periods of 500 years and 2000 years with and without the offshore segments of the Kerepehi fault are shown in Figures 1–8. A feature is the fairly uniform distribution of intensities and PGAs across the region for both return periods. The higher seismicity in the Coromandel region and the presence of the Kerepehi offshore fault segment to the east of Auckland produces a slight reduction in the MM Intensities and PGAs from east to west, but only by modest amounts. The inclusion of the fault segment produces a slight shift towards the west of the contours, with a westwards bulge in the contours in the region adjacent to the centre of the fault segment. With the offshore fault segment included, the 2000 year PGA map shows an additional contour, at 0.4g, around the fault. For the other maps, the increased hazard in the immediate vicinity of the fault is less than the resolution of the contours for the mapped return periods of 500 and 2000 years. Even at 2000 years return period, the fault has only a minor effect, including in its immediate vicinity, as the average recurrence interval modelled for the fault earthquakes, taken as magnitude 6.9, is 5000 years.

Although the PGA and MM Intensities distributions for the Auckland region for return periods of 500 years and 2000 years are reasonably uniform, it must be emphasised that for any particular earthquake there will in general be a rapid reduction in strength of shaking away from the source, although modified by local amplification. The uniform hazard estimates corresponding to a given return period combine the estimated effect of all possible earthquakes and their probabilities of occurrence. For widely separated sites, the mix of earthquakes contributing to their hazard will be different. Although their level of hazard for a given return period may be similar, in any given earthquake the strength of shaking at the two sites is likely to be quite different. It is unlikely that the 2000 year return period values will be realised together at two widely separated sites in a single earthquake.

III.2 Scenario Versus Uniform Hazard Approaches

The difference in the distribution of shaking for a single earthquake event and for a given return period raises questions as to which is the relevant approach for estimating hazard for a particular purpose: a scenario or a return period approach.

In some studies, it is the level of hazard that is relevant. This may be the case in selecting levels of earthquake motion for engineering design. Even then, often a dual approach is taken for critical structures. In this approach, earthquake shaking motions for a selected return period are estimated as the basis for design, but the uniform hazard results are anchored to a particular scenario earthquake that gives rise to this level of motion. The purpose of this approach is to provide a physical realisation of the type of earthquake corresponding to the particular return period.

For response planning in this initial stage of the Auckland Engineering Lifelines Project involving networks or facilities at a number of locations, a scenario approach is more appropriate. The scenario approach recognises that levels of earthquake motion with a long return period are unlikely to occur together at a series of sites across a region unless very large magnitude events with recurrence intervals of no more than a few thousand years occur — a case that will be revealed by an appropriately chosen scenario, and which is not appropriate for Auckland. For central Auckland, the offshore extension of the Kerepehi fault is likely to produce the largest magnitude earthquake possible in the region, but it is necessary to determine whether the effects of this source do in fact dominate throughout the Auckland region at long return periods. A drawback with the scenario approach is that there may be several scenarios that match the target motions at one locality, but give very different levels of motion elsewhere. The selection of one particular scenario becomes subjective.

III.3 Selection of Scenario Event

In this section we outline the process for the development of scenarios to match the 2000 year return period PGAs for Auckland. Of the possibilities, one particular scenario is developed in detail as the basis for a response planning exercise for the Auckland Engineering Lifelines Project, but sufficient information is given to allow planners to judge whether other possible scenarios are perhaps more relevant for their purposes.

Our brief defined the scenario to be developed for the Auckland Engineering Lifelines Project; as follows:

"The seismic event for analysis is defined as a 2000 year return period event earthquake on the Kerepehi Fault at its closest point to Auckland (however this event may need to be modified to a return period considered more appropriate after an initial assessment)".

As a first step, peak horizontal ground accelerations and Modified Mercalli intensities were estimated for the Kerepehi fault offshore extension scenario earthquake described in Section II.1.2. The results for the "soil" class of the PGA model and for MM Intensities are assumed to apply for Hazard Zones 2 and 3, referred to as "standard soils". The justification for selecting these Hazard Zones as having site conditions equivalent to those for which the attenuation models apply is given in Section IV.1.2, in the discussion of amplification of ground motions.

The offshore Kerepehi fault scenario is a magnitude M_W 6.9 earthquake on a fault at a shortest horizontal distance of 43 km from downtown Auckland. The scenario was estimated as having an average recurrence interval of about 5000 years. This recurrence interval is longer than the target return period for the motions of 2000 years, but may still lead to 2000 year return period motions when the contribution of other earthquake sources is added. For the initial assessment, the earthquake ground motion estimates correspond to the mean values given by the attenuation models, i.e. with k=0 in equations (1) and (2).

A magnitude 6.9 earthquake on the offshore extension of the Kerepehi fault gives a mean PGA of 0.15g on soil in central Auckland city.

The 500 year, 1000 year and 2000 year return period probabilistic hazard PGAs for standard soil in central Auckland were found to be 0.17g, 0.22g and 0.28g, which are in excess of the mean PGA of 0.15g for the Kerepehi fault offshore segment scenario.

These results suggest that the offshore Kerepehi fault event scenario produces lower accelerations than required to represent 1000–2000 year return period motions in central Auckland. One possibility is to take motions from the offshore Kerepehi fault event at more than their mean level e.g. at their mean + σ levels, but this is not felt to be justified given the long average recurrence interval estimated for rupture of the offshore segment of the Kerepehi fault. It seems that another scenario is required to represent approximately 2000 year return period motions for central Auckland.

To obtain contenders for alternative scenarios, it was decided to analyse the mix of events contributing to the 1000 year and 2000 year motions. The outcome was that the magnitude range 5.8–6.4 at distances of less than 20 km was assessed as the primary contributor to the 2000 year motions. The analysis also showed that the contribution to the 2000 year motions from this combination of magnitude and distance ranges came at a level about 0.8σ above the mean level of the attenuation expression, an enhancement of about 50% over the mean PGA. As a candidate for a scenario event, magnitude 6.0 at a depth of 10 km at an epicentral distance of 20 km gives a mean PGA on standard soil of 0.17g, enhanced to 0.26g, approximately the target value, when account is taken of the variability in the attenuation.

Because of the different attenuation models used for intensities and PGA, it is possible that a scenario event that produces the 2000 year PGA in central Auckland may not produce 2000 year intensities. This is the case in this study. A magnitude 6.0 earthquake at 20 km at the mean + 0.8σ level produces an MM intensity of MM 7.5 for Hazard Zone 2 and 3 site conditions, while the 2000 year value from the distributed model is ~MM 8. The scenario event produces 2000 year return period PGAs in central Auckland city, but only about 1000 year return period intensities.

For the scenario approach, the placement of the event will have an effect on the Lifelines study. Three possible options are: (i) to perform lifeline analyses for several event locations; (ii) to consider a location that is likely to be more critical for overall facilities; (iii) to select a locality that gives reasonably uniform accelerations over the more densely populated areas, but does not place accelerations significantly in excess of the 2000 year return period values at any locations of importance.

Alternative placements of the magnitude 6.0 scenario event, centred 20 km north, south, west or east of central Auckland, are shown in Figure 9. The locations north, south and west of Auckland have the problem that important parts of the region have very strong motions, up to 0.4g on the reference ground conditions of Hazard Zones 2 and 3, with associated return periods much longer than the target 2000 years.

A location 20 km due east of Auckland is suggested as a reasonable scenario, consistent with option (iii) above. The higher accelerations then lie mainly offshore, with the target values being achieved in a band from central Auckland along the southern motorway. One disadvantage is that the Waitakere Ranges, which are important for the Lifelines study as the location of several water supply dams and pipelines, have PGAs of only ~0.1–0.05g for "standard soils", less than the target value. This shows a disadvantage of the scenario approach. Unless the hazard is governed by a single major source, the selected scenario event cannot satisfy the target ground motions everywhere. For an exercise that concentrates on the Waitakere facilities, it may be appropriate to develop another similar scenario in which the target PGAs are satisfied in the Waitakere region rather than in downtown Auckland.
A summary of radii for various PGAs on standard soil at the mean + 0.8σ level for a 10 km deep magnitude 6.0 earthquake are: 0.35g at 11 km epicentral distance; 0.30g at 16 km; 0.25g at 21 km; 0.20g at 27 km; 0.15g at 35 km; 0.10g at 49 km; and 0.05g at 81 km.

III.4 Selection of Scenario Event to Represent 2000 Year PGAs in Central Auckland

To obtain contenders for alternative scenarios, we analysed the mix of earthquake events contributing to the 1000 year and 2000 year motions for central Auckland. PGA values given in this Appendix for various return periods differ slightly from those in the body of the report, in that at the time that these calculations were performed, a slightly different attenuation model than that finally adopted was used, and the effects of the offshore segments of the Kerepehi fault were not included in the return period calculations. These differences are unlikely to alter the results relating to the mix of magnitudes and distances making up the 2000 year return period motions for central Auckland to any significant extent.

From the information available in the computer printouts from the hazard calculations, it is easier to determine the mix of earthquakes contributing to a given level of hazard when the attenuation model is used deterministically rather than when the variability in attenuation is included i.e. using only mean value PGAs for various magnitude and distance combinations rather than taking account of the full probabilistic distribution of PGA values. There is an approximate relation between the results of a deterministic and fully probabilistic analysis for uniformly distributed seismicity (Bender, 1984). This relationship is applicable in the Auckland Engineering Lifelines study because the hazard results are dominated by the contributions from the uniformly distributed seismicity of the Auckland source zone. The approximate relation gives the "probabilistic enhancement" factor for PGA as a factor of $\exp[2.3^2 b\sigma^2_{\log 10 PGA}/2c]$, where b is a parameter of the Gutenberg-Richter frequency magnitude relation

$$\log_{10} N(M) = a - bM$$

c is the magnitude coefficient in the attenuation relation

$$\log_{10} PGA = cM + \text{Function (distance)}$$

and $\sigma_{\log 10 PGA}$ is the standard deviation of the attenuation relation.

For the Auckland region, b ~0.9, c ~0.3 and $\sigma_{\log10PGA}$= 0.23, leading to an enhancement factor of 1.52. For the deterministic analysis, the 500 year, 1000 year and 2000 year PGAs for central Auckland in the initial analysis were 0.12g, 0.15g and 0.18g respectively. The ratios of the fully probabilistic results to deterministic values were 1.45, 1.50 and 1.54 for 500 years, 1000 years and 2000 years respectively, in reasonable agreement with the enhancement factor approach.

From the deterministic analysis, 42% of the contribution to the 1000 year motions came from magnitude 5.2-5.8 events at distances of less than 15 km from central Auckland, 36% from magnitude 5.8-6.4 events at distances of less than 25 km and 22% from magnitude 6.4-7.0 events at distances of less than 36 km. Smaller magnitudes and greater distances did not contribute. For the 2000 year motions, the mix of contributions was slightly different: 32% from magnitude 5.2-5.8 events closer than 9.5 km, 41% from magnitude 5.8-6.4 events at distances of less than 20 km, and 27% from magnitude 6.4-7.0 events at distances less than 30 km. None of these contributions change for the final model, although the PGA values for a given return period or magnitude-distance combination change slightly.

These analyses suggest events in the M 5.2-5.8 range as candidate scenarios for 1000 year motions: for the initial attenuation relation, M 5.5 at 15 km distance gave a mean PGA of 0.145g, while M 5.75 at 20 km gave a mean PGA of 0.148g, essentially the target values for mean PGAs. The probabilistic enhancement raised these values by a factor of about 1.5, corresponding approximately to mean + 0.8σ values. The probability of exceeding the mean value in any given event is 0.5, while the probability of exceeding the mean + 0.8σ value is about 0.2.

In the estimation of the 2000 year motion, slightly larger magnitudes were found to be the primary contributor, namely the M 5.8-6.4 range at distances of less than 20 km. M 6.0 at 20 km gave a mean PGA of 0.176g, the target value, again enhanced by about 50% to 0.27g taking account of the variability in the attenuation.

The detailed breakdown of contributions by magnitude and distance, with the PGA attenuation expression used deterministically is given below. These contributions are unchanged for the final model.

From programme printout:

No. of events magnitude 4.0-4.6 per year=0.168
No. of events magnitude 4.6-5.2 per year= 0.0490
No. of events magnitude 5.2-5.8 per year = 0.0140
No. of events magnitude 5.8-6.4 per year = 0.0042
No. of events magnitude 6.4-7.0 per year = 0.0007

Without variability, 2000 year PGA = 0.178g (reduces slightly to 0.173g in final model).
This value exceeds the mean PGA for the magnitude 4.0-4.6 and 4.6-5.2 ranges at all distances. It is exceeded by other magnitude ranges at the distances shorter than the following:

M 5.2-5.8 < 10 km
M 5.8-6.4 < 20 km
M 6.4-7.0 < 30 km

The annual frequency of events in these magnitude and distance classes can be found by taking the total numbers in the magnitude ranges in the Auckland region multiplied by the ratio of the areas of the circles to the total area of the source region.

Thus:

N (M 5.2-5.8 < 10 km) = 314/22567 x 0.0140 = 0.000195 yr (return period 5130 yr)
N (M 5.8-6.4 < 20 km) = 1257/22567 x 0.0042 = 0.000234/yr (return period 4275 yr)
N (M 6.4-7.0 < 30 km) = 2827/22567 x 0.0007 = 0.000088/yr (return period 11400 yr)
Total : 0.000517/yr, return period 1930 yr
(= target value of 2000 yr to accuracy of calculations)

From these results, the biggest contribution comes from the magnitude 5.8-6.4 range at distances less than 20 km.

Magnitude 6.0 at 20 km gave a mean PGA of 0.176g according to the attenuation model used in this stage of the study, increasing to 0.269g at the mean + 0.8σ level. For this model, the mean PGA in central Auckland from the offshore segment of the Kerepehi fault was 0.133g. In the final model, the corresponding values for the magnitude 6.0 scenario event at 20 km epicentral distance were 0.167g and 0.258g, compared to 0.148g for the mean PGA of the Kerepehi offshore segment scenario.

Although the probabilistic enhancement factor approach leads to the correct results in terms of the hazard level for a given return period, the mix of events from probabilistic calculations will be different. As the target PGA level corresponds approximately to the mean plus 0.8σ level of the attenuation expression for the above events, and the probability of exceedance of the mean plus 0.8 is only about 0.2, the classes of events listed above reach this level with a combined frequency of only about 0.0001 per year, rather than the required frequency of 0.0005 per year. The shortfall is made up by contributions from other magnitude and distance combinations at PGA levels that are more than 0.8σ above their mean. The relative frequency of small magnitude events means that they are likely to contribute most of the shortfall.

However, the mix of events given by the deterministic analysis leads to a physically reasonable scenario. Taking a small magnitude event at a level several standard deviations above its mean value, which may well be the outcome suggested by the largest contributor to a fully probabilistic analysis, is less appealing as a scenario event. It will also produce the target ground motions only over a very localised area.

We note that if a similar analysis was performed in terms of MM intensities, a somewhat different mix of events contributing to the 2000 year motions may be derived. Thus while the related scenario gives PGAs corresponding to 2000 year return period values for central Auckland city, the intensities from the scenarios are less than 2000 year values in central Auckland, corresponding approximately to the 1000 year value. This occurs because there is not a one-to-one correspondence between intensity and peak acceleration.

Appendix IV: Earthquake Shaking from the Scenario Earthquake

In this section we discuss the detailed scenario for the placement of a magnitude 6.0 earthquake 20 km due east of Auckland. Earthquake ground motions in terms of PGAs and MM Intensities are estimated taking into account the mapped site conditions, modifying the estimates that come directly from the PGA and MM Intensities intensity models by empirical site factors that have been developed in overseas studies.

IV.1 Model for Amplification of Ground Motions in the Auckland Region

The ground condition zoning of the Auckland region has led to four Hazard Zones in terms of site conditions (Williams and Hull, 1997; Appendix 1). To determine appropriate modifications of the results of the PGA and MM Intensities attenuation models to account for site conditions, it is necessary to select a model relating relative earthquake responses to site conditions, and to assign equivalences between the site conditions of the four Hazard Zones for Auckland and the site classes used in the site response model.

The New Zealand PGA attenuation studies differentiate only between "rock" and "soil" site conditions. "Rock" is a subgroup of those sites satisfying site subsoil category (a) (Rock or very stiff soil sites) of the New Zealand Loadings Standard NZS4203:1992, namely rock outcrop sites, or sites with no more than 3 metres of soil overlying rock. All other subsoil category (a), (b) and (c) sites of NZS4203:1992 are treated as "soil sites" in the PGA attenuation expression. In developing the attenuation expression, a variety of other site classes were considered, but there was found to be no statistically significant difference in the site effect term for these classes from that for the "soil" class. This does not necessarily mean that all "soil" sites will produce the same PGAs, but rather that there was insufficient data in our study to determine statistically significant differences.

The MM Intensities attenuation study did not distinguish between site conditions, in that it was concerned only with an analysis of mapped isoseismals. Isoseismal maps do not give indications of site conditions.

Over recent years, there has been much research in the United States on the development of site response factors for various site conditions. We have made use of two of those models in this study. Borcherdt (1991, 1994, 1996) has developed a model based on a combination of relative site responses in the Loma Prieta earthquake, and weak-motion responses in the San Francisco and Los Angeles reasons from nuclear test blasts in Nevada. The results of Borcherdt's work and others have been used by a National Earthquake Hazards Reduction Program (NEHRP) MM Intensities to develop new site classifications and associated response factors for the next generation of United States earthquake design codes (Crouse and McGuire 1996).

Table IV.3: Borcherdt's site classes

	Mean Shear-Wave Velocity V_{30}(m/s)		
	Min	Ave	Max
SC-Ia HARD ROCKS e.g. metamorphic rocks with very widely spaced fractures	1400	1620	
SC-Ib FIRM to HARD ROCKS e.g. granites, igneous rocks, conglomerates, sandstones, and shales with close to widely spaced fractures	700	1050	1400
SC-II GRAVELLY SOILS and SOFT to FIRM ROCKS e.g. soft igneous sedimentary rocks, sandstones, and shales, and soils with > 20% gravel	375	540	700
SC-III STIFF CLAYS and SANDY SOILS e.g. loose to very dense sands, silt loams and	200	290	375

sandy clays, and medium stiff to hard clays and silty clays (N > 5)			
SC-IVa NON SPECIAL-STUDY SOFT SOILS e.g. loose submerged fills and very soft to soft (N < 5) clays and silty clays 5-37m thick	100	150	200
SC-IVb SPECIAL-STUDY SOFT SOILS e.g. liquefiable soils, quick and sensitive clays, peats, highly organic clays, very high plasticity clays (PI>75%), and soft soils more than 37m thick			

Initially we proposed to use the Borcherdt model for the current study. However, in applying the model, which accounts for nonlinear soil response through amplitude-dependent response factors, it became apparent that the amount of nonlinearity for one of the Borcherdt classes, SC-III, that corresponds to two of the Auckland Hazard Zones (see Section IV.1.2) was greater than suggested by site responses in the Northridge earthquake, a point that has been acknowledged by Borcherdt (1996) in an evaluation of his model against Northridge earthquake data. Accordingly, it was decided to use some site response factors from the more recent NEHRP study. The NEHRP study uses similar site classifications to Borcherdt, and gives similar site response factors in low- to moderate-amplitude shaking , but predicts less nonlinearity at high amplitudes. Site modifications for intensities are not specified in the NEHRP study, so use has been made of the Borcherdt values. Also, it was judged that one of the Auckland hazard classes corresponds to a site condition for which response factors are specified by Borcherdt but not in the NEHRP study.

IV.1.1 Borcherdt Site Classifications

Borcherdt's site response factors were developed as a function of mean shear wave velocity to 30 m depth, V_{30}, defined as 30 m divided by the shear-wave travel time to that depth. In recognition that this parameter is often not available, Borcherdt used an extensive correlation between geotechnical descriptions of sites and measured V_{30} values to develop descriptive site classes when the shear-wave velocity is unknown. Borcherdt's site classes and their associated V_{30} ranges and mean values are given in Table IV.3.

The NEHRP study produced a site classification with very similar shear-wave velocity bounds to that of Borcherdt. The NEHRP site classes are listed in Table IV.4. In adapting the NEHRP site response factors for the Borcherdt site classes, NEHRP site classes A, B, C, D, E and F have been taken as equivalent to the Borcherdt classes Ia, Ib, II, III, IVa and IVb respectively.

IV.1.2 Proposed Borcherdt Classifications for Auckland Hazard Zones

To use the Borcherdt or NEHRP site response factors for the Auckland Lifelines study, it is first necessary to determine equivalences between the site conditions of the Auckland Hazard Zones (Table I.1) and the Borcherdt and NEHRP site classes (Table IV). The descriptions for each of the Auckland Hazard Zones, and their associated geotechnical properties, correspond to a wide range of site conditions, spreading over several of the Borcherdt and NEHRP classes. Accordingly, the approach taken has been to identify the predominant material in each of the hazard zones, and map the site responses corresponding to that predominant material. A series of notes are used to identify appropriate site response factors for other materials in each of the Hazard Zones.

IV.1.2.1 Hazard Zone 1: Residual Soil Overlying Rock

- For mapping site response amplitudes, treat as the SC-(II+III) combination used by Borcherdt to represent the S2 category of the earlier 1991 NEHRP Provisions and Uniform Building Code.
Classes SC-II and SC-III span the shear-wave velocity range, averaged to 30 m depth, V_{30}, of 200 to 700 m/s, with a value of 450 m/s used for amplification estimates for the combination.
The predominant material in this category is taken to be in the HW (highly weathered) category, gravel in a silty sand/clay mixture, with an assessed shear-wave velocity of 200-500 m/s. Class SC-(II+III) is appropriate to this description.

Table IV.4: NEHRP site classes

Site Class	Site Class Name /Generic Description	Site Class Definition
A	Hard Rock	V_{30}> 1500 m/s
B	Rock	760 m/s < V_{30} ^{3} 1500 m/s
C	Very Dense Soil and Soft Rock	360 m/s < V_{30} 760 m/s, or N > 50, or S_u> 100 kPa
D	Stiff Soil	180 m/s < V_{30} 360 m/s, or 15 ^{2} N^{3} 50, or 50 kPa ^{2} S_u ^{3} 100 kPa
E	Soft Soil Soft clay with soil profile	V_{30}< 180 m/s PI>20, w>40% and S_u< 25 kPa
F	Site specific geotechnical investigations and dynamic site response analyses. 1. Soils vulnerable to potential failure or collapse under seismic loading: (liquefiable soils, quick and highly sensitive clays, collapsible weakly-cemented soils, etc.). 2. Peats and/or highly organic clays: (H > 3m of peat and/or highly organic clay, where H = thickness of soil). 3. Very high plasticity clays: (H > 8m with PI > 75). 4. Very thick "soft/medium stiff clays" (H > 36m).	

The SW-UW (slightly weathered to unweathered) category , with shear-wave velocities assessed as 500-2000 m/s, in the main more appropriately fits the Borcherdt SC-Ib class (V_{30}=700-1400 m/s).
The MW (moderately weathered) category, very weak rock, in the main fits SC-(II+III), although the higher velocity end of its assessed shear-wave velocity range of 300-1000 m/s falls in the SC-Ib class.
The CW (completely weathered) category, sand/silt/clay, in the upper half of its 100-300 m/s shear-wave velocity range lies in the SC-III class, and in the lower part of its velocity range in the SC-IVa class. None of its velocity range overlaps with the SC-II range, so it seems unjustified to place it in the combined SC-(II+III) category. The 450 m/s average velocity for SC-(II+III) lies above the range for the CW category.

IV.1.2.2 Hazard Zone 2: Firm to Stiff Sediment of Pleistocene Age

-For site response mapping purposes, treat as SC-III Stiff Clays and Sandy Soils.

SC-III has a velocity range of 200-375 m/s. This class is applicable for: loose to dense sand and breccia; silt, peat and clay with N 5-25, i.e. in the firm to very stiff ranges; and stiff to very stiff alluvium.

Both soft alluvium with N=2-4 and firm alluvium with N=4-8 fit the SC-IVa class. Soft alluvium, for which N=2-4 in standard classifications, does not seem to be covered by the N range of 5-25.

Sensitive pumiceous silt belongs to SC-IVb, Special-Study Soft Soils.

Liquefiable materials belong in the SC-IVb, Special Study Soft Soils class.

Ash, tuff and basalt are difficult to classify; where there are only veneers over deeper deposits of other materials, they are perhaps best classified the same as their underlying materials.

IV.1.2.3 Hazard Zone 3: Coastal Deposits

- For site response mapping purposes, treat as SC-III, Stiff Clay and Sandy Soils.

SC-III covers the velocity range 200-375 m/s. This class is applicable in general for loose fine sand, N=4-10 and medium dense fine sand, N=10-30.

Lower velocities in the 100 m/s–200 m/s range, for which the SC-IVa class is appropriate, are possible in loose sand.

The higher velocity (375-500 m/s) end of the range for coastal deposits is generally beyond the sand range, corresponding more typically to gravelly sand. Velocities in this range correspond to the SC-II class.

Liquefiable materials belong in class SC-IVb, Special Study Soft Soils.

IV.1.2.4 Hazard Zone 4: Estuarine Deposits of Holocene Age

- For site response mapping purposes, treat as SC-IVa, Non Special-Study Soft Soils.

The 50-200 m/s velocity range specified for Class 4 corresponds closely to the range defined for the SC-IVa class. Liquefiable materials belong in the SC-IVb class, that requires special studies.

IV.1.3 Site Response Factors - PGAs

Both the Borcherdt and NEHRP models give site response factors with respect to a reference site condition in various period ranges. In this study, where we are interested in PGAs, a short-period measure of the strength of ground shaking, we use the short-period site response factors. The short-period range is stated by Borcherdt (1994) as 0.1–0.5s, and the amplification factors were evaluated from Fourier spectra, so the factors are not strictly applicable for PGAs, which correspond to the acceleration response spectrum values at zero second period. However, in the absence of similar studies for PGAs, the short period factors are taken as relevant to PGAs. The factors are reasonably consistent with results given in graphical form by Dickenson and Seed (1996).

The short period factors from the two studies are listed in Table IV.5 for various site classes (B, C, D and E for NEHRP; SC-Ib, SC-II, SC-III and SC-IVa for Borcherdt), with the approximately equivalent classes in the two classifications paired. The factors are a function of the strength of the reference class motions, with the reference class chosen as B and SC-Ib in the two cases. The factors are generally similar. For Hard Rocks (site factors not listed in Table IV.5), the site class A factors are consistently smaller than those for the SC-Ia class. The Hard Rock classification is largely

irrelevant for Auckland because it does not occur. The response factor for site class D reduces less rapidly with amplitude than that for site class SC-III, more in line with data from the Northridge earthquake where the effects of nonlinearity were less pronounced than suggested by the Borcherdt model. The variation of the NEHRP amplifications as a function of rock PGA are also more in line than those of Borcherdt with the results given in Figure 5 of Dickenson and Seed (1996) for PGA amplifications.

Table IV.5: Short-period amplification factors (with respect to classes B and SC-Ib)

PGA(g)	B	SC-Ib	C	SC-II	SC (II+III)[1]	D	SC-III	E	SC-IVa
0.1	1.0	1.0	1.2	1.3	1.4*	1.6*	1.6	2.5	2.0*
0.2	1.0	1.0	1.2	1.2	1.2*	1.4*	1.4	1.7	1.6*
0.3	1.0	1.0	1.0	1.0	1.0*	1.1*	0.9	0.9	0.9*
0.4	1.0	1.0	1.0	1.0	1.0*	1.1*	0.9	0.9	0.9*
0.5	1.0	NS[2]	1.0	NS	NS	10*	NS	(--)[3]	NS

Notes:

* Factors selected for mapping in this study.

1 Determined from amplification expression with respect to class SC-Ib given in Table 2 of Borcherdt (1994), with velocity of 450 m/s used for SC-(II+III), as specified in the same table.

2 NS = "not specified". Borcherdt does not give amplification factors for 0.5g rock motion.

3 Site-specific geotechnical investigations and dynamic site response analyses required for site class E at this level of motion.

The recent New Zealand PGA attenuation model (Zhao et al, 1997)provides some verification of the factors in Table IV.5. Conditions at rock sites in the New Zealand network most commonly correspond to the classes SC-II or NEHRP C, as they are usually weak and/or weathered. However the PGA dataset also contains records from stronger unweathered rocks, through to granites, corresponding to classes SC-Ia and SC-Ib of Borcherdt, or NEHRP A and B. Overall, this means that the "rock" category for the PGA attenuation expression corresponds on average to stronger rock than the SC-II or NEHRP C classes i.e. approximately SC-Ib or NEHRP B. The soil sites cover the range from SC-II to SC-IV, or NEHRP C to E, and perhaps a few examples of F. SC-III or NEHRP D are reasonable approximations to the average soil conditions, and are used as the reference category corresponding to standard soil conditions in this study.

The site factor in the Zhao et al. (1997) PGA attenuation model has been evaluated so far only as a constant, with no amplitude dependence. In the model used in this study it corresponds to an average ratio of 1.56 between the soil and rock PGAs. This rounds to 1.6, which equals the factor between PGAs for SC-III and SC-Ib or NEHRP D and NEHRP B in motions with accelerations of up to 0.1g on rock. This is believed to provide reasonable confirmation that the Borcherdt and NEHRP short-period amplification factors are relevant for New Zealand PGAs at low amplitudes (N.B. the mean PGA in the NZ soil site records is 0.06g).

Only three sets of factors from Table IV.5 are used in our mapping. The other columns are given to indicate appropriate values for those soils that do not fit the overall classification for their hazard zone, as detailed above.

For Hazard Zone 1, Residual Soil Overlying Rock, we have selected the Borcherdt combined class SC-(II+III) as most appropriate.

Hazard Zone 2, Firm to Stiff Sediment of Pleistocene Age, and Hazard Zone 3, Coastal Deposits, are mapped with the same set of site response factors, those for NEHRP class D, Stiff Soil. These are the "standard soils" to which the results of the PGA and MM Intensities attenuation models are taken to apply directly. The Borcherdt SC-III, Stiff Clays and Sandy Soils, classification is equally appropriate, but as discussed above, the NEHRP site response factors agree better with recent data from the Northridge earthquake in strong shaking. In low amplitude motions, up to rock motions of 0.2g, the factors for SC-III and NEHRP D are identical.

For Hazard Zone 4, Estuarine Deposits of Holocene Age, we have selected the Borcherdt SC- IVa factors. Recommendations for the NEHRP code subdivided class E into subcategories $E_1$and E_2, depending on the thickness of soft to medium stiff clay in the profile, but simplified this to a single class in the final code. The site factors of the final code correspond to the E1 values, while the E_2values were the same as for SC-IVa. Our reason for adopting the NEHRP factors in preference to the Borcherdt values for other hazard zones is because of their more linear behaviour with increasing amplitude. The equivalence of the SC-IVa and NEHRP E_2 values indicate that the SC-IVa values do not exhibit too much nonlinearity at large amplitudes. The Borcherdt values have been well verified in low levels of motion. Therefore, for Hazard Zone 4, we have retained the Borcherdt SC-IVa values, rather than those of the final NEHRP code that produce stronger amplifications for rock motions less than 0.3g.

The Borcherdt and NEHRP site response factors given in Table IV.5 are with respect to site classes SC-Ib and NEHRP B. As discussed above, these correspond approximately to the rock sites of the New Zealand PGA attenuation expression, while soil PGAs are judged as appropriate for site conditions corresponding to classes SC-III and NEHRP D.

It would seem appropriate then to evaluate the New Zealand PGA expression for rock, and then apply the amplification factors selected from Table IV.4 for other site conditions. However, the factors of Table IV.5 are amplitude dependent, while the site factor in the New Zealand PGA relation is a constant for all amplitudes. The soil PGAs in the dataset used to develop the attenuation relation ranged from 0.0005g to 0.58g from New Zealand data, and up to 0.98g in the overseas data used. Most of the rock PGAs were for lower amplitude motions in the PGA attenuation model, with the maximum New Zealand value of 0.21g.

We judge that the New Zealand PGA site factor is relevant for low- to moderate- amplitude motions, up to about 0.2g rock accelerations, for which it is consistent with the values from the Borcherdt and NEHRP studies. At higher amplitudes of motion, the New Zealand attenuation expression is likely to be more correct for soil than rock conditions, given that the soil data extend up to high amplitudes. It was decided to take the soil PGA expression as the reference, corresponding to site classes SC-III or NEHRP D, or Auckland Hazard Zones 2 and 3. Other PGAs are evaluated from their ratio to the SC-III/D values.

This is achieved by constructing in Table IV.6 equivalent PGAs for the various site classes and hazard zones from the amplifications given in Table IV.5. Piecewise linear interpolation is then used to convert PGAs from the attenuation expression for site classes SC-III/NEHRP D to equivalent values for other site conditions.

Table IV.6: PGA conversion table

Site Class i:	Ib	II	II+III	III	IVa
Hazard Zone:	-	-	1	2, 3	4
PGA range	PGA(g)				
j=0	0.0	0.0	0.0	0.0	0.0
j=1	0.1	0.12	0.14	0.16	0.20
j=2	0.2	0.24	0.24	0.28	0.32
j=3	0.3	0.33	0.33	0.36	0.36
j=4	0.4	0.40	0.40	0.44	0.36
j=5	0.5	0.50	0.50	0.50	NS[1]

1 NS = not specified

Intermediate PGAs in the range j to j+1 for site class i are derived from the PGA attenuation expression value PGA_{III} given for site class III using the interpolation:

$$PGA_{i,j\rightarrow j+1} = PGA_{ij} + (PGA_{III} - PGA_{III,j})/(PGA_{III,j+1} - PGA_{III,j}) * (PGA_{i,j+1} - PGA_{i,j})$$

The site classifications and PGA response factors used in the production of the hazard maps are summarised in Table IV.7.

IV.1.4 Site Response Factors - MM Intensities

There have been fewer recent studies on site response modifications for Modified Mercalli intensities than for instrumental measures of earthquake ground motions. The NEHRP study was performed for revision of United States loadings codes, where MM intensities are no longer a parameter.

Borcherdt (1991) gave some results for intensities at an early stage of his study. He gave a single expression for intensity modifications, with no amplitude dependence. The difference δI from standard intensities for a deposit with an average shear-wave velocity V_{30} was given by Borcherdt (1991) as:

$$\delta I = 0.27 + 2.70 \log AHSA$$

AHSA is the average spectral amplification over the period band 0.4–2.0s. Borcherdt expressed AHSA as a function of V_{30}, measured in m/s:

$$AHSA = 701/V_{30}$$

This leads to the difference in intensities between two soil deposits with average shear-wave velocities V_{30} of v_{s1} and v_{s2} as

$$\delta I(v_{s1}) - \delta I(v_{s2}) = 2.70 \log (v_{s2}/v_{s1})$$

Table IV.7: Soil response PGA amplification factors

Hazard Zone	Soil Foundation Condition	Amplification Factors used in mapping (based on Borcherdt 1994 and NEHRP 1994)
1	*Residual Soil Overlying Rock*	SC (II+III) Stiff Soils - Soft Rock Applies for V_S200-700m/s with typical value of 450m/s PGA factors w.r.t. SC-Ib[1] @ 0.1g[2]: 1.4; @ 0.2g 1.2 @ 0.3g: 1.1; @ 0.4g: 1.0 @ 0.5g: not specified *Exceptions[3]: SW-UW, part MW, CW*
2	*Firm to stiff Sediment of Pleistocene Age*	SC III Stiff Clays and Sandy Soil Applies for V_S200-375m/s with typical value of 290m/s PGA factors w.r.t. SC-Ib @ 0.1g: 1.6; @ 0.2g: 1.4 @ 0.3g: 1.2; @ 0.4g: 1.1; @ 0.5g: 1.0 *Exceptions: Soft alluvium N=2-4; firm alluvium N=4-8; sensitive pumiceous silt; liquefiable materials; ash, tuff and basalt veneers as for underlying materials*
3	*Coastal Deposits*	SC III Stiff Clays and Sandy Soil V_S ranges and PGA factors as for Hazard Zone 2 *Exceptions: Loose sand in V_S 100-200m/s range; V_S 375-500m/s material (e.g. gravelly sand); liquefiable materials*
4	*Estuarine Deposits of Holocene Age; Reclaimed Land*	SC IVa Soft Soils Applies for V_S 100-200m/s with typical value of 150m/s PGA factors w.r.t. SC-Ib @ 0.1g: 2.0; @ 0.2g: 1.6; @ 0.3g: 1.2; @ 0.4g: 0.9; @ 0.5g: not specified *Exceptions: Liquefiable materials*

Notes:

1 PGA factors correspond to short-period amplification factors noted in Table IV5.

2 PGA value corresponds to Borcherdt class SC-Ib, Firm to Hard Rock (see Table IV.3). Conversion to PGAs for other classes, including SC-III corresponding to PGA attenuation relation, given in Table IV.6.

3 See Section IV.1.2 for selection of appropriate Borcherdt classifications and discussion of exceptions.

The appropriate V_{30} values for the hazard zones have been taken as those given by Borcherdt for his corresponding classes. The differences in intensities with respect to Borcherdt class SC-III, assumed

to be the reference class for the New Zealand MM Intensities attenuation model, are given in Table IV.8, rounded to the closest 0.05 unit.

Table IV.8: Intensity differences with respect to mm intensities attenuation expression (for low to moderate amplitude shaking, i.e. ^{2} MM8)

Hazard Zone	Borcherdt Class	V_{30}(m/s)	δI wrt SC-III
1	II+III	450	-0.5
2, 3	III	290	0.0
4	IVa	150	0.75
	Ia	1620	-2.0
	Ib	1050	-1.5
	II	540	-0.75

IV.2 Predicted Shaking for Scenario Earthquake

In this section we describe the procedure for developing the maps in GIS.

IV.2.1 Procedure to Develop Maps

The classification of soil type was derived from underlying geology captured from regional geological maps produced at varying scales. For Region A, the data capture scale was 1:50,000. Geological boundaries from the geological maps were captured with an average interval of about 30 m between vertices, and we estimate that 80% of well known points are within ±50 m of their actual position. Once the geological units were classified, adjacent polygons of the same soil class were amalgamated, and the data converted from vector to raster format with a grid resolution of 100 m.
Attenuation of earthquake shaking (PGA, MM Intensities) was determined for a source with M 6.0, centroid depth 10 km, centred 20 km east of Auckland city. Attenuation was modelled for three soil classes (Hazard Zones 1, 2+3, and 4) using attenuation formulae described above. In each case the entire area of Region B was modelled as if it comprised only that soil class. Attenuation results were stored in raster format with a grid resolution of 100 m.

Shaking intensity (PGA, MM Intensities) was determined by overlaying the three attenuation grids with the soil class grid and then selecting the shaking value from the attenuation grids based on the soil class grid.

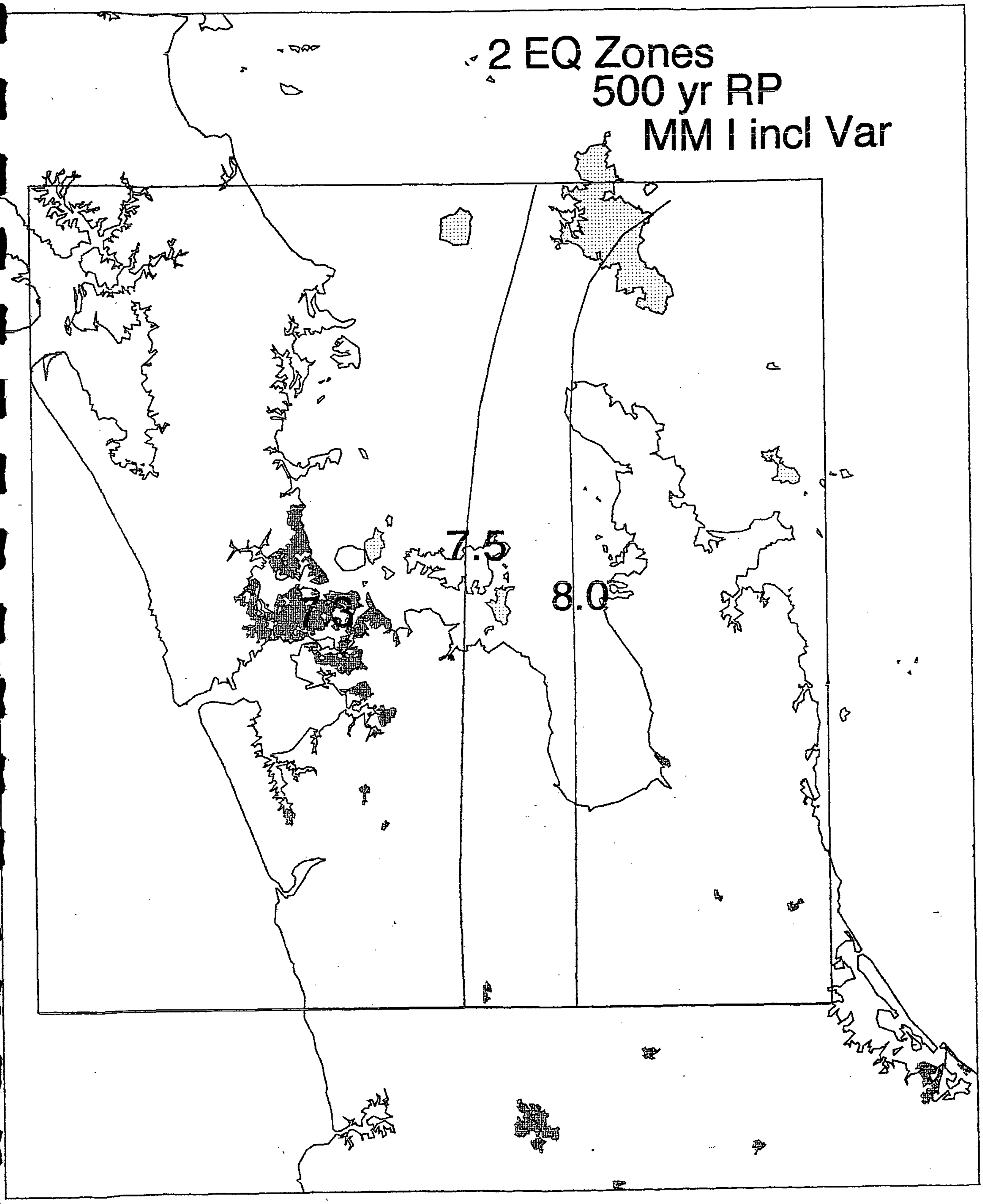


Figure 1: MM Intensities for 500 year return period using Auckland and Coromandel source zones, attenuation model after Dowrick (1992) and accounting for variability in the attenuation relationship. Shading in Figures 1–8 indicates the principal built-up urban areas in the region.

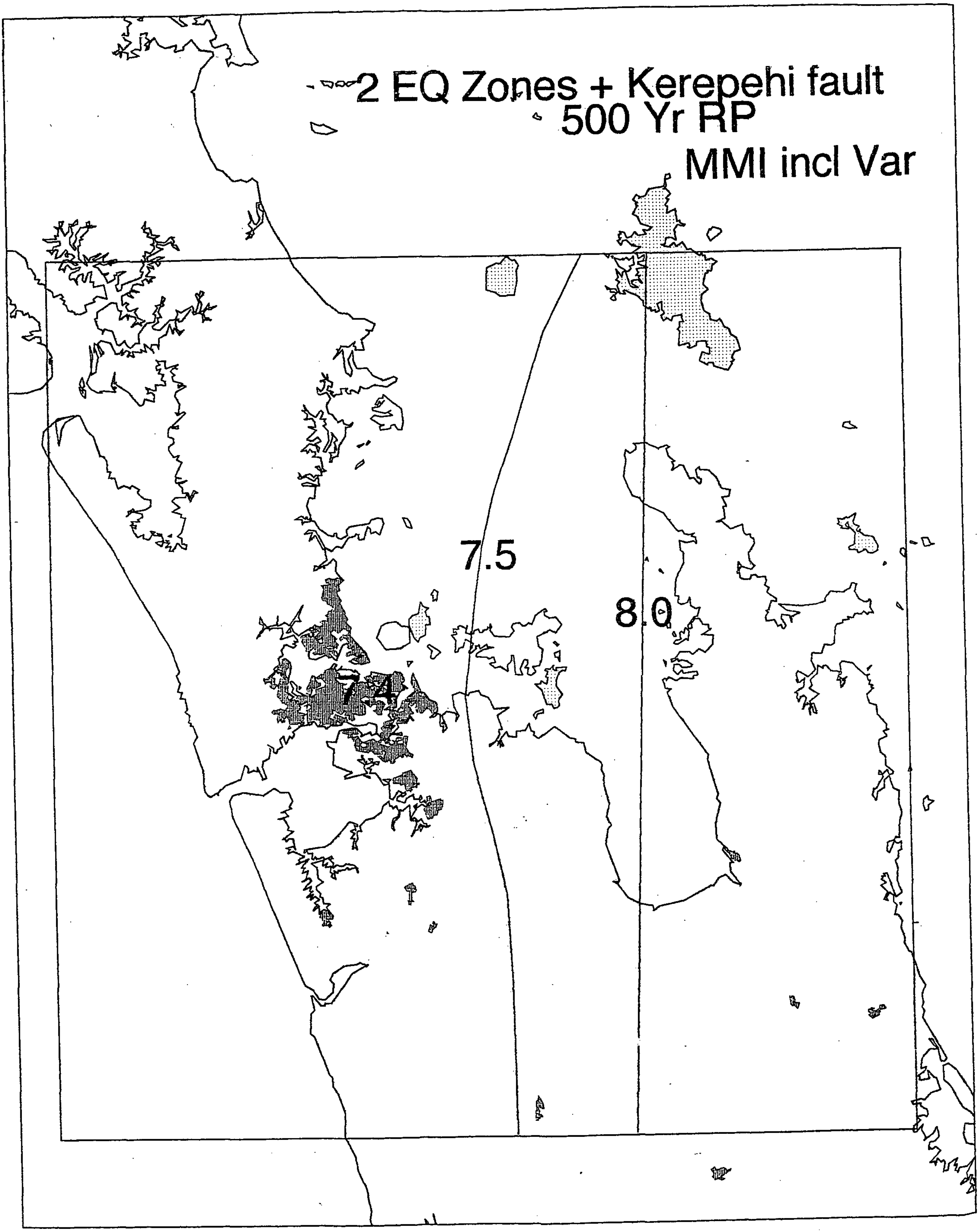


Figure 2: MM Intensities for 500 year return period using Auckland and Coromandel source zones, attenuation model after Dowrick (1992), a 5,000 year return period for a Kerepehi fault rupture and accounting for variability in the attenuation relationship.

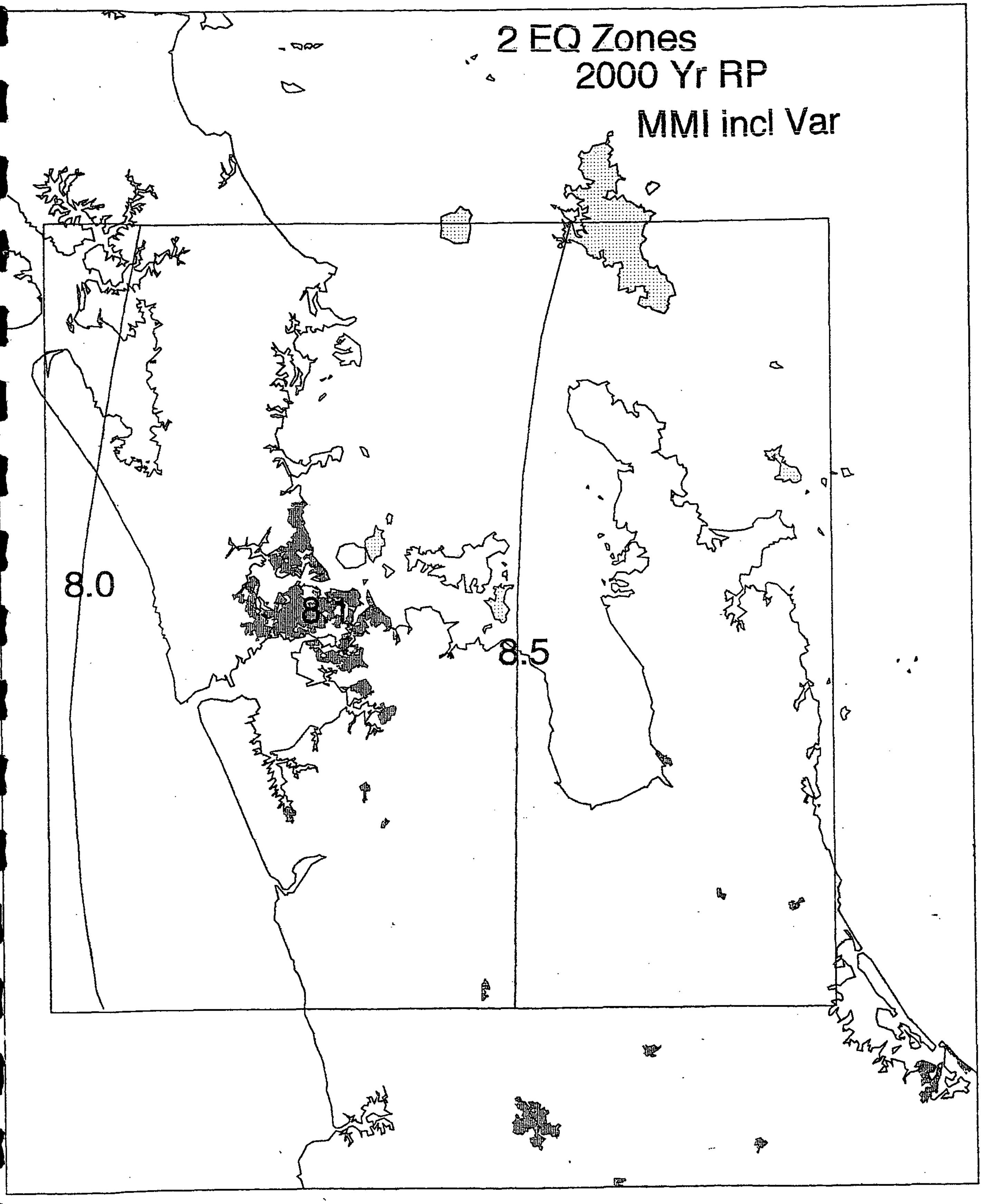


Figure 3: MM Intensities for 2000 year return period using Auckland and Coromandel source zones, attenuation model after Dowrick (1992) and accounting for variability in the attenuation relationship.

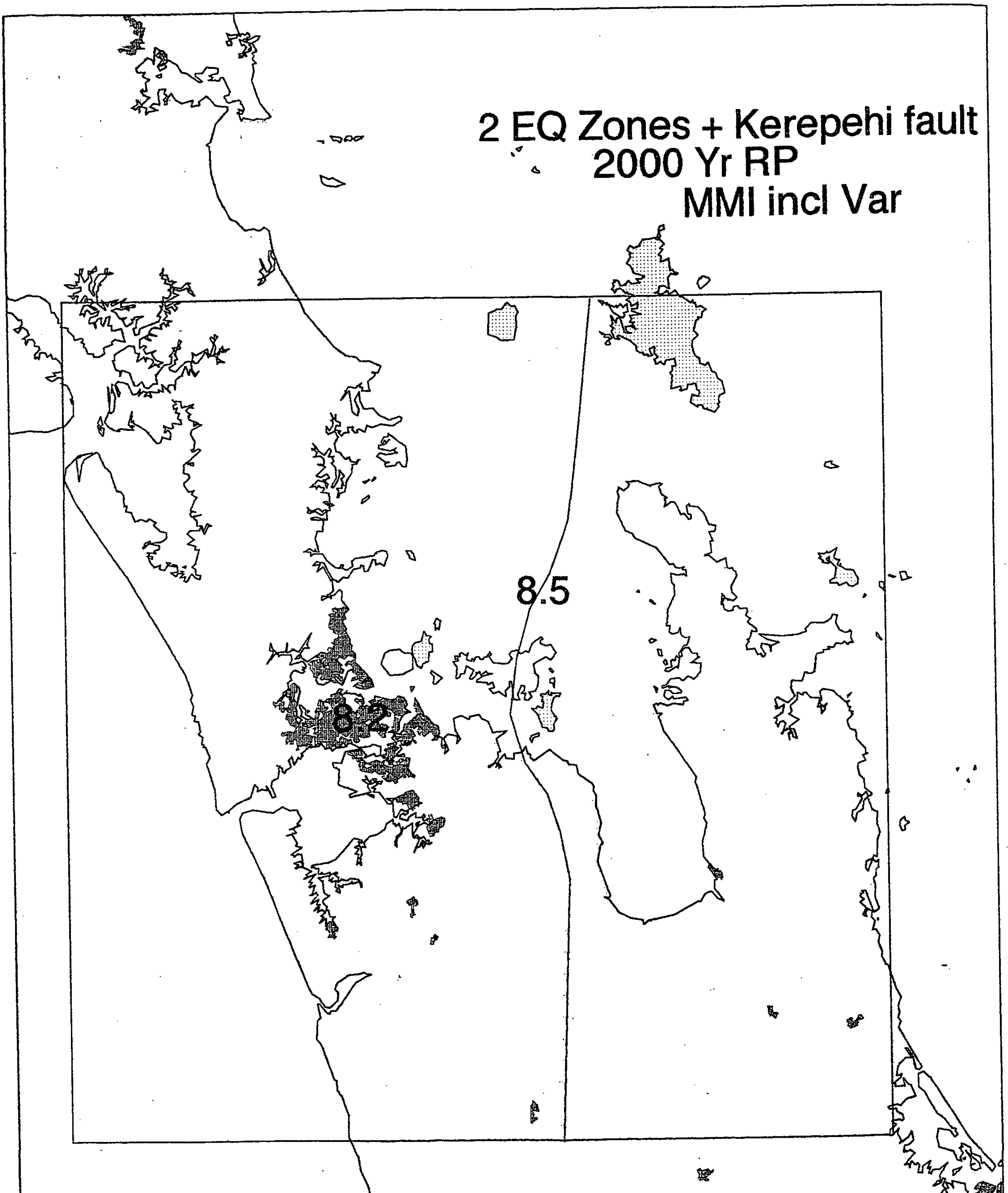


Figure 4: MM Intensities for 2000 year return period using Auckland and Coromandel source zones, attenuation model after Dowrick (1992), a 5,000 year return period for a Kerepehi fault rupture and accounting for variability in the attenuation relationship.

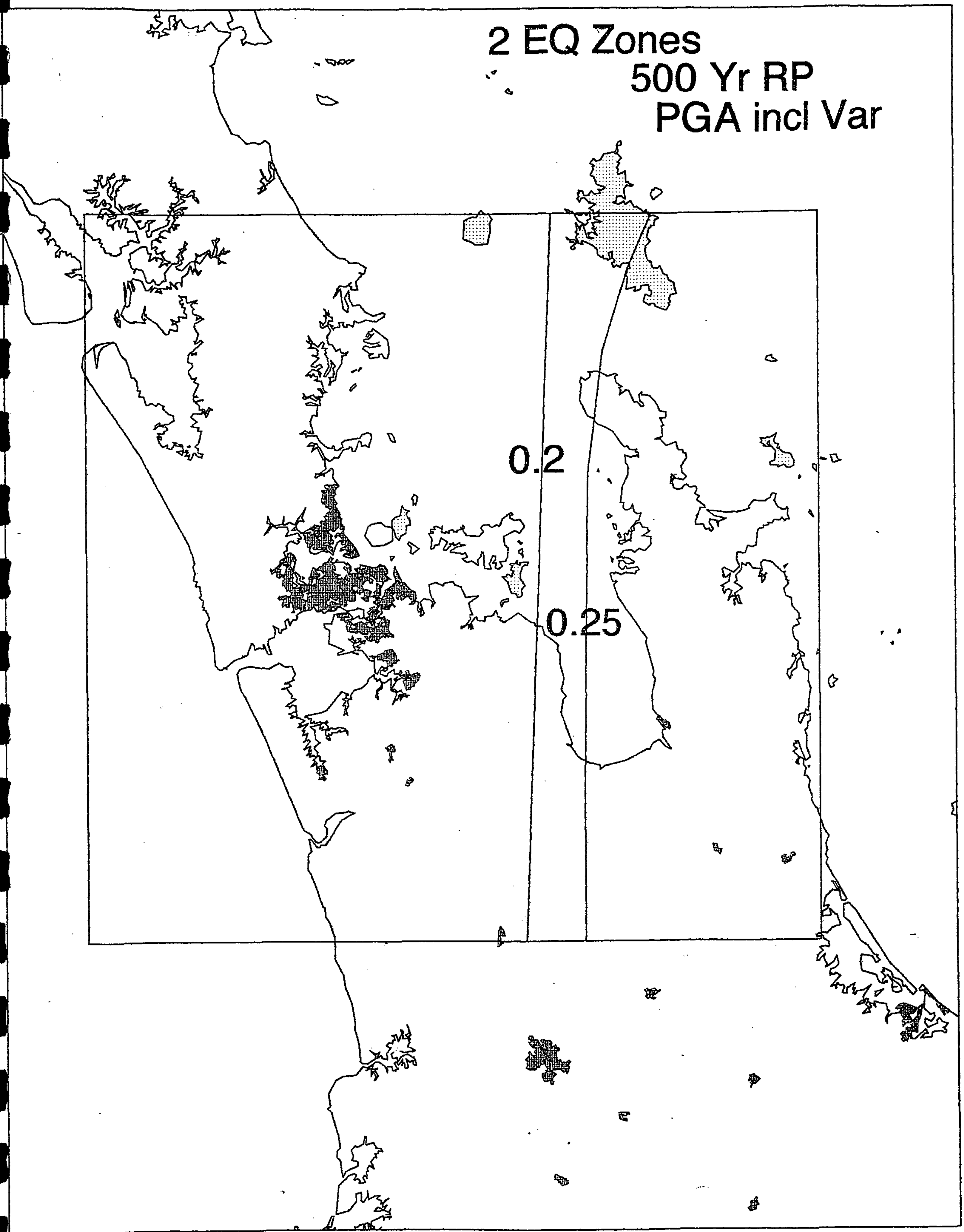


Figure 5: Peak horizontal ground accelerations for 500 year return period using Auckland and Coromandel source zones, New Zealand-based PGA attenuation model developed for this study and accounting for variability in the attenuation relationship.

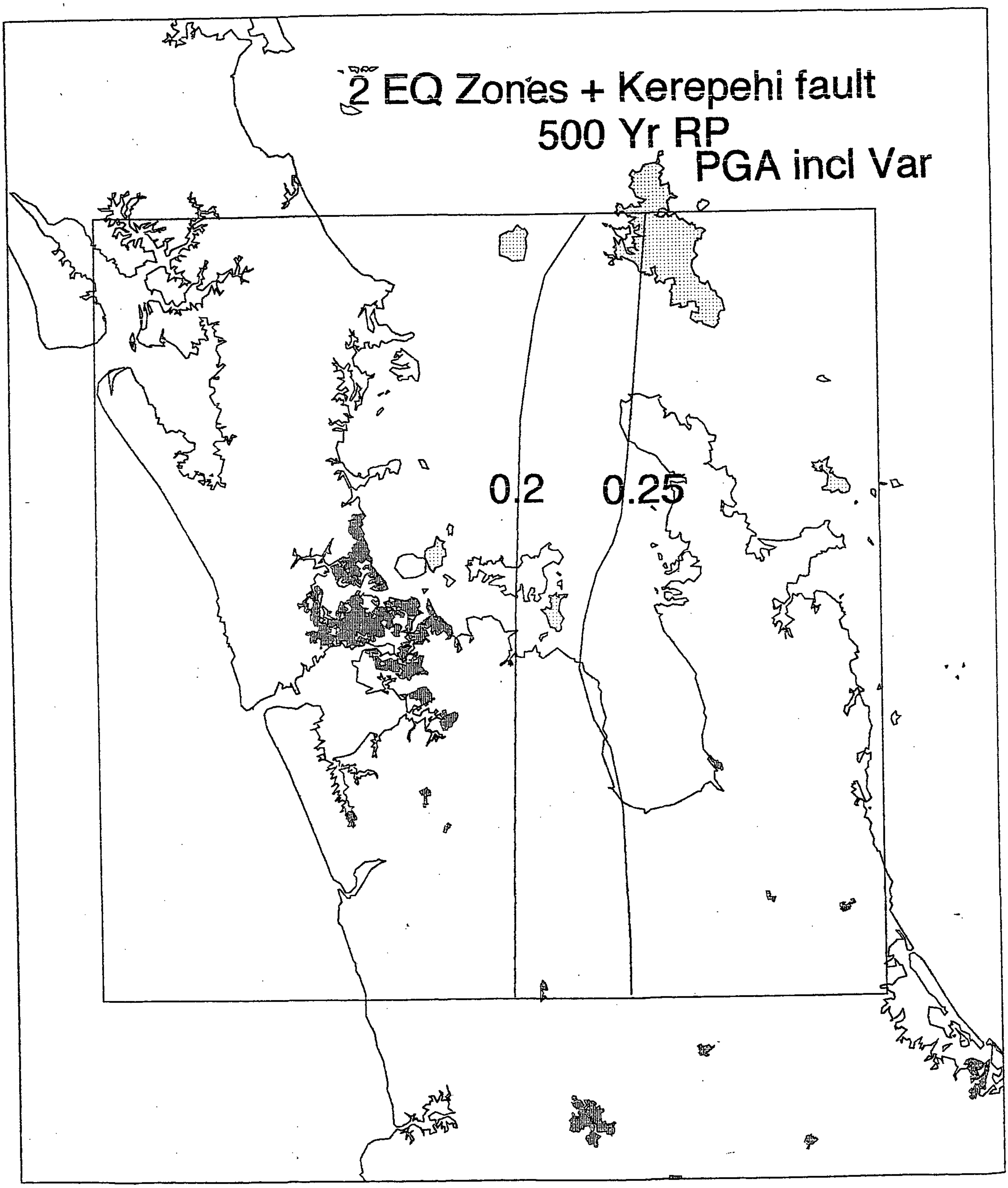


Figure 6: Peak horizontal ground accelerations for 500 year return period using Auckland and Coromandel source zones, New Zealand-based PGA attenuation model developed for this study, a 5,000 year return period for a Kerepehi fault rupture and accounting for variability in the attenuation relationship.

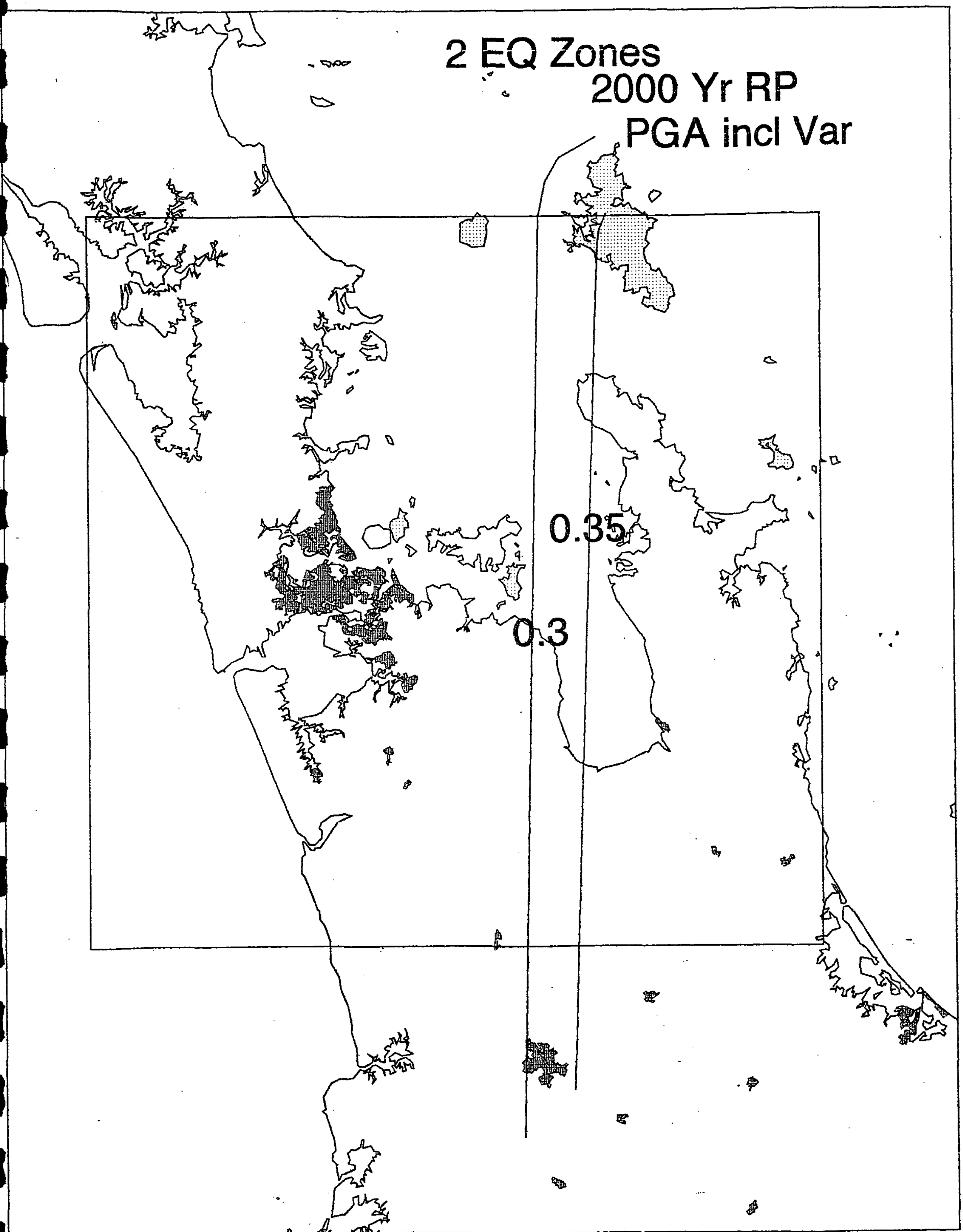


Figure 7: Peak horizontal ground accelerations for 2000 year return period using Auckland and Coromandel source zones, New Zealand-based PGA attenuation model developed for this study and accounting for variability in the attenuation relationship.

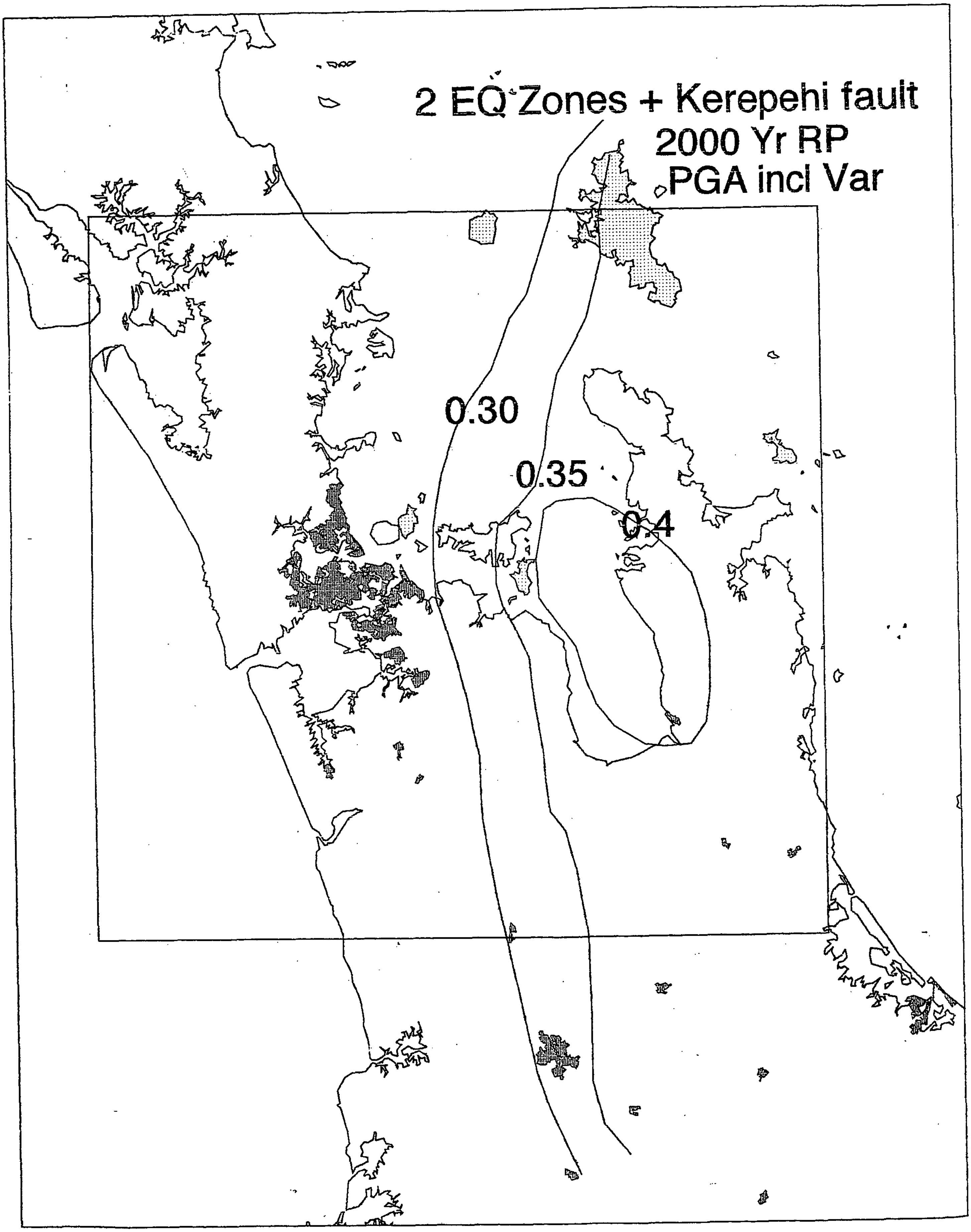


Figure 8: Peak horizontal ground accelerations for 2000 year return period using Auckland and Coromandel source zones, New Zealand-based PGA attenuation model developed for this study, a 5,000 year return period for a Kerepehi fault rupture and accounting for variability in the attenuation relationship.

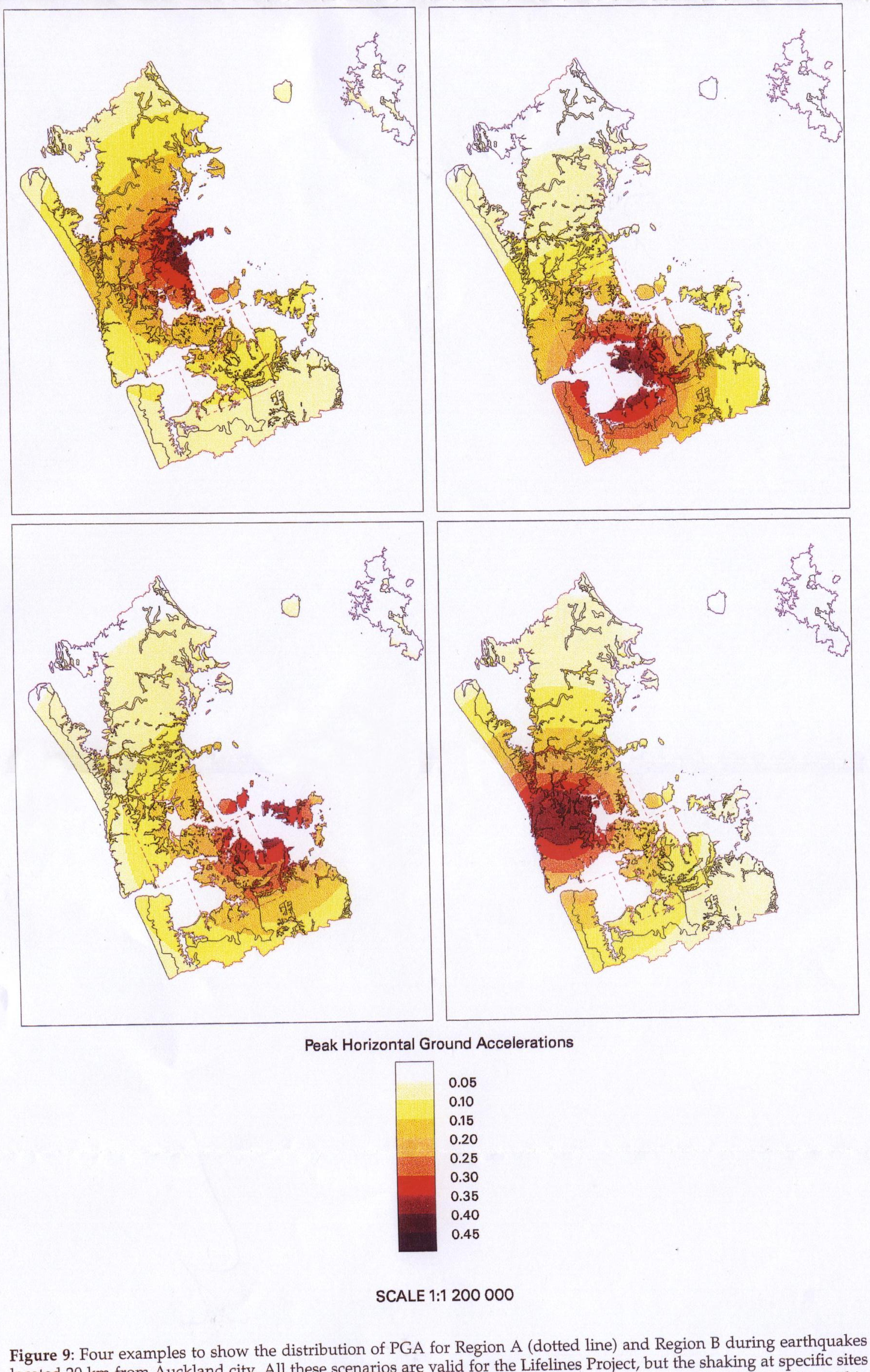


Figure 9: Four examples to show the distribution of PGA for Region A (dotted line) and Region B during earthquakes located 20 km from Auckland city. All these scenarios are valid for the Lifelines Project, but the shaking at specific sites within the study region is different. The scenario chosen (bottom left) was selected to produce shaking intensities within the main urban areas of Region A close to those estimated from a uniform hazard model (see text for detailed discussion).

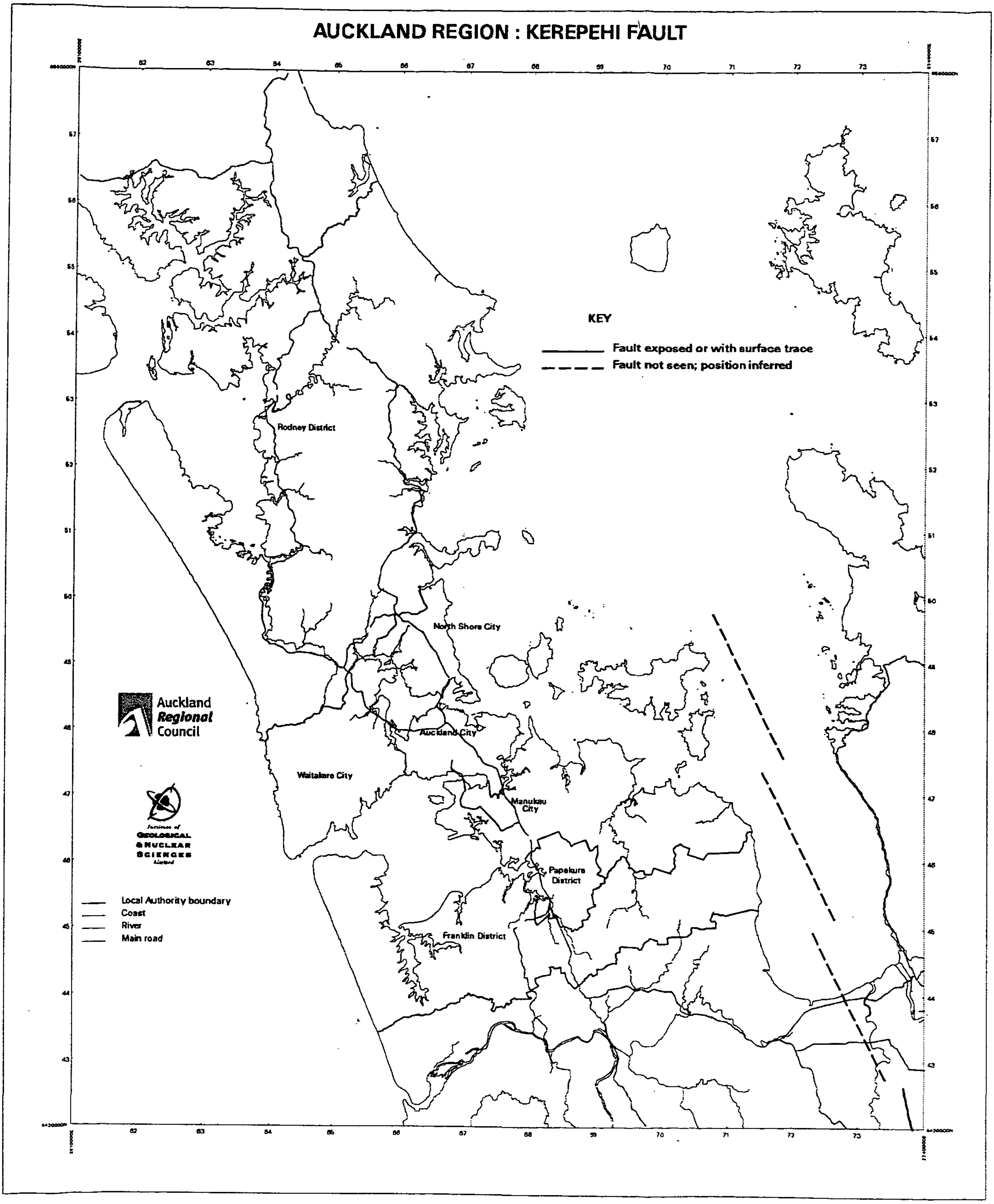
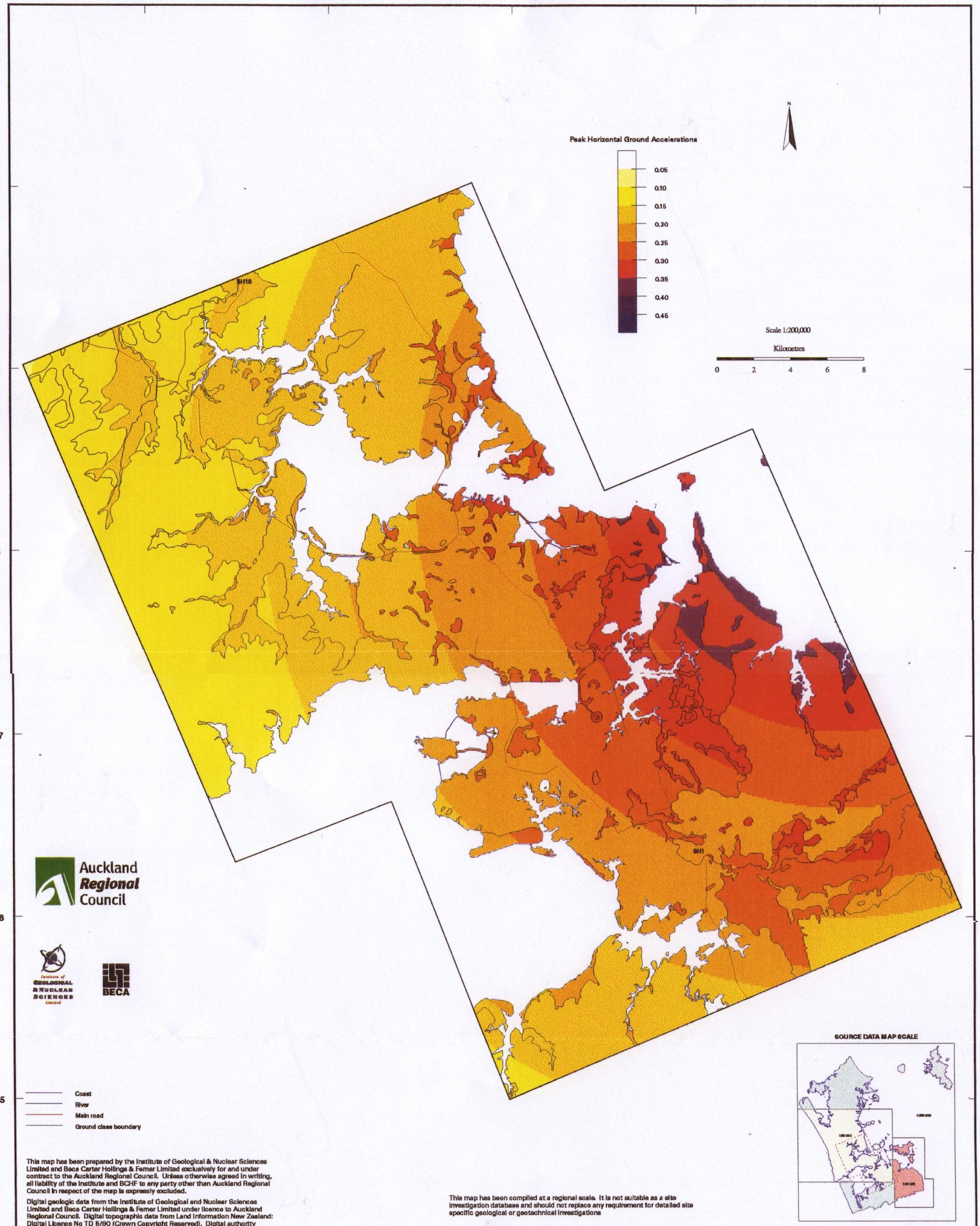


Figure 10: Map of Auckland region showing segments of Kerepehi fault offshore. Northern segment east of Waiheke Island was used for earthquake scenario development.

Ground Shaking Hazard (Peak Horizontal Ground Accelerations)

Region A



Auckland Regional Council

Institute of Geological & Nuclear Sciences Limited

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This map has been compiled at a regional scale. It is not suitable as a site investigation database and should not replace any requirement for detailed site specific geological or geotechnical investigations

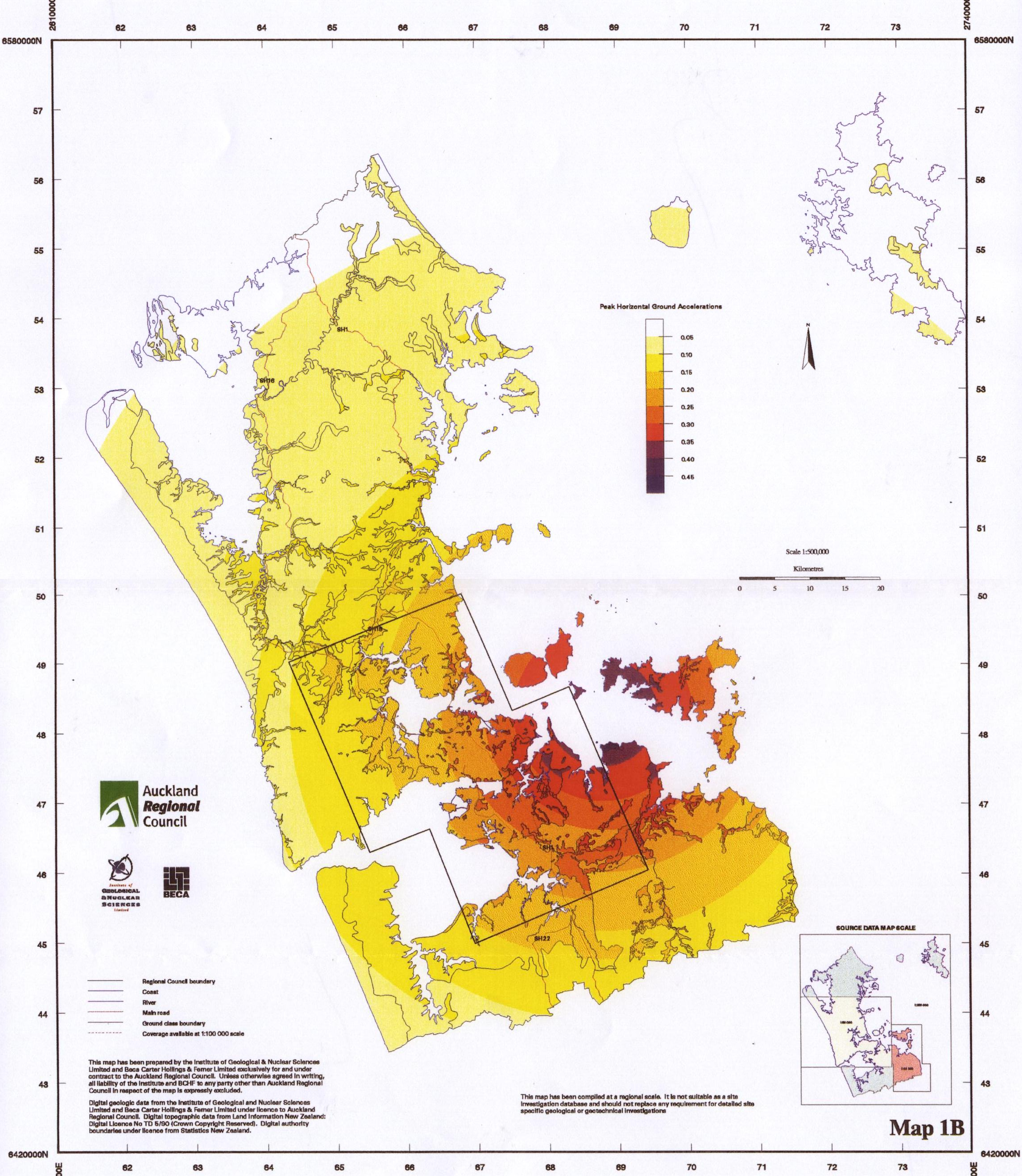
Map 1A

Auckland Engineering Lifelines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Ground Shaking Hazard (Peak Horizontal Ground Accelerations)

Region B



Auckland Engineering Lifelines

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It accompanies and should be read in conjunction with the
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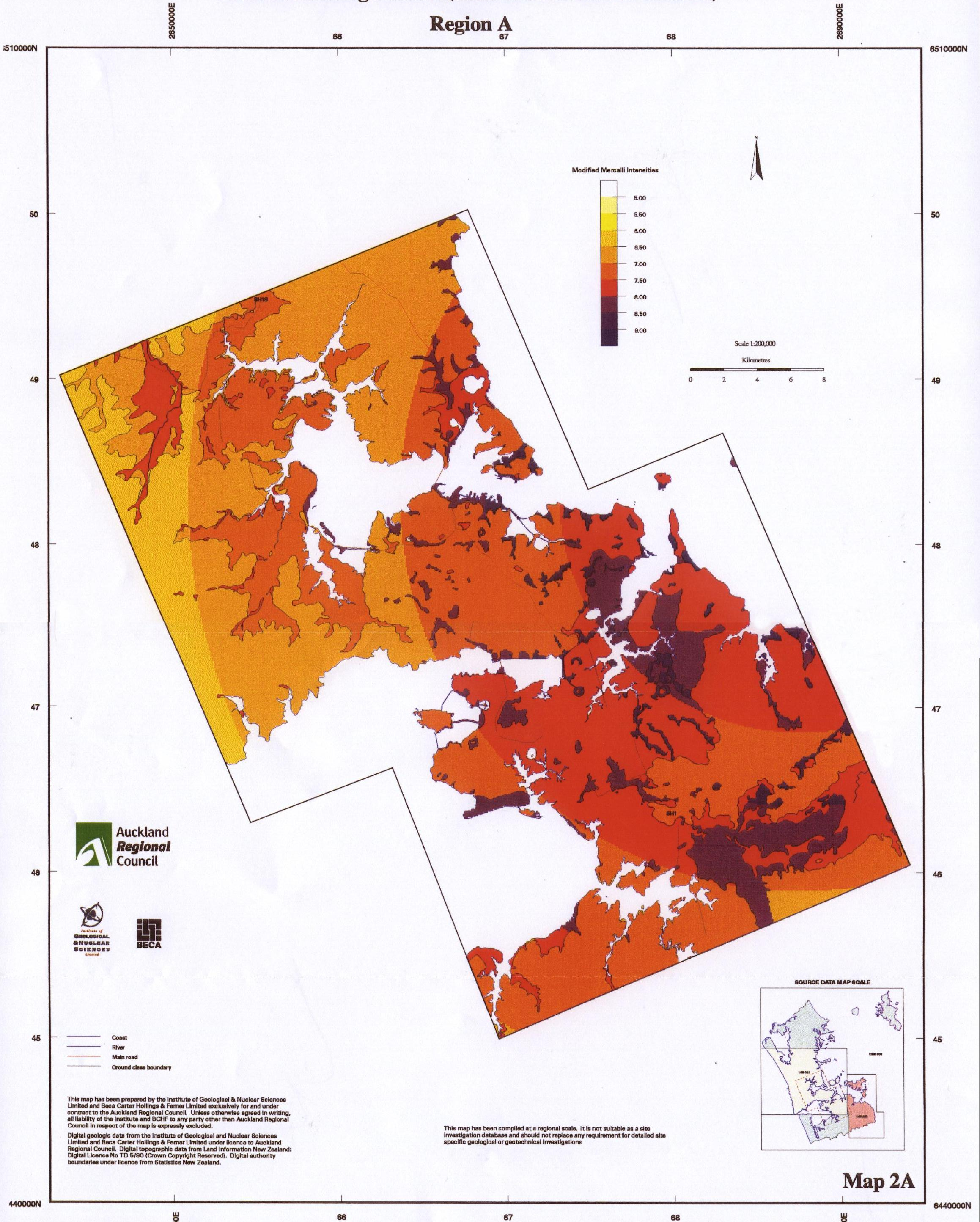
Ground Shaking Hazard (Modified Mercalli Intensities)

Region A



Auckland Engineering Lifelines

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It accompanies and should be read in conjunction with the
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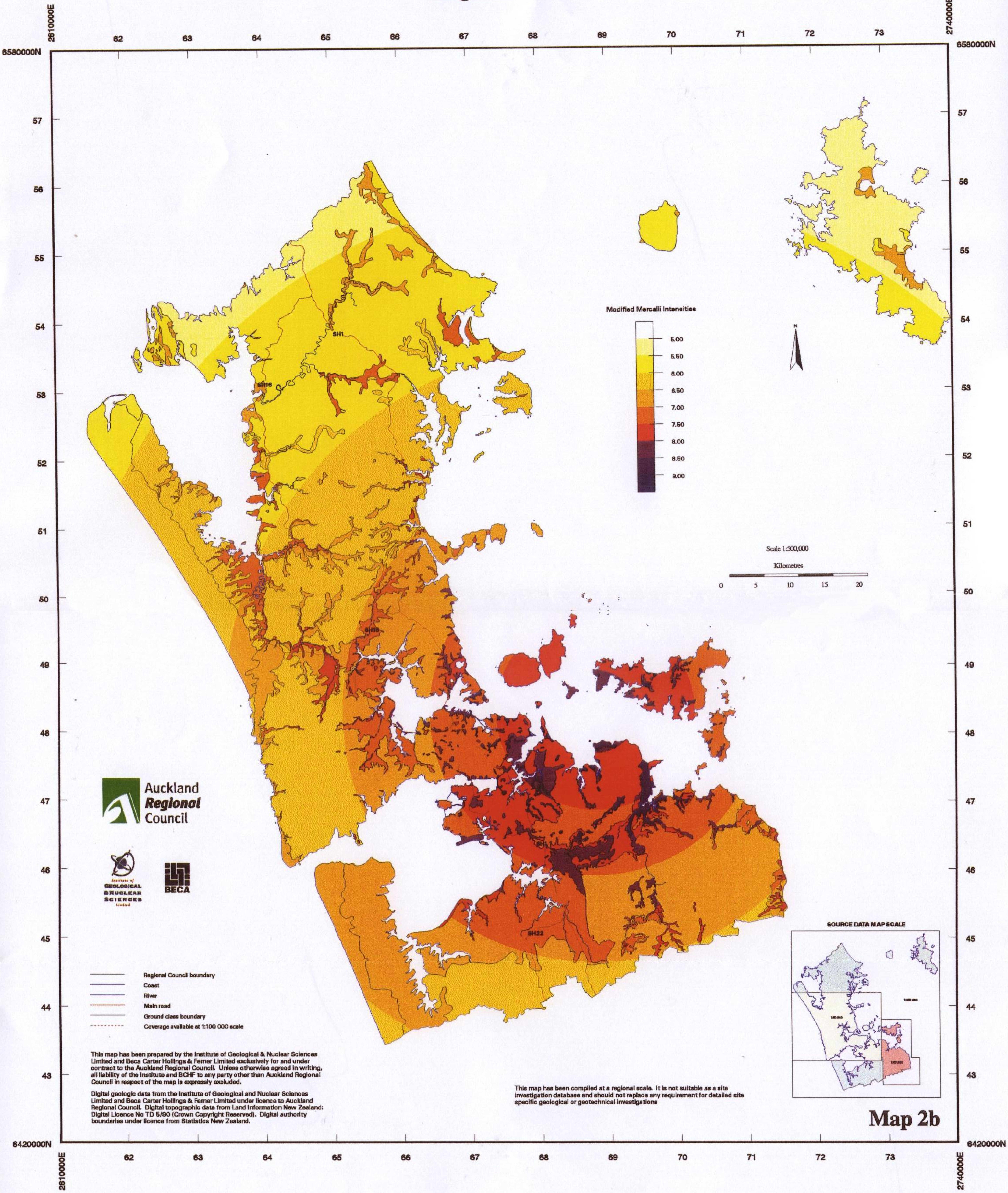
Ground Shaking Hazard (Modified Mercalli Intensities)

Region B



This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Auckland Engineering Life Lines

REPORT 2.3

EARTHQUAKE - INDUCED SLOPE INSTABILITY HAZARD MAP (Accompanying Notes)

Prepared for

AUCKLAND REGIONAL COUNCIL

By

BECA CARTER HOLLINGS & FERNER LTD

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CONTENTS

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Report Reviewed By
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1.0 INTRODUCTION

The Resource Management Act (1991) designates responsibility for integrated management of the land, natural and physical resources, and avoidance or mitigation of natural hazards to Central, Regional and Local Government. As part of the Auckland Regional Council's responsibilities under the Act, a series of studies are being undertaken to assess the potential risks and impacts of earthquake on the Auckland Region. The current study makes use of the slope instability maps presented in ARC Technical Publication No.71 to provide an assessment of the susceptibility of the Auckland Region to earthquake induced slope movement.

The objectives of this study are to:

- Identify those areas of the Auckland Region that are potentially susceptible to slope failure in the event of a 2000-year earthquake. The slope instability hazard is assessed both in terms of a uniform hazard for the Auckland Region and a scenario caused by a single earthquake with its epicentre within 20km of Auckland City. Details of the uniform hazard model and the scenario earthquake are provided by IGNS 1997[1];

- Identify the proportion of slopes likely to be affected by Peak Ground Accelerations (PGA's) predicted by the selected scenario; and

- Assess the vulnerability of services (next stage of the Auckland Engineering Lifelines Project).

The Earthquake-Induced Slope Instability Map is prepared at the following scales:

- Region A, areas of medium to high population and services density, 1:100,000;
- Region B, areas of low population and services density, 1:250,000.

For ease of presentation and reproduction, maps accompanying this report are produced at scales of 1:200,000 and 1:500,000 respectively. This report accompanies the maps and provides background information on earthquake induced slope instability in the Auckland Region.

Notice to Reader/User of this Document:

This report is the property of our Client, the Auckland Regional Council, and Beca Carter Hollings & Ferner Ltd. This document discusses ground instability at a regional scale. It is not suitable for a site investigation database and should not be used as such.

Should you be in any doubt as to the applicability of this report or its recommendations and/or encounter materials or conditions that differ from those described herein, it is essential that you discuss these issues with the authors before proceeding with any work based on this document.

[1] *IGNS 1997: Peak Horizontal Ground Accelerations and Modified Mercalli Intensities forScenario Earthquakes in the Auckland region: Auckland Engineering Lifelines Project. Report Prepared for the Auckland Regional Council., June 1997.*

2.0 HISTORICAL RECORDS

2.1 EARTHQUAKE EVENTS RECORDED WITHIN THE AUCKLAND REGION

The Auckland Region occurs within one of the least historically (last 150 years) seismically active regions of New Zealand. This is in part because Auckland is located some 300km from the major northeast-southwest oriented seismically active zone which lies beneath the east coast of the North Island and marks the junction between the Australian and Pacific tectonic plates. This zone is judged to be capable of producing large (Richter magnitude, M ≥ 8) earthquakes.

Historical earthquakes and their effects are described together with known faults of the Auckland Region in the ARC Technical Publication No.57 dated April 1995[2]. A summary of historical earthquakes producing observed or inferred felt intensities of Richter magnitude ≥ 5 is presented in Table 1.

Table 1: Historical earthquakes of magnitude >5 recorded within the Auckland region

Date	Latitude (°S)	Longitude (°E)	Magnitude[A]	Distance of Epicentre from Central Auckland (km)
1834/1835	37	175	5.5 - 5.6	25
23.06.1891	37.4	174.7	5.7 - 5.9	60
28.02.1974	36.6	177.0	5.9	>200

[A] Magnitude (Richter) is a measure of the energy released by an earthquake at its source.

2.2 2000 YEAR EARTHQUAKE SCENARIO

2.2.1 Kerepehi Fault

In the past, earthquake scenarios for engineering and emergency management projects in the Auckland area have modelled ground shaking derived from an earthquake along the Kerepehi fault, a known active fault to the east of Auckland. Although the Kerepehi fault is located outside the Auckland Region, the fault is known to be active on land (multiple movements within the last 125,000 years) in the central Hauraki Plains[2]. Investigations suggest it extends offshore of the central Hauraki Plains into the Firth of Thames where it is probably also active. From investigations of fault length and single-event displacements, the fault is believed to be capable of generating earthquakes of about magnitude 7. Shaking from these earthquakes would cause moderate to strong ground accelerations within the Auckland Region[2].

Studies as part of the Auckland Engineering Lifelines Project indicate that an earthquake of magnitude 6.9 on the offshore extension of the Kerepehi fault, and an expected return period of about 5000 years, would generate a Peak Ground Acceleration (PGA) of 0.15g in Auckland City[3].

2.2.2 Uniform Hazard Model

A uniform hazard model developed for several engineering studies within Auckland was used to estimate the ground motions expected in central Auckland from a 2000 year return period earthquake event[3]. The uniform hazard model is based on the available historical record of earthquakes felt in the Auckland Region (refer Table 1). This model estimates a PGA of 0.17g to 0.27g (depending on the soil type) for the central Auckland area.

[2] *Auckland Regional Council Technical Publication No.57, April 1995.*
[3] *IGNS 1997: Peak Horizontal Ground Accelerations and Modified Mercalli Intensities for Scenario Earthquakes in the Auckland region: Auckland Engineering LifelinesProject. Report Prepared for the Auckland Regional Council., June 1997.*

When applied uniformly to the whole of the Auckland Region, this model allows an assessment of the earthquake-induced slope instability hazard within 20km of any potential epicentre, which could be located anywhere within the Region (Map 4).

However, for the purposes of the engineering lifelines project, it is useful to simulate one realistic earthquake with a selected earthquake epicentre. This event will generate the highest levels of PGA at the epicentre, reducing with distance from the epicentre.

The scenario earthquake selected for the Lifelines Project is one that generates the expected higher level of PGA (derived from the uniform hazard model), rather than an earthquake associated with the Kerepehi fault. The Kerepehi fault scenario was not used for the Engineering Lifelines Project because it does not produce levels of ground shaking as high as those likely to occur in a 2000 year return period earthquake.

The scenario adopted is a point source magnitude 6.0 earthquake at 10km depth, with an epicentre 20km east of central Auckland. This location was selected so that:

- The higher PGA values calculated from the uniform hazard model for a 2000 year earthquake cover the central Auckland area; and
- PGA values higher than expected for a 2000 year event (ie PGA's indicative of a longer average return period) occur at less critical areas (in terms of engineering lifelines) offshore, and would not affect the central part of Auckland City.

Because this scenario earthquake is arbitrarily selected, its epicentre could equally be at any other location within the Auckland Region, resulting in a different distribution of ground motions.

3.0 SLOPE INSTABILITY IN THE AUCKLAND REGION

3.1 SOIL AND ROCK TYPES

Much of the Auckland urban area is built on Miocene, Pliocene and Quaternary sedimentary rocks and soils. Younger basaltic volcanoes have erupted through these rocks, resulting in a wide range of volcanic landforms such as scoria cones, lava fields, explosion craters and tuff rings. The majority of these volcanic deposits rest upon residual and transported soil masses, rather than rock.

To the west of Auckland City, the hills of the Waitakere Ranges are underlain by volcanic and volcaniclastic rocks (sedimentary rocks derived from eroded Miocene-age volcanoes), and to the east, the hills of the Whitford-Brookby district and the islands of Motutapu, Motuihe, and in part, Waiheke, Kawau, Little Barrier and Great Barrier are underlain by weathered Mesozoic greywacke rocks. To the north, soft sedimentary rocks and hard volcanic rocks support gentle to moderately sloping lowlands and upstanding ranges respectively. Weathering has produced a thick regolith of residual soil and slope debris up to 20m to 30m thick.

The Quaternary deposits (Pleistocene and Holocene age, ie <1.6 million years) comprise soils which have been transported into place. Because the Pleistocene deposits (10,000 years to 1.6 million years) are considerably older than the Holocene deposits (<10,000 years), and generally occur on higher ground, these materials tend to be stronger, and are often less saturated than the Holocene deposits. However, they are soils (ie much weaker than rock) and do contain some liquefiable loose sands and sensitive silts.

The Holocene age deposits comprise both loose sandy coastal deposits and soft clayey estuarine deposits. The soft clayey deposits are generally the weakest materials encountered in the Auckland Region.

3.2 CONDITIONS THAT AFFECT INSTABILITY

Conditions that primarily influence the behaviour of slopes in response to earthquake-induced ground shaking include:

- Geology (interaction of the soil and rock mass, including defects), the degree of weathering of the rock mass, the depth of residual soil, and whether the slope is subject to recurring instability;
- Slope height and angle;
- Groundwater level; and
- Earthquake magnitude and slope location with respect to the direction of shaking.

3.2.1 Geology

Weathering has produced a thick layer of soil and slope debris up to 20m to 30m thick over most of the older rock types outcropping in the Auckland Region. In rock masses of pre-Pleistocene age, the behaviour of the residual soils, slope debris and rock defects dominate the response of slopes to ground shaking. Many failures occur within the residual soils, along the interface between rock and soil, or along defects within the rock mass.

(i) *Pre-Pleistocene Age Rock-Masses*. The stability of these slopes was analysed using a range of slope heights, slope angles and groundwater levels.

These models take into account the predisposition of the Pre-Pleistocene rock masses and their residual soil cover to failure along fractures, faults, bedding planes, clay seams, the soil/rock interface, and within the residual soil mantle.

(ii) *Pleistocene Age Sediments*. Pleistocene age sediments are generally of lower permeability and occur in lower slopes than the older soils and rocks. These materials have typically been subject to slope creep or shallow sliding, where they exist in steeper slopes.

(iii) *Holocene age Deposits*. These deposits can be broadly divided into sandy coastal deposits and soft clayey estuarine deposits. The high permeability and friction angle of the sandy deposits means that these soils tend to stand in relatively steep slopes with a relatively low margin of stability close to the slope face.

Because of their low strength, and location typically in low lying areas adjacent to swamps and water courses, the soft estuarine sediments tend to be saturated, of low permeability and tend only to exist in relatively modest slopes.

(iv) *Quaternary Volcanics*. The behaviour of young volcanic deposits in slopes is dominated by the underlying materials described above.

3.2.2 Past Instability

Evidence of past instability indicates a potential for failure of geologically similar slopes with like angle and height in the same area, thereby providing and important guide to the likely future behaviour of slopes in the locality.

3.2.3 Slope Height and Angle

Lower, more gentle slopes will generally be less susceptible to instability. However, pre-Pleistocene age soils and rock can achieve a relatively high margin of stability even in quite steep slopes (for example coastal slopes up to 40°), depending on the degree of weathering of the rock, the level of groundwater within the slope and the orientation of major, continuous defects such as clay seams and crush zones. The strength parameters of Holocene age estuarine deposits mean that these soils do not generally occur in slopes higher than 5m or steeper than 20°.

3.2.4 Groundwater Level

Raising the water level within a slope, as occurs during the winter months of each year, (or as a result of heavy rain over a period of days or weeks) reduces the margin of stability of that slope.

3.2.5 Earthquake Magnitude and Epicentre Location

Strong ground shaking is one of the principal effects of earthquakes. A larger magnitude earthquake produces stronger and larger periods of shaking than a smaller earthquake at the same focal depth. In general, locations more distant from the source receive a lower level of shaking than locations near the epicentre. However, because ground conditions are locally variable, the level of shaking felt from the same earthquake at a similar distance from the epicentre will vary from site to site. This occurs because different geological materials and conditions at different sites amplify or filter earthquake shaking frequencies by different amounts.

Strong ground shaking and associated ground failure may cause damage to man-made structures during earthquakes.

4.0 HAZARD ASSESSMENT

The stability of a series of slopes of different height, slope angle, soil/rock mass composition and groundwater-level were back-analysed[4] for differing levels of earthquake acceleration to provide an assessment of the conditions under which the margin of stability is reduced as a result of earthquake shaking, and the importance of each factor to that margin of stability.

The earthquake-induced slope instability hazard for the 2000 year earthquake was assessed through preparation of a series of maps of these conditions:

- slope angle;
- soil/rock mass category; and
- peak ground accelerations calculated for a uniform hazard and for the selected 2000 year earthquake scenario.

(The affect of variation of groundwater level has been built into the slope angle and soil/rock mass category scores presented in Sections 4.1 and 4.2).

Categories were developed for each condition, and the categories were then weighted according to their influence on slope stability, as indicated by the back-analyses referred to above. The categories established and the weighted scores are described in the following Sections. These data were superposed using the GIS based ArcInfo system, to produce Tables 5 and 6 (Section 4.4) and the hazard maps, Map 4 (uniform hazard, Regions A and B at 1:250,000), Map5A (earthquake scenario, Region A

[4] *Back-analysis starts with a known stability situation (ie a known balance of gravitational forces versus soil resistance) and works back to assess the relative stability of the same soil or rock slope at different slope angles and groundwater conditions. Refer also to Appendix B.*

prepared at 1:100,000) and Map 5B (earthquake scenario, Region B prepared at 1:250,000). These maps are attached at the reduced scales of 1:200,000 and 1:500,000 respectively.

4.1 SOIL/ROCK MASS CLASSIFICATION

The revised ground shaking hazard map, prepared jointly by BCHF and IGNS, was used as a base plan for the Auckland Region Soil/Rock Mass Classification.

The soil categories developed as part of the ground shaking hazard study[5] are described in the Soil Classification Table (Appendix A) and presented on maps 1A and 1B.

Scores were allocated to each class (Table 2) according to the known geotechnical characteristics of that class and their contribution to the margin of stability according to the back-analyses. Scores indicate the relative susceptibility of the soils to earthquake-induced instability.

For example, Holocene age estuarine deposits and reclaimed land (Class D) are considered to be more susceptible to earthquake-induced instability than the other soil and rock types inthe Auckland Region (Classes A, B and C). This reflects the lower effective strength parameters of Class D deposits.

Table 2: Soil category contribution

Soil/Rock Mass	Class	Score
Residual Soil Overlying Rock	A	0.7
Firm to Stiff Sediment of Pleistocene Age	B	0.4
Coastal Deposits	C	0.6
Estuarine Deposits of Holocene Age	D	0.25

4.2 SLOPE GRADE CLASSIFICATION

Slope information was sourced from the New Zealand Land Resource Inventory data licensed to the ARC by Landcare (NZ) Ltd, (1:250,000), and was used in conjunction with 20m contour intervals from which slope angles were calculated using the GIS system.

Slopes were grouped into the four classes shown in Table 3 and illustrated in Maps 2A and 2B. Relative scores were assigned to each slope category based on the back-analysed behaviour of the soil classes within each slope range. Scores allocated are related to the relative reduction in stability as compared with a slope of 0-7°. For example a very steep slope (Class D) subject to the 2000-year earthquake scenario proposed, has a margin of stability four times lower than a gentle slope (Class A).

Table 3: Slope grade contribution

Slope Grade	Class	Score
Gentle (0 - 7°)	A	1.0
Moderately Steep (8 - 15°)	B	0.8
Steep (16-20°)	C	0.5
Very Steep (> 20°)	D	0.25

[5] *BCHF and IGNS 1997: Accompanying Notes. Ground Shaking Hazard Map. Prepared for Auckland Regional Council, May 1997.*

4.3 EARTHQUAKE SCENARIO

Scores were allocated to the ranges of ground acceleration levels according to the contribution of ground shaking to reduction in the margin of slope stability predicted in the back-analyses. The predicted peak ground accelerations for the selected 2000-year earthquake scenario have been grouped into five classes described in Table 4. Higher levels of PGA cause an increased likelihood of slope failure. For example, the risk of failure for slopes experiencing Class D shaking is five times more than when experiencing Class A shaking. The distribution of the PGA classes is shown on Map 3.

Table 4: 2000-year earthquake, PGA contribution

PGA (g)	Class	Score
≤ 0.05	A	1.0
0.05 - 0.10	B	0.7
0.10 - 0.15	C	0.35
0.15 - 0.20	D	0.2
> 0.20	E	0.1

4.4 HAZARD ASSESSMENT

The combined scores form Tables 2, 3 and 4 are presented as Hazard Scores in Table 5. The allocated scores have been combined to produce the Earthquake-Induced Slope Instability Hazard maps (Maps 4, 5A and 5B), which designate zones of low, moderate, moderately high and high hazard, as described in Table 6.

For example, PGA Class A (Table 5), is likely to have little effect on the pre-existing margin of stability of a slope of soil category B (firm to stiff sediment of Pleistocene age) and slope category B (8 - 15°), with a factor of safety[6] of about 1.5 (Table 6). Table 6 indicates that only 0.5% of all slopes in this category are likely to fail as a result of ground accelerations of this magnitude.

However, if the same soil slope was exposed to ground accelerations of more than 0.2g (PGA Class E, Table 5), the margin of stability is likely to be more strongly affected, causing 20% or more of these slopes to fail (Table 6).

Table 5: Hazard scores

Soil/Slope Category	PGA Category				
	A	B	C	D	E
A/A	0.70	0.49	0.25	0.14	0.07
A/B	0.56	0.39	0.20	0.11	0.06
A/C	0.35	0.25	0.12	007	0.04
A/D	0.18	0.12	0.06	0.04	0.02
B/A	0.40	0.28	0.14	0.08	0.04
B/B	0.32	0.22	0.11	0.06	0.03
B/C	0.20	0.14	0.07	0.04	0.02
B/D	0.10	0.07	0.04	0.02	0.01
C/A	0.60	0.42	0.21	0.12	0.06
C/B	0.48	0.34	0.17	0.10	0.05
C/C	0.30	0.21	0.11	0.06	0.03
C/D	0.15	0.11	0.05	0.03	0.02
D/A	0.25	0.18	0.09	0.05	0.03
D/B	0.20	0.14	0.07	0.04	0.02
D/C	0.13	0.09	0.04	0.03	0.01
D/D	0.06	0.04	0.02	0.01	0.00

[6] *Refer Appendix B*

Table 6: Interpretation of hazard score			
Hazard Class	**Factor of Safety***	**Interpretation**	**Score**
A	≥ 1.5	Low Hazard: 0.5% of slopes fail	> 0.2
B	≥ 1.2 - 1.5	Moderate Hazard: 0.5% to 5% of slopes fail	> 0.10 - 0.20
C	≥ 1.1 - 1.2	Moderately High Hazard: 5% to 20% of slopes fail	≥ 0.05 - 0.10
D	1.0 - 1.1	High Hazard: 20% or more of slopes fail	< 0.05
* during or immediately following earthquake. The concept of factor of safety is described in Appendix B.			

4.5 EARTHQUAKE-INDUCED SLOPE INSTABILITY HAZARD MAPS

Map 4 illustrates the slope-instability hazard for the Auckland Region, assuming a uniform level of PGA of 0.17g to 0.27g depending on the soil/rock type (ie. no particular epicentre is modelled). This is the level of PGA expected within 20km of a potential 2000 year return period earthquake epicentre.

Maps 5A and 5B designate areas of low, moderate, moderately high and high hazard corresponding to expected percentages of all slopes within each hazard zone, likely to fail as a result of the 2000 year earthquake scenario adopted. ***It is important to note that these zones will change (ie have a different distribution) if different epicentres are adopted.***

The maps show that slopes within the radial area in closest proximity to the earthquake epicentre will generally experience the highest level of earthquake-induced slope failure. Locally, areas of steep ground in Class B and D deposits, some distance from the epicentre are also affected.

Map 5A shows that the adopted earthquake scenario would result in failure of 20% or more of slopes in the vicinity of many of Auckland's essential lifelines corridors, in particular, in the vicinity of the water supply dams of the Hunua Ranges. Slopes adjacent to water supply dams in the Waitakere Ranges would also be affected, with 5 to 20% of slopes expected to fail.

It is noted that almost all slopes within the Auckland Region fall within the high hazard zone when subjected to ground accelerations in excess of 0.2g (Map 4). This needs to be considered when evaluating the effects of earthquake on slope stability for other, equally plausible, 2000 year earthquake scenarios, with epicentres at different locations from the one selected for this study.

Appendix A: Ground shaking hazard zones and soil classification table

Hazard Zone	Soil Foundation Condition	Soil Category	Engineering Description of Soils/Rock	SPT Blows/300mm (N)	Shear Wave Velocity (m/s)[1]	Typical Ground Failures Resulting From Earthquakes
1	*Residual Soil Overlying Rock*	Residual and colluvial soils, ash and weathered tuff: • up to 30m, overlying greywacke; • up to 20m overlying interbedded sandstone and mudstone; conglomerate and basalt	• CW:[2] sand/silt/clay • HW: gravel in a silty sand/clay matrix • MW: very weak rock • SW-UW: weak to moderately strong rock	5 - 25+ 15 - 50+ 30 - 100+ 50 - 200+	100 - 300 200 - 500 300 - 1000 500 - 2000	• Generally minor to nil damage to gentle slopes; • Movements on critically steep slopes, and on gentle slopes in sandstone and mudstone with clay seams, undercut by streams and coastal erosion.
2	*Firm to Stiff Sediment of Pleistocene age*	• Alluvium; • Basalt, ash and tuff overlying alluvium	• Soft to very stiff alluvium; • Sensitive pumiceous silt; silt, peat and clay; • Loose to dense sand and breccia; • Ash, tuff and basalt overlying these deposits	5 - 25[3]	100 - 300	• Widespread failure of coastal cliffs and river banks; • Movement on moderate to steep slopes; • Localised liquefaction of saturated loose sand lenses in severe[4] shaking
3	*Coastal Deposits*	• Beach and dune sands; • Man-made fills overlying zone 1 or 2 deposits	• Medium dense fine sand and shell, saturated; • Loose fine sand, unsaturated	5 - 40	100 - 500	Localised liquefaction of saturated loose sand pockets
4	*Estuarine Deposits of Holocene age*	• Stream alluvium and swamp deposits; • Man-made fills overlying zone 3 or 4 deposits	Very soft to stiff mud, silt, peat, pumiceous clay; typically saturated	0 - 10	50 - 200	• Widespread sliding failures of moderate slopes; • Widespread liquefaction of saturated sand deposits in moderate shaking

(1) Values of shear wave velocity are assessed

(3) Where basalt rock overlies deep alluvium, the rock stiffness does not significantly influence site behaviour

(4) Shaking levels:
Severe ≥ 0.40g ≥ Strong 0.20g ≥ Moderate 0.15g ≥ Moderate to Low 0.1g ≥ Low 0.05g

(2) Rock Weathering Grades:
CW completely weathered; HW highly weathered (soil)
MW moderately weathered (very weak rock)
SW slightly weathered; UW unweathered (rock)

APPENDIX B: FACTORS OF SAFETY

In slope stability studies, the factor of safety, F is the ratio of resisting forces (shear strength of the soil) to the disturbing forces (gravity). A factor of safety of unity (F = 1.0) indicates that the disturbing forces are equal to the resisting forces an that the soil mass is just on the point of moving, that is, becoming unstable.

Factors of safety of greater than unity (F > 1.0) ae used in engineering design to cover variation and uncertainty in both the properties of materials and the method of calculation. Factors of safety are used in design to provide a **margin of stability** and to limit the risk of failure.

It is important to note that the theoretically calculated factor of safety allows for variations in the soil strength (lower bound of expected values are generally used) and inaccuracies in the method of analysis. In practice, it has been found that on the average, F = 1.0 means that there is a risk of 1:5 that failure will occur in any single year. Table A below shows the average level of risk for different factors of safety used.

Table A: Factors of safety versus risk level

Factor of Safety, F	Risk of Failure per Annum
0.8	1:1
1.0	1:5
1.1	1:10
1.2	1:20
1.5	1:200
1.7	1:1,000
2.0	1:10,000

It is noted that in general engineering practise, F = 1.5 is normally used for permanent civil engineering works such as subdivisional slopes, cuts, bridge abutments and road embankments. Other factors of safety are used for more specialised applications. An F = 1.7 has been used in recent years for major earth dams.

A lesser F = 1.2 to 1.3 is normally used for temporary conditions, ie a few weeks to a few months. F = 1.1 is only considered appropriate for earthquake loading.

MAP 1A: GROUND SHAKING HAZARD AND SOIL/ROCK MASS DISTRUBUTION: REGION A

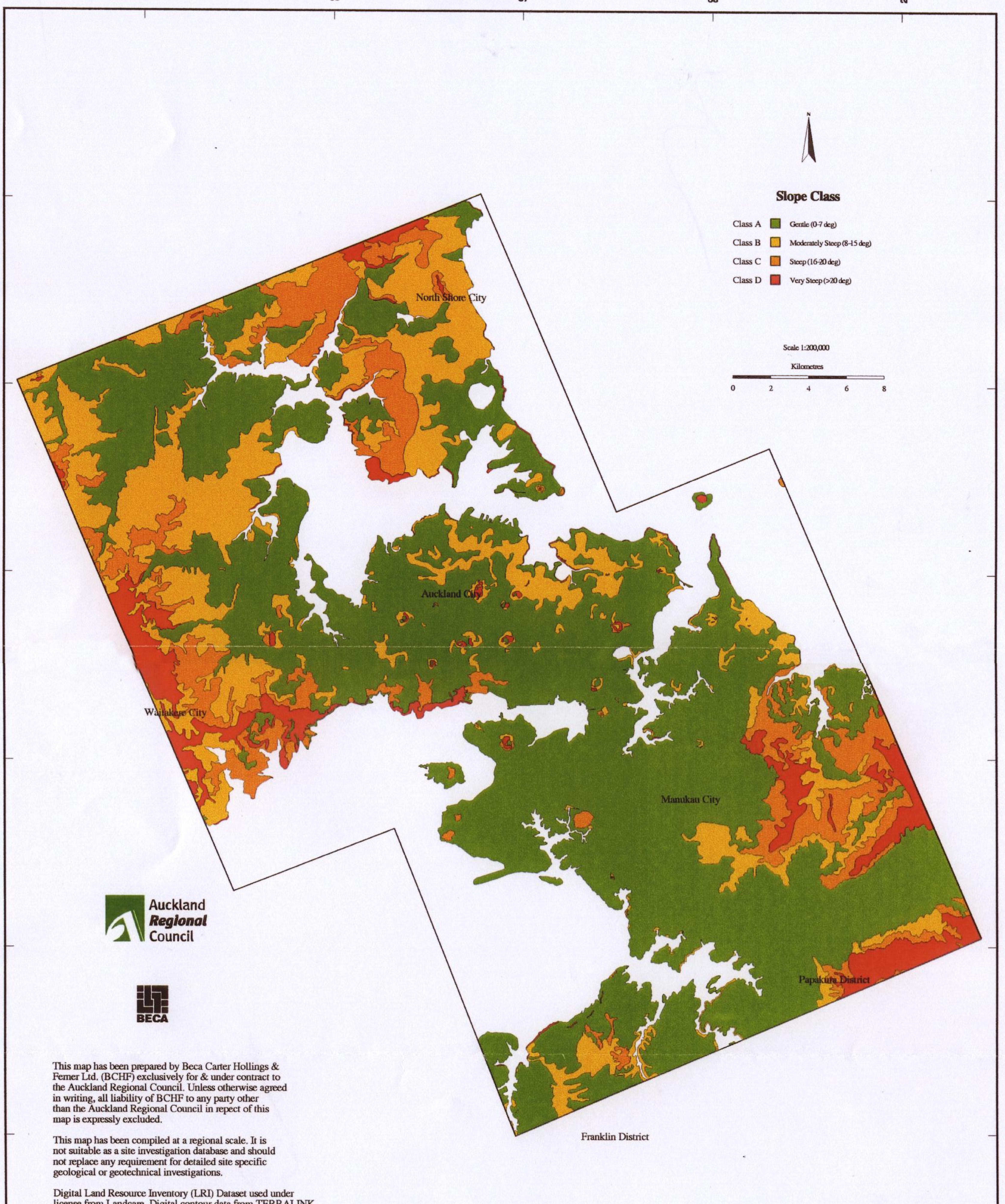
This is the same as Map 1A, Report 2.1 (Ground Shaking Hazard)

Map 1B: GROUND SHAKING HAZARD AND SOIL/ROCK MASS DISTRIBUTION: REGION B

This is the same as Map 1B, Report 2.1 (Ground Shaking Hazard)

Slope Grade Distribution

Region A



Auckland Regional Council

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This map has been compiled at a regional scale. It is not suitable as a site investigation database and should not replace any requirement for detailed site specific geological or geotechnical investigations.

Digital Land Resource Inventory (LRI) Dataset used under license from Landcare. Digital contour data from TERRALINK 1:50,000 (20m contour) data set, licence no. TD093602/2/94. Digital topographic data from TERRALINK, licence no. TD5/90.

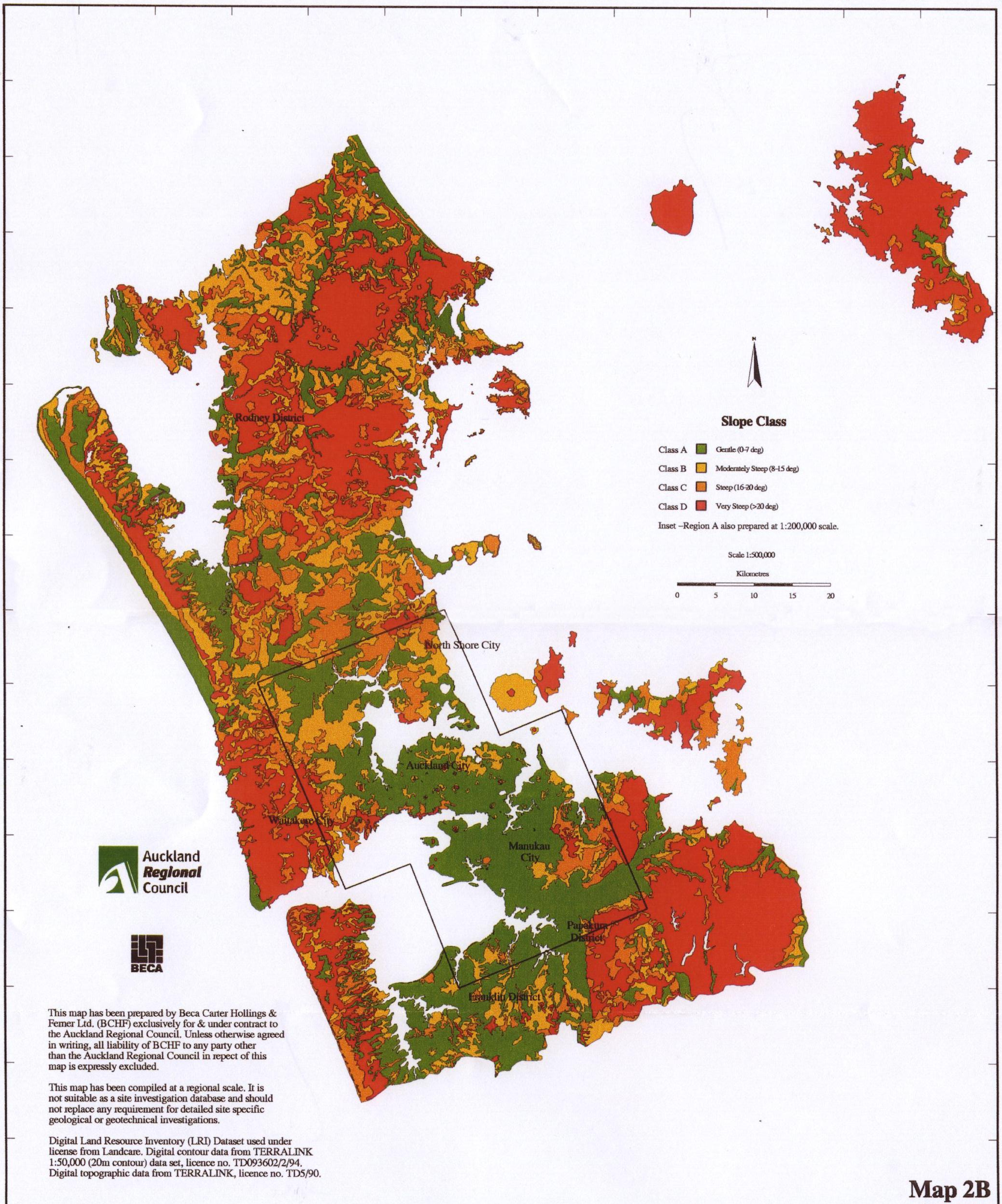
Map 2A

Auckland Engineering Life Lines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Slope Grade Distribution

Region B



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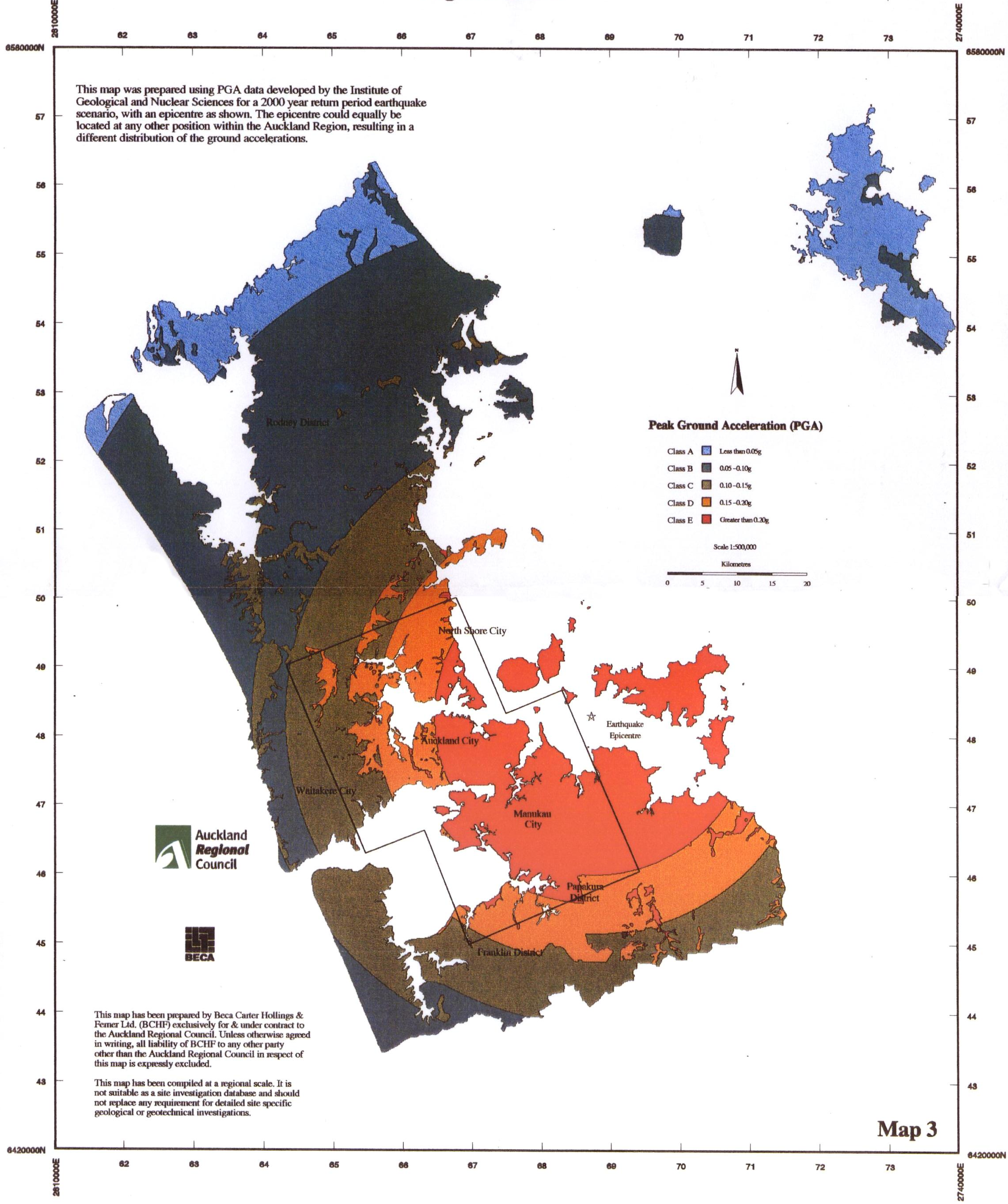
Peak Ground Accelerations : 2000 Year Earthquake Scenario

Region A and B



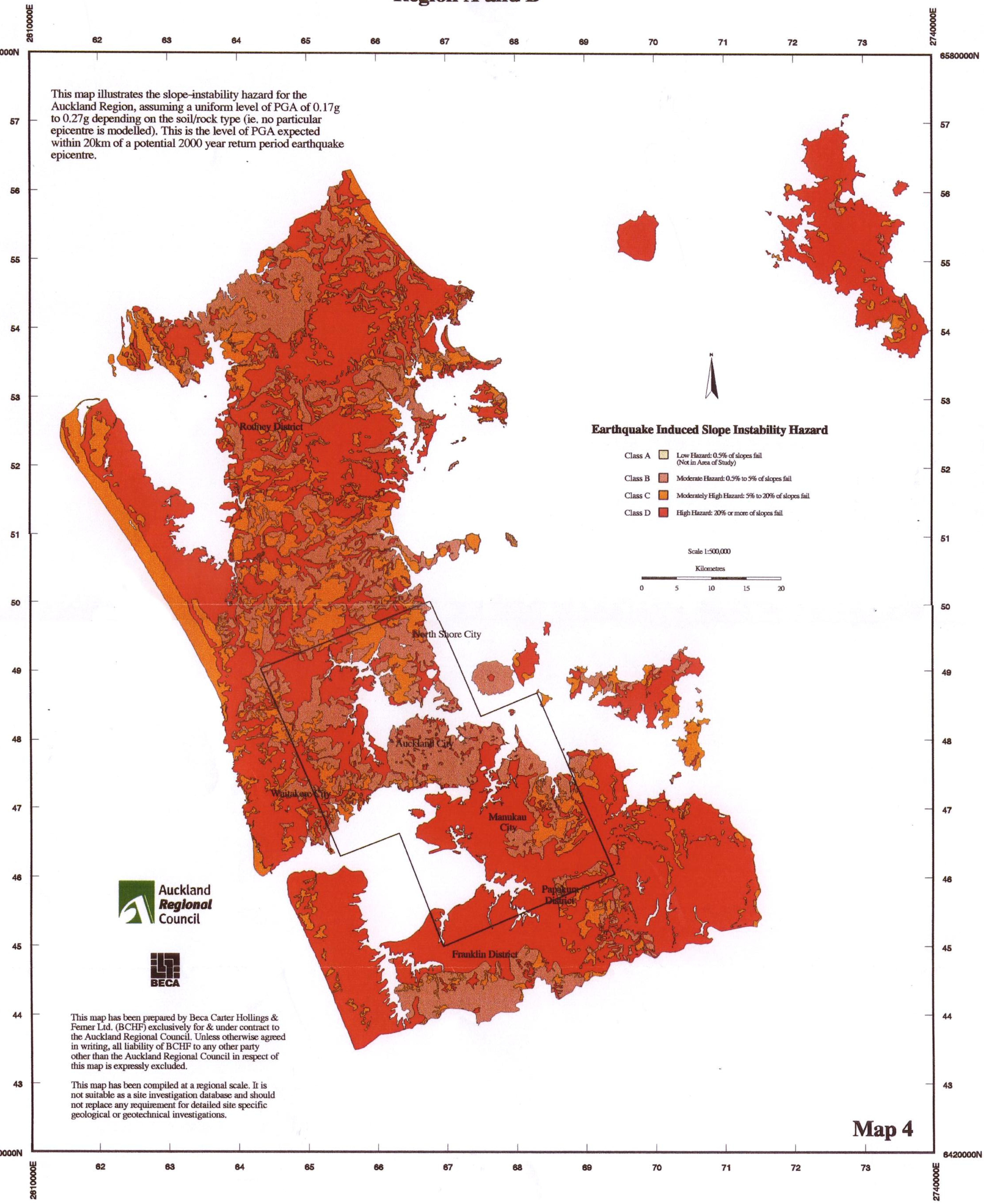
Auckland Engineering Life Lines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Earthquake Induced Slope Instability : 2000 Year Earthquake Uniform Hazard

Region A and B

This map illustrates the slope-instability hazard for the Auckland Region, assuming a uniform level of PGA of 0.17g to 0.27g depending on the soil/rock type (ie. no particular epicentre is modelled). This is the level of PGA expected within 20km of a potential 2000 year return period earthquake epicentre.



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Map 4

Auckland Engineering Life Lines

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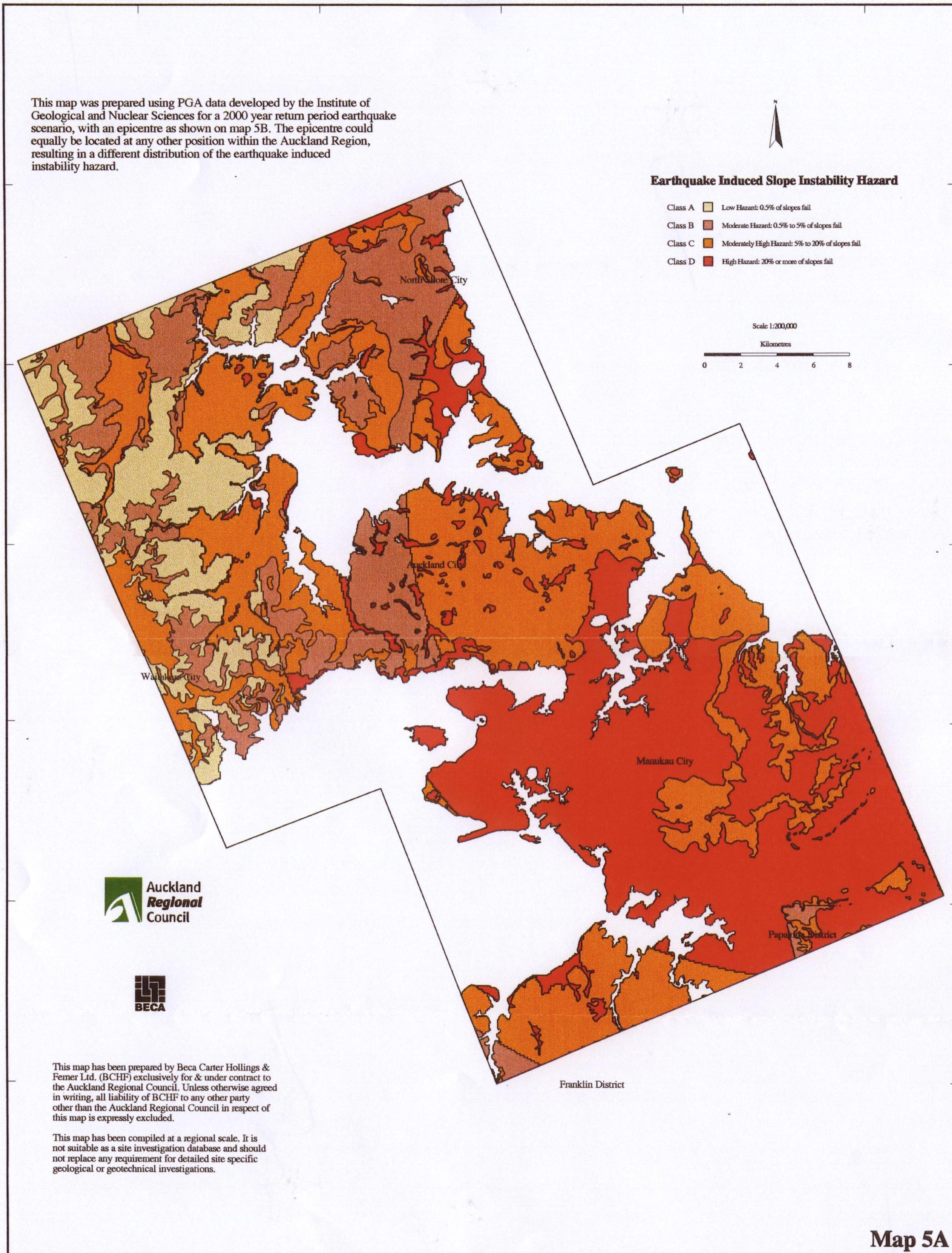
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Earthquake Induced Slope Instability Hazard : 2000 Year Earthquake Scenario

Region A

This map was prepared using PGA data developed by the Institute of Geological and Nuclear Sciences for a 2000 year return period earthquake scenario, with an epicentre as shown on map 5B. The epicentre could equally be located at any other position within the Auckland Region, resulting in a different distribution of the earthquake induced instability hazard.



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Map 5A

Auckland Engineering Life Lines

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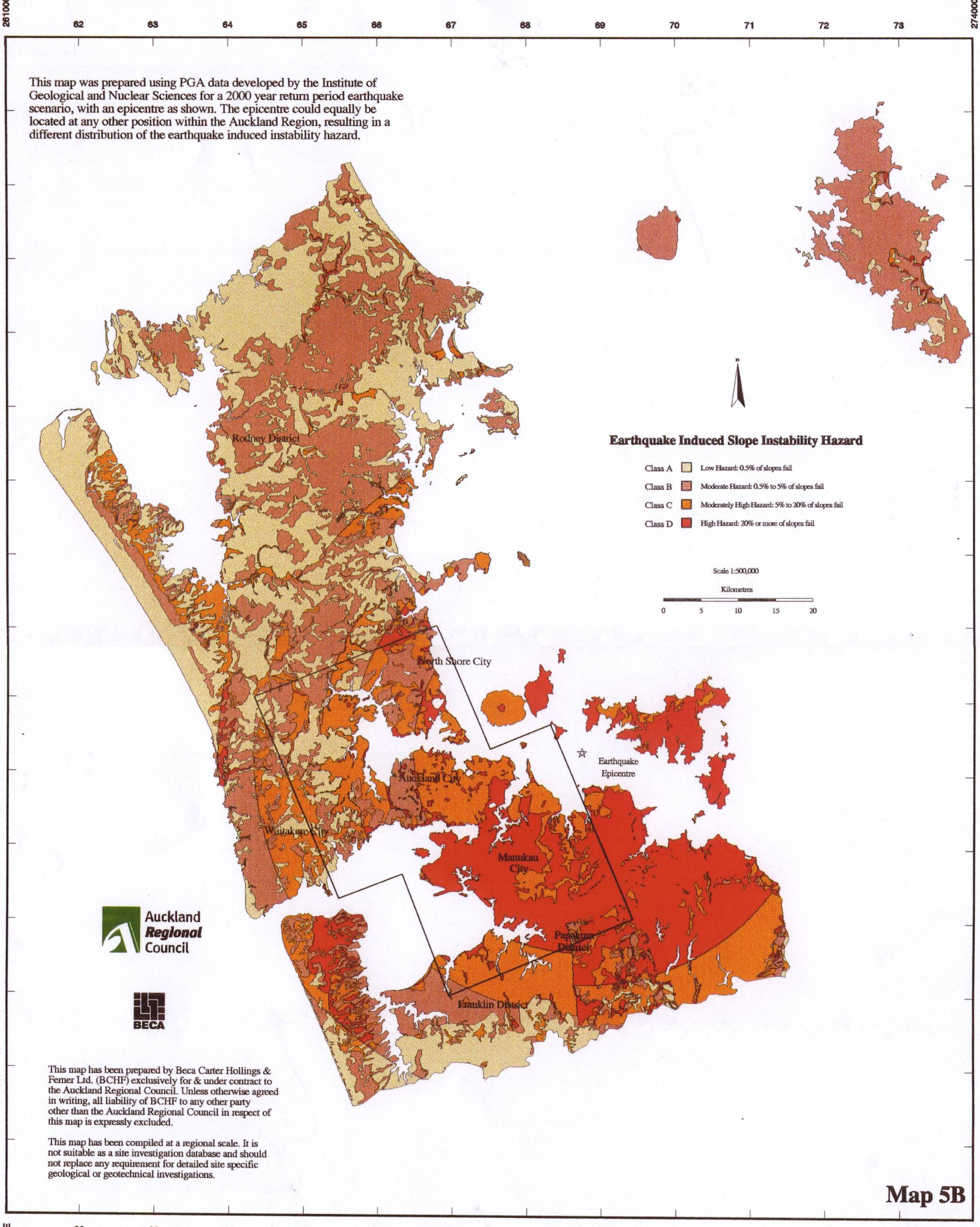
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Earthquake Induced Slope Instability Hazard : 2000 Year Earthquake Scenario

Region B

This map was prepared using PGA data developed by the Institute of Geological and Nuclear Sciences for a 2000 year return period earthquake scenario, with an epicentre as shown. The epicentre could equally be located at any other position within the Auckland Region, resulting in a different distribution of the earthquake induced instability hazard.



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Map 5B

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It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

REPORT 2.4

LIQUEFACTION SUSCEPTIBILITY HAZARD MAP (Accompanying Notes)

Prepared for

AUCKLAND REGIONAL COUNCIL

By

BECA CARTER HOLLINGS & FERNER LTD

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CONTENTS

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1.0 INTRODUCTION

The Resource Management Act (1991) designates responsibility for integrated management of the land, natural and physical resources, and avoidance or mitigation of natural hazards to Central, Regional and Local Government. As part of the Auckland Regional Council's responsibilities under the Act, a series of studies are being undertaken to assess the potential risks and impacts of seismic hazard to the Auckland Region. These studies make use of the fault hazard and ground shaking maps presented in ARC Technical Publication No.57 and the preliminary slope instability hazard map presented in ARC Technical Publication No.71, and include assessments of:

- Ground Shaking Hazard;
- Earthquake Induced Slope Instability Hazard; and
- Liquefaction Susceptibility Hazard, the subject of this document.

The Auckland Engineering Lifelines Project was developed to provide a contemporary scientific base to aid agencies responsible for Auckland's lifelines services in their understanding of the likely effects of future earthquakes in the Auckland Region and hence assist in the identification of services vulnerability as part of the next stage of the Lifelines Project. A 2000 year return period earthquake scenario was developed as part of the project[1]. This document discusses the resultant susceptibility of Auckland's soils to liquefaction .

The objectives of the Liquefaction Susceptibility Hazard assessment are to:

(i) Identify those areas of the Auckland Region that are potentially susceptible to liquefaction as a result of ground shaking associated with a 2000 year return period earthquake in the Auckland Region. The liquefaction susceptibility hazard is assessed both in terms of a uniform hazard model for the Auckland Region and a scenario caused by a single earthquake with its epicentre within 20km of Auckland City. Details of the uniform hazard model and the scenario earthquake are provided by IGNS[1]; and

(ii) Identify the likely effects of earthquake induced liquefaction on lifeline structures (next stage of the Auckland Engineering Lifelines Project).

The Liquefaction Susceptibility Hazard Maps are produced at the following scales:

- Region A, areas of medium to high population and services density, 1:100,000;
- Region B, areas of low population and services density, 1:250,000.

For ease of presentation and reproduction, maps accompanying this report are produced at scales of 1:200,000 and 1:500,000 respectively. This report should be read in conjunction with the maps and provides background information on liquefaction and the methodology for compilation of the maps.

Notice to Reader/User of this Document:

This report is the property of our Client, the Auckland Regional Council, and Beca Carter Hollings & Ferner Ltd. This document discusses soil types and liquefaction at a regional scale. It is not suitable for use as a regional or site investigation database and shall not replace any requirement for detailed site specific geological or geotechnical investigation and/or analysis.

[1] *IGNS 1997: Peak Horizontal Ground Accelerations and Modified Mercalli Intensities forScenario Earthquakes in the Auckland region: Auckland Engineering Lifelines Project Report Prepared for The Auckland Regional Council, June 1997.*

2.0 SEISMICITY OF THE AUCKLAND REGION

2.1 EARTHQUAKE EVENTS RECORDED WITHIN THE AUCKLAND REGION

The Auckland Region occurs within one of the least historically (last 150 years) seismically active regions of New Zealand. This is in part because Auckland is located some 300km from the major northeast-southwest oriented seismically active zone which lies beneath the east coast of the North Island and marks the junction between the Australian and Pacific tectonic plates. This zone is judged to be capable of producing large (Richter magnitude, M ≥ 8) earthquakes.

Historical earthquakes and their effects are described together with known faults of the Auckland Region in the ARC Technical Publication No.57 dated April 1995. A summary of historical earthquakes of Richter magnitude ≥ 5 is presented in Table 1.

Table 1: HISTORICAL EARTHQUAKES OF MAGNITUDE >5 RECORDED WITHIN THE AUCKLAND REGION

Date	Latitude (°S)	Longitude (°E)	Magnitude[A]	Distance of Epicentre from Central Auckland (km)
1834/1835	37	175	5.5 - 5.6	25
23.06.1891	37.4	174.7	5.7 - 5.9	60
28.02.1974	36.6	177.0	5.9	>200

[A] Magnitude (Richter) is a measure of the energy released by an earthquake at its source.

2.2 2000 YEAR EARTHQUAKE SCENARIO

2.2.1 Kerepehi Fault

In the past, earthquake scenarios for engineering and emergency management projects in the Auckland area have modelled ground shaking derived from an earthquake along the Kerepehi fault, a known active fault to the east of Auckland. Although the Kerepehi fault is located outside the Auckland Region, the fault is known to be active on land (multiple movements within the last 125,000 years) in the central Hauraki Plains[2]. Investigations suggest it extends offshore of the central Hauraki Plains into the Firth of Thames where it is probably also active. From investigations of fault length and single-event displacements, the fault is believed to be capable of generating earthquakes of about magnitude 7. Shaking from these earthquakes would cause moderate to strong ground accelerations within the Auckland Region[2].

Studies as part of the Auckland Engineering Lifelines Project indicate that an earthquake of magnitude 6.9 on the offshore extension of the Kerepehi fault, and an expected return period of about 5000 years, would generate a Peak Ground Acceleration (PGA) of 0.15g in Auckland City[3].

2.2.2 Uniform Hazard Model

A uniform hazard model developed for several engineering studies within Auckland was used to estimate the ground motions expected in central Auckland from a 2000 year return period earthquake event[3]. The uniform hazard model is developed using the available historical record of earthquakes felt in the Auckland Region (refer Table 1). This model estimates a PGA of 0.17g to 0.27g (depending on the soil type) for the central Auckland area.

[2] *Auckland Regional Council Technical Publication No.57, April 1995.*

[3] *IGNS 1997: Peak Horizontal Ground Accelerations and Modified Mercalli Intensities forScenario Earthquakes in the Auckland region: Auckland Engineering Lifelines Project Report Prepared for The Auckland Regional Council, June 1997.*

When applied uniformly to the whole of the Auckland Region, this model allows an assessment of liquefaction susceptibility within 20km of any potential epicentre, which could be located anywhere within the Region (Map 3).

However, for the purposes of the engineering lifelines project, it is useful to simulate one realistic earthquake with a selected earthquake epicentre. This event will generate the highest levels of PGA at the epicentre, reducing with distance from the epicentre.

The scenario earthquake selected for the Lifelines Project is one that generates this expected higher level of PGA, rather than an earthquake associated with the Kerepehi fault. The Kerepehi fault scenario was not used for the Engineering Lifelines Project because it does not produce levels of ground shaking as high as those likely to occur in a 2000 year return period earthquake.

The scenario adopted is a point source magnitude 6.0 earthquake at 10km depth, with an epicentre 20km east of central Auckland. This location was selected so that:

- The higher PGA values calculated from the uniform hazard model for a 2000 year earthquake cover the central Auckland area; and

- PGA values higher than expected for a 2000 year event (ie PGA's indicative of a longer average return period) occur at less critical areas (in terms of engineering lifelines) offshore, and would not affect the central part of Auckland City.

Because this scenario earthquake is arbitrarily selected, its epicentre could equally be at any other location within the Auckland Region, resulting in a different distribution of ground motions.

2.3 LIQUEFACTION HAZARD

Liquefaction occurs in saturated cohesionless soils, that is, relatively clean sands and gravels, in response to repeated ground shaking generated during earthquakes. Under the influence of repeated shearing, the soils tend to compact, with a resulting transfer of stress to the pore water and a severe reduction of stress between the soil grains. If the resultant increase in pore water pressure rises to the point of equalling the overburden stresses in the soil, the strength of the soil is reduced to near zero and bearing capacity failure, mass soil movement (liquefaction-induced slope instability and lateral spreading) and subsidence can occur. The soil is then said to have liquefied.

The response to earthquake shaking is dependant on a number of factors including the density and grading of the sands being shaken, whether the sands are saturated and the duration and strength of ground shaking. Standard Penetration Tests (refer Soil Classification Table, Appendix A) have traditionally been used to assess liquefaction potential based on correlation between the blowcounts recorded and the density of the in-situ sands.

The likely effects of liquefaction on structures are outlined in the Earthquake-Induced Damage to Structures Matrix (Report 2.5).

3.0 SOILS AND ROCKS OF THE AUCKLAND REGION

3.1 SOIL AND ROCK TYPES

Much of the Auckland urban area is built on Miocene, Pliocene and Quaternary sedimentary rocks and soils. Younger basaltic volcanoes have erupted through these rocks, resulting in a wide range of volcanic landforms such as scoria cones, lava fields, explosion craters and tuff rings. The majority of these volcanic deposits rest upon residual and transported soils, rather than rock.

West of central Auckland, the hills of the Waitakere Ranges are underlain by volcanic and volcaniclastic rocks (sedimentary rocks derived from eroded Miocene-age volcanoes), and to the east, the hills of the Whitford-Brookby area and the islands of Motutapu, Motuihe, and in part, Waiheke, Kawau, Little Barrier and Great Barrier are underlain by weathered greywacke rocks. To the north, soft sedimentary rocks and hard volcanic rocks support gentle to moderately sloping lowlands and upstanding ranges respectively. Weathering has produced a regolith of soil and slope debris up to 20m to 30m thick.

The Quaternary deposits (Pleistocene and Holocene age, ie <1.6 million years) comprise soils which have been transported into place. The Pleistocene deposits (10,000 to 1.6 million years) generally occur on higher ground, and tend to be stronger and have a lower moisture content than the Holocene deposits. However, they are soils (not rock) and do contain some loose sands and sensitive pumiceous silts which are susceptible to liquefaction (refer Maps 1A and 1B).

In general, the Holocene age deposits comprise both sandy coastal deposits and soft clayey estuarine deposits. These are the weakest materials encountered in the Auckland Region and, because of their location, typically in low lying areas adjacent to swamps and water courses, they tend to be saturated.

3.2 SUSCEPTIBILITY TO LIQUEFACTION

Parameters of particular importance when considering susceptibility of soils to liquefaction include:

- Soil type, including relative density of the sands;
- Soil profile, including depth and thickness of the sand layer;
- Ground-water level; and
- Level and duration of earthquake shaking.

The less dense, saturated Quaternary sands and man-made ground (including reclamations constructed from sandy hydraulic fill) are likely to have the highest liquefaction susceptibility.

4.0 LIQUEFACTION HAZARD CONTRIBUTIONS

4.1 SOIL/ROCK CATEGORY

The soil and rock mass types (detailed in ARC Technical Publication No.71, June 1996) have been grouped according to their expected response to ground shaking from earthquakes (Appendix A). The groupings are based on the characteristic physical properties and known behaviour of the soil and rock types both in the Auckland Region and in other parts of New Zealand. Some soils within Zones 2, 3 and 4 are potentially liquefiable:

Soils Unlikely to Liquefy (These soils are mapped as Class A on Maps 1A and 1B):

Zone 1. *Residual Soils overlying Rock*

- Residual and colluvial soils, ash and weathered tuff:
- up to 30m thick, overlying greywacke;
- up to 20m thick overlying interbedded sandstone and mudstone; and associated with conglomerate and basalt.

Zone 2. *Firm to Stiff Sediment of Pleistocene Age*

- Firm to stiff alluvium; and
- Basalt, ash and tuff overlying alluvium.

Soils Susceptible to Liquefaction

Zone 2. *Sediment of Pleistocene Age* (Class B, Maps 1A and 1B):

- Soft to firm (loose to medium dense) pumiceous deposits up to several metres thick.

Zone 3. *Coastal Deposits* (Class C, Maps 1A and 1B):

- Beach and dune sands;
- Man-made fills overlying zone 1. or 2. deposits.

Zone 4. *Estuarine Deposits of Holocene Age* (Class D, Maps 1A and 1B):

- Stream alluvium and swamp deposits; and
- Man-made fills overlying zone 3. or 4. deposits.

Soils susceptible to liquefaction are identified on Maps 1A and 1B.

4.2 LEVEL OF EARTHQUAKE SHAKING

Liquefaction susceptibility is assessed in terms of:

(i) a uniform level of peak horizontal ground accelerations (PGA's) at bedrock (which gives rise to PGA's at the ground surface of 0.17g to 0.27g depending on the soil/rock type) expected within 20km of a potential 2000 year return period earthquake epicentre. No specific earthquake epicentre is modelled; and

(ii) PGA's likely to be generated by the selected 2000 year return period earthquake scenario modelled by the IGNS. The scenario PGA data has been grouped into classes and reproduced as Map 2 of this report.

4.3 GROUNDWATER LEVEL

In view of the large area covered, and the scale of the maps, a uniform groundwater level of 1.5m below ground surface has been assumed, except for areas within Region A (1:100,000) in which the groundwater level is clearly known to differ from this level.

4.4 LIQUEFACTION HAZARD ASSESSMENT

The liquefiable soil types (Maps 1A and 1B) were superposed on the uniform hazard model (PGA's of > 0.2g for liquefiable soils) and the PGA scenario (Map 2) using the GIS based ArcInfo system to produce the liquefaction susceptibility hazard maps, Maps 3, 4A and 4B.

The liquefaction susceptibility hazard is dependent on the level of ground accelerations that the potentially liquefiable soils are subject to, as described in Table 2. Manual adjustment of the categories was made to take into account thin layers of sand occurring between or together with clayey soils, thin surficial sand layers that are not saturated, and areas where the groundwater table is known to occur at depth.

Table 2: LIQUEFACTION SUSCEPTIBILITY HAZARD

Class	PGA (g)	Liquefaction Susceptibility Hazard
A	≤ 0.05	0% liquefaction
B	0.05 - 0.10	0 - 0.5% liquefaction of all Class B soils
C	0.10 - 0.15	0.5 - 10% liquefaction of all Class C soils
D	0.15 - 0.20	10 - 30% liquefaction of all Class D soils
E	> 0.20	30 - 90% liquefaction of all Class E soils

5.0 LIQUEFACTION SUSCEPTIBILITY HAZARD

5.1 LIQUEFACTION SUSCEPTIBILITY HAZARD MAPS

Map 3 illustrates the liquefaction susceptibility hazard for the Auckland Region, assuming a uniform level of PGA of 0.17g to 0.27g depending on the soil/rock type. As soil types which are potentially liquefiable are likely to experience ground shaking of >0.2g for this model (which corresponds to Class E of Table 1), the likelihood of liquefaction of such soils within 20km of any 2000 year return period earthquake epicentre is high, that is, in the order of 30-90%.

For the 2000 year return period earthquake scenario selected, all of Region A (Map 4A) is subject to levels of PGA of greater than 0.15g, and much of the area is subject to levels of PGA greater than 0.2g. This means that on average, 30 - 90% of potentially liquefiable soils within Region A will liquefy as a result of the scenario event.

Essential lifelines services particularly vulnerable to liquefaction include Auckland International Airport sited on insitu and reclaimed ground, and Auckland's rail and port facilities located on reclamations comprising a range of hydraulic and other fill materials (refer Report 2.5).

Map 4B shows that the scenario event will also impact liquefiable soils in the northernmost part of the region, with, on average, 0.5 - 10% of such soils expected to liquefy.

5.2 ANTICIPATED EFFECTS OF LIQUEFACTION ON STRUCTURES

The consequences of liquefaction to structures are outlined in the Earthquake-Induced Damage to Structures Matrix (Report 2.5) and include:

- loss of vertical support;
- large lateral movements (including lateral spreading and liquefaction-induced slope failure) which would damage any structures founded at a shallow depth;
- failure and/or severe damage to coastal reclamation structures; and
- rupture of pavements, and services such as pipelines, constructed over or founded within these soils.

Appendix A: GROUND SHAKING HAZARD AND SOIL CLASSIFICATION TABLE

Hazard Zone	Soil Foundation Condition	Soil Category	Engineering Description of Soils/Rock	SPT Blows/300mm (N)	Shear Wave Velocity (m/s)[1]	Typical Ground Failures Resulting From Earthquakes
1	*Residual Soil Overlying Rock*	Residual and colluvial soils, ash and weathered tuff: • up to 30m, overlying greywacke; • up to 20m overlying interbedded sandstone and mudstone; conglomerate and basalt	• CW: [2] sand/silt/clay • HW: gravel in a silty sand/clay matrix • MW: very weak rock • SW-UW: weak to moderately strong rock	5 - 25+ 15 - 50+ 30 - 100+ 50 - 200+	100 - 300 200 - 500 300 - 1000 500 - 2000	• Generally minor to nil damage to gentle slopes; • Movements on critically steep slopes, and on gentle slopes in sandstone and mudstone with clay seams, undercut by streams and coastal erosion.
2	*Firm to Stiff Sediment of Pleistocene age*	• Alluvium; • Basalt, ash and tuff overlying alluvium	• Soft to very stiff alluvium; • Sensitive pumiceous silt; silt, peat and clay; • Loose to dense sand and breccia; • Ash, tuff and basalt overlying these deposits	5 - 25 [3]	100 - 300	• Widespread failure of coastal cliffs and river banks; • Movement on moderate to steep slopes; • Localised liquefaction of saturated loose sand lenses in strong (>0.2g) shaking
3	*Coastal Deposits*	• Beach and dune sands; • Man-made fills overlying zone 1 or 2 deposits	• Medium dense fine sand and shell, saturated; • Loose fine sand, unsaturated	5 - 40	100 - 500	Localised liquefaction of saturated loose sand pockets
4	*Estuarine Deposits of Holocene age*	• Stream alluvium and swamp deposits; • Man-made fills overlying zone 3 or 4 deposits	Very soft to stiff mud, silt, peat, pumiceous clay; typically saturated	0 - 10	50 - 200	• Widespread sliding failures of moderate slopes; • Widespread liquefaction of saturated sand deposits in moderate shaking

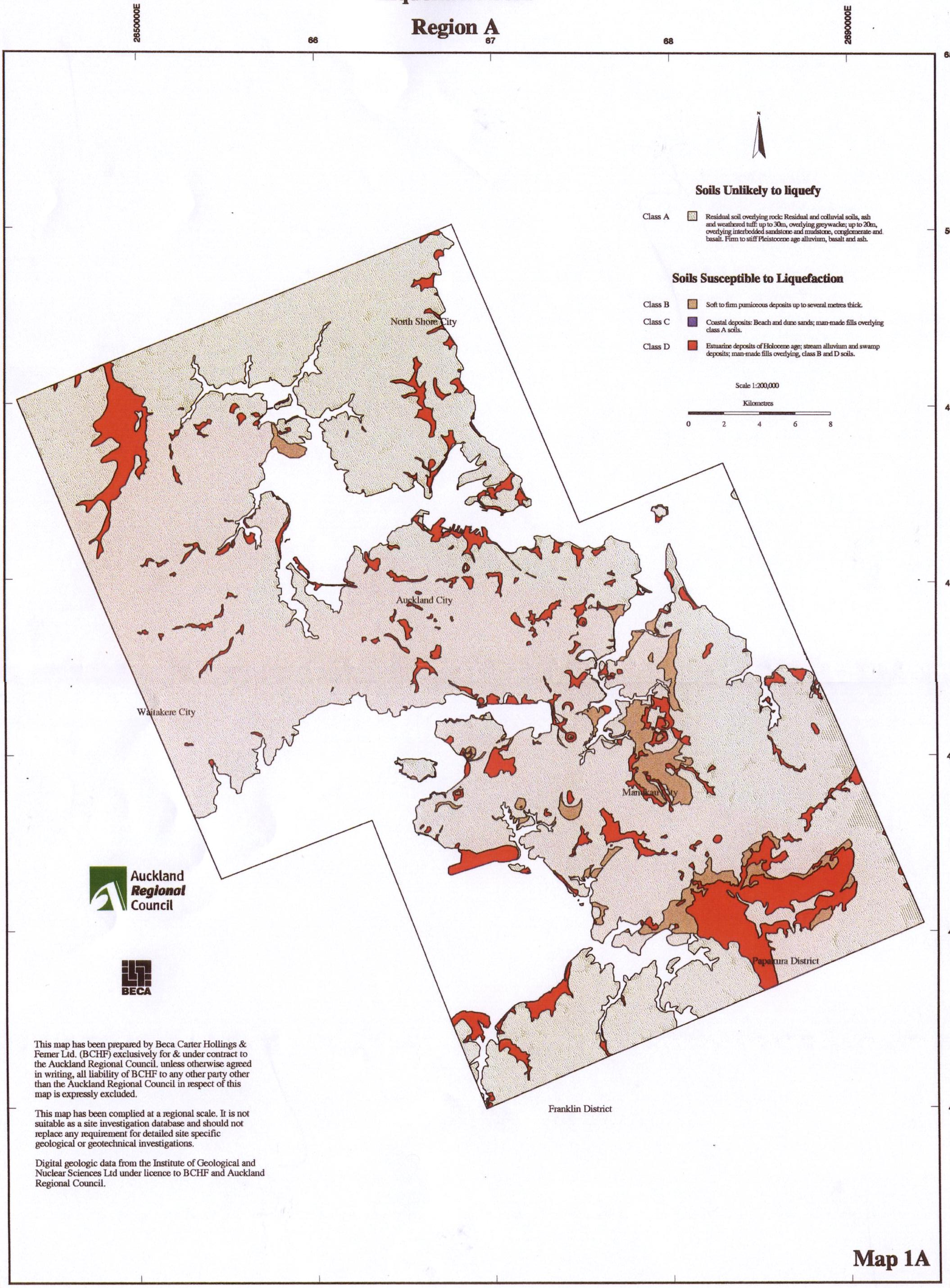
(1) Values of shear wave velocity are assessed

(3) Where basalt rock overlies deep alluvium, the rock stiffness does not significantly influence site behaviour

(2) Rock Weathering Grades:
CW completely weathered; HW highly weathered (soil)
MW moderately weathered (very weak rock)
SW slightly weathered; UW unweathered (rock)

Liquefiable Soils

Region A

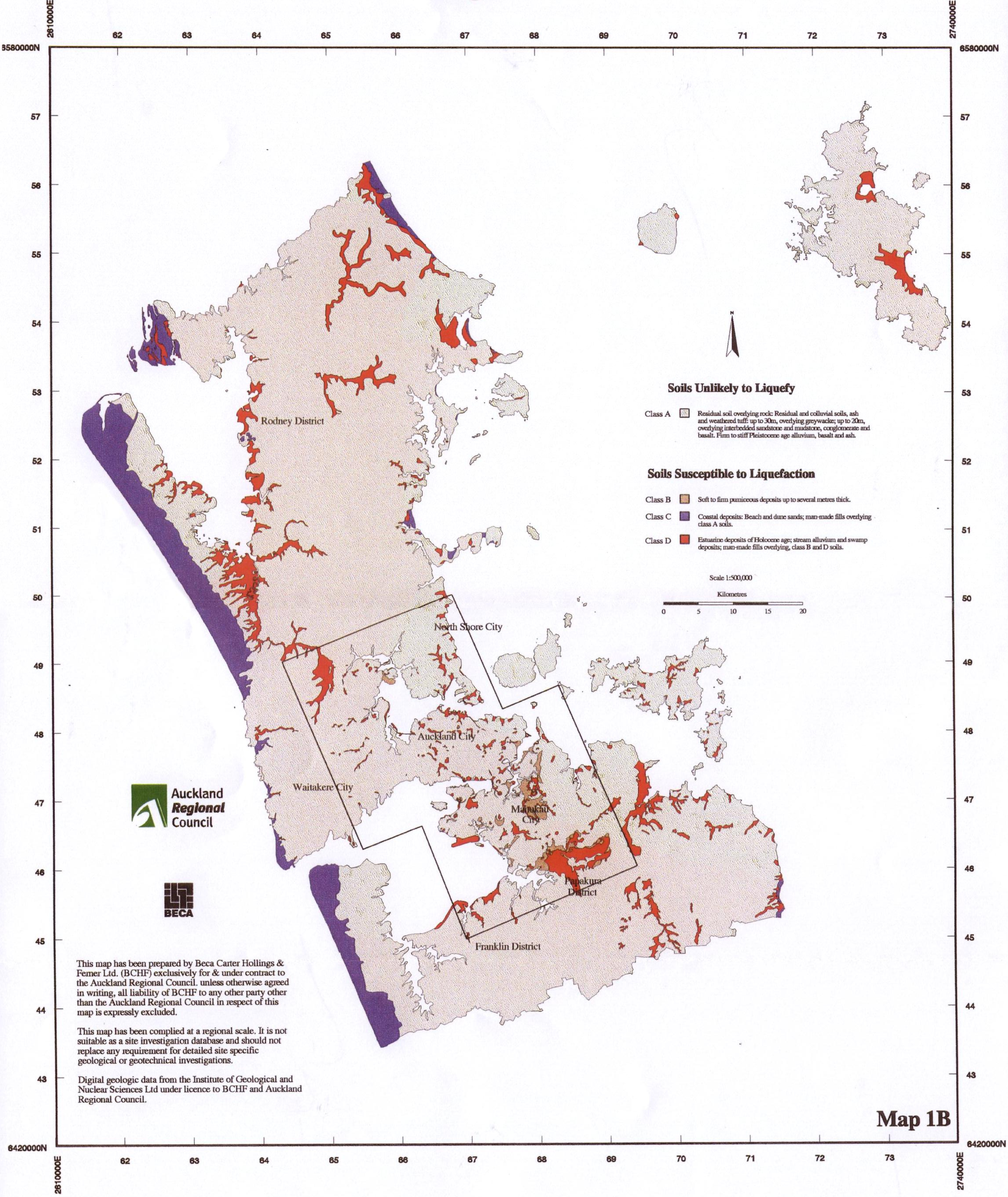


Auckland Engineering Life Lines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Liquefiable Soils

Region B



This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

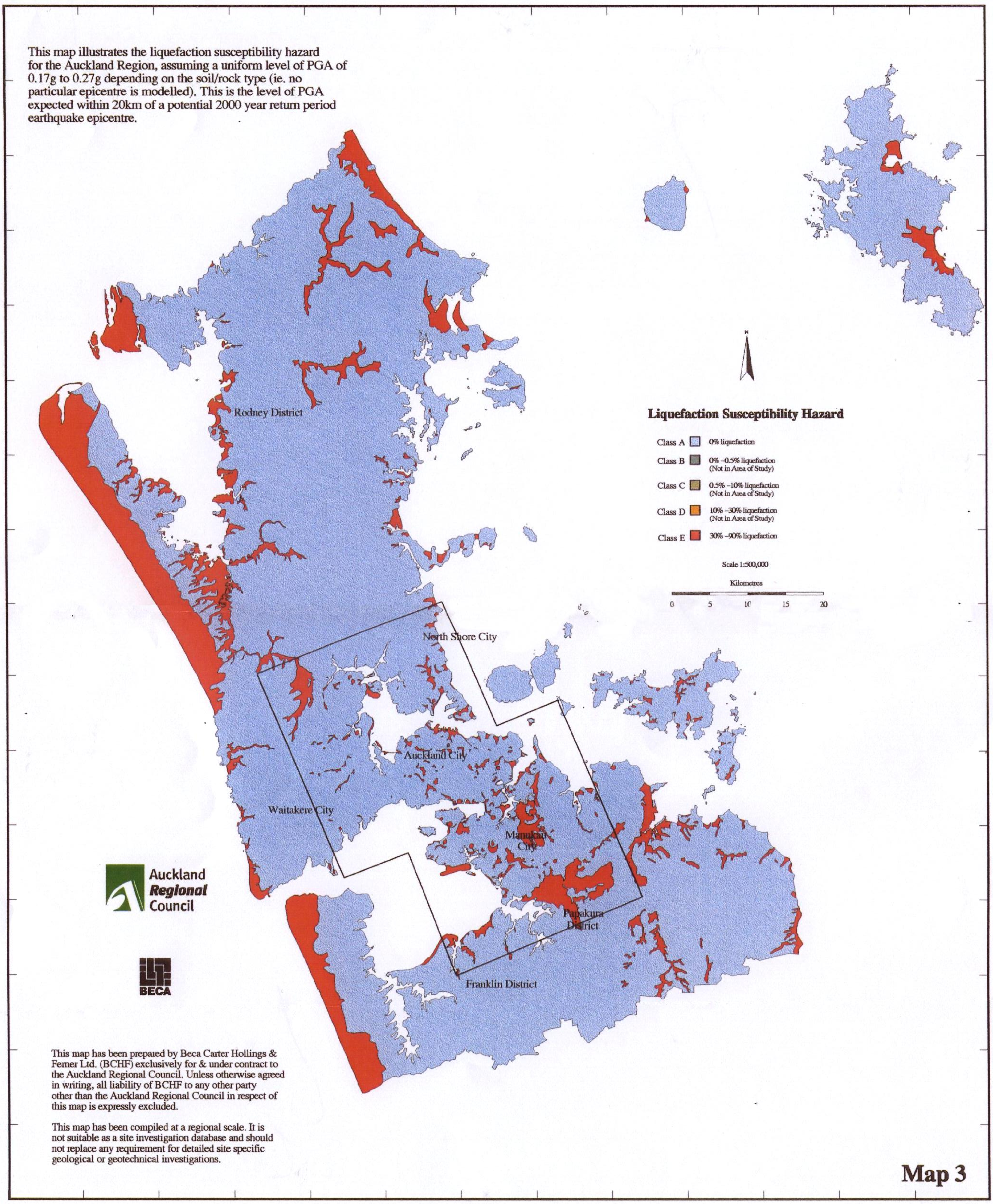
Auckland Engineering Life Lines

MAP 2: PEAK GROUND ACCELERATIONS: 2000 YEAR EARTHQUAKE SCENARIO, REGION A AND B

This is the same as Map 3, Report 2.3 (Earthquake - Induced Slope Instability Hazard).

Liquefaction Susceptibility : 2000 Year Earthquake Uniform Hazard

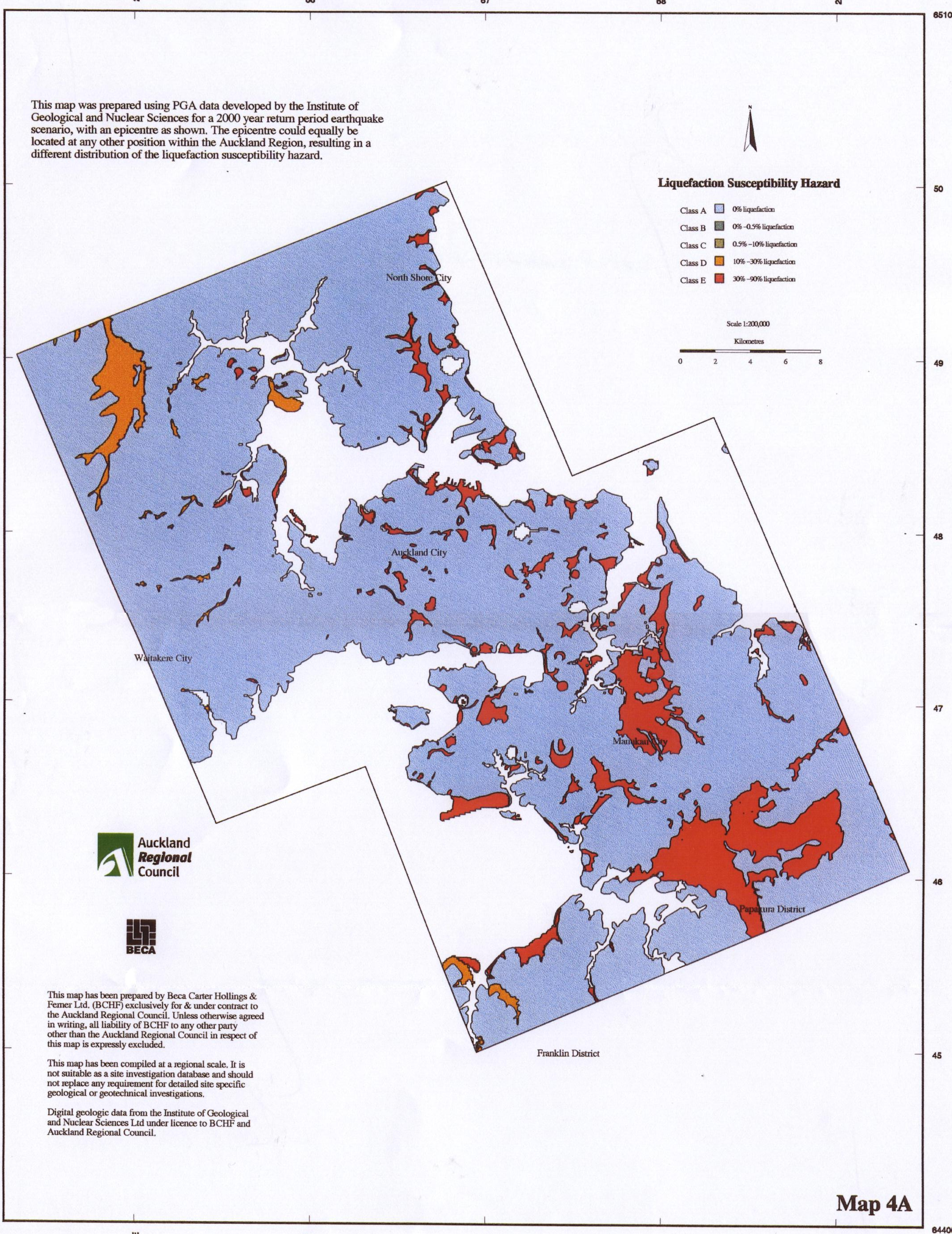
Region A and B



This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Liquefaction Susceptibility Hazard Map : 2000 Year Earthquake Scenario

Region A



This map was prepared using PGA data developed by the Institute of Geological and Nuclear Sciences for a 2000 year return period earthquake scenario, with an epicentre as shown. The epicentre could equally be located at any other position within the Auckland Region, resulting in a different distribution of the liquefaction susceptibility hazard.

This map has been prepared by Beca Carter Hollings & Ferner Ltd. (BCHF) exclusively for & under contract to the Auckland Regional Council. Unless otherwise agreed in writing, all liability of BCHF to any other party other than the Auckland Regional Council in respect of this map is expressly excluded.

This map has been compiled at a regional scale. It is not suitable as a site investigation database and should not replace any requirement for detailed site specific geological or geotechnical investigations.

Digital geologic data from the Institute of Geological and Nuclear Sciences Ltd under licence to BCHF and Auckland Regional Council.

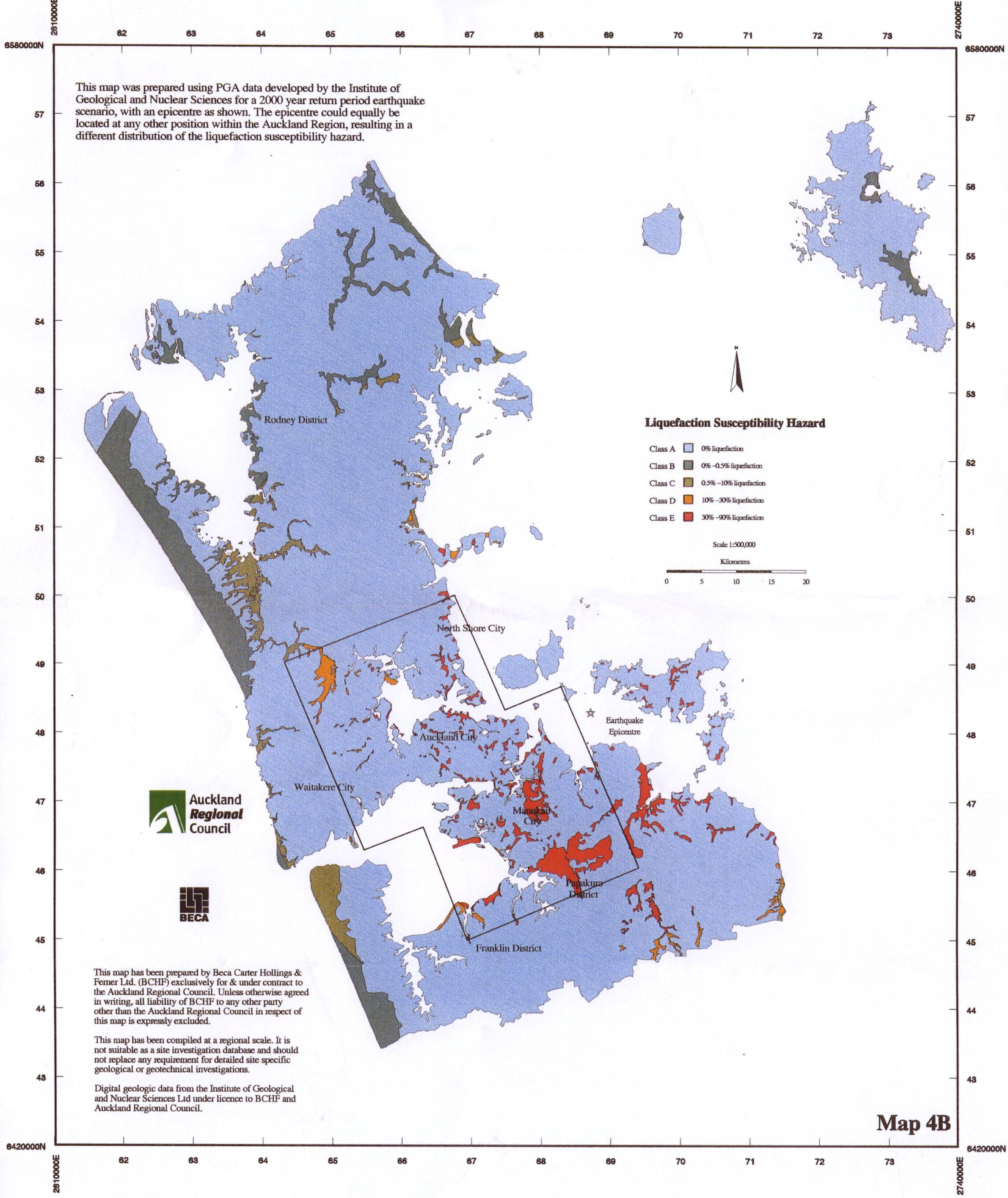
This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Auckland Engineering Life Lines

Liquefaction Susceptibility Hazard Map : 2000 Year Earthquake Scenario

Region B

This map was prepared using PGA data developed by the Institute of Geological and Nuclear Sciences for a 2000 year return period earthquake scenario, with an epicentre as shown. The epicentre could equally be located at any other position within the Auckland Region, resulting in a different distribution of the liquefaction susceptibility hazard.



Auckland Regional Council

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Auckland Engineering Life Lines

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It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

REPORT 2.5

EARTHQUAKE INDUCED DAMAGE TO STRUCTURES (Effects Matrix)

Prepared for

AUCKLAND REGIONAL COUNCIL

By

BECA CARTER HOLLINGS & FERNER LTD

Rev 0
June 1997

1.0 INTRODUCTION

A uniform hazard model developed for several engineering studies in Auckland was used to estimate the ground motions expected in central Auckland from a 2000 year return period earthquake event[4]. Following on from this work and related studies[2,3], an earthquake-induced damage to Structures Matrix has been prepared to provide a qualitative assessment of the likely damage to a range of infrastructure within the Auckland Region which might result from such an event.

2.0 EARTHQUAKE-INDUCED DAMAGE TO STRUCTURES MATRIX

The damage matrix combines the findings of the Earthquake-Induced Slope Instability Hazard Study[5] and the Liquefaction Susceptibility Assessment[6] with the anticipated effect on lifelines services and structures existing within the Auckland Region, and specific key lifelines structures located within central Auckland, including:

- Auckland Airport;
- Auckland Ports; and
- the water supply dams located in the Hunua and Waitakere Ranges.

The matrix addresses earthquake-induced damage in broad terms based on:

- the likely design factors of safety for each type of structure;
- earthquake hazard models developed for recent engineering projects in Auckland City; and
- observed performance of similar structures in other recent earthquakes (for example Edgecumbe, New Zealand 1987; Northridge, Los Angeles 1994; and the Great Hanshin Earthquake, Japan, 1995).

The matrix indicates that at peak horizontal ground accelerations (PGA's) of 0.05g to 0.10g, damage to most structures is likely to be negligible. There is however a low probability of minor damage to older port and dam structures and of damage to brick residential structures.

At PGA's of 0.10g or more, the steepness of the slope on, or in which a structure is founded, contributes to the likely impact potential. In particular, there is a moderate risk to non-ductile pipework laid in steeper, Class C/D slopes (ie slopes steeper than 15°), to older multi-level brick or masonry buildings, embankments constructed on Class C/D slopes, and to older port structures. It is also considered that there would be a low to moderate probability of damage to dam structures.

At PGA's of 0.15g to 0.20g, 10-30% of potentially liquefiable soils are likely to liquefy. The risk to pipework becomes moderate to high when laid in Class C/D slopes. The risk to brick residential structures is also high, mainly due to toppling of chimneys. The risk to port structures is moderate to high and there is a risk of movement or cracking of water supply dams. The potential for dam-break exists at this level of ground shaking. Should liquefaction occur at Auckland Airport, resulting in pavement cracking or settlement, a short shut-down period would be required for repairs.

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[4] *IGNS 1997: Peak Horizontal Ground Accelerations and Modified Mercalli Intensities forScenario Earthquakes in the Auckland region: Auckland Engineering Lifelines Project Report Prepared for the Auckland Regional Council, June 1997.*

[5] *BCHF 1997: Accompanying Notes. Earthquake-Induced Slope Instability Hazard Map Prepared for the Auckland Regional Council, June 1997.*

[6] *BCHF 1997: Accompanying Notes. Liquefaction Susceptibility Hazard Map Prepared for the Auckland Regional Council, June 1997.*

For PGA's in excess of 0.2g, the risk to most structures is moderate to high. 30-90% of potentially liquefiable soils are expected to liquefy, causing a high to very high probability of damage to structures founded in or on these soils. In particular, the risk of damage to the major infrastructure considered (wide cracks or pavement buckling at the airport, failure of wharves at the port, and significant movement and/or cracking of the water supply dams) is high.

The likely probability / impact potential ratings given can be used in conjunction with the earthquake scenarios developed to initiate earthquake response planning.

EARTHQUAKE-INDUCED DAMAGE TO STRUCTURES MATRIX

STRUCTURE	Range of Ground Acceleration (PGA) and Modified Mercalli Felt Earthquake Intensities (MMI)							
	MMI ≤ VI 0.05 - 0.10g	MMI VI - VII 0.1 - 0.15g		MMI VII - VIII 0.15 - 0.20g		MMI > VIII > 0.2g		
	No risk of Liquefaction	Minor Risk of Liquefaction		Some Risk of Liquefaction		Non-Liquefiable Soils		Liquefiable Soils
		Slopes A/B	Slopes C/D	Slopes A/B	Slopes C/D	Slopes A/B	Slopes C/D	
PIPEWORK								
Moderately Ductile Pipes	negligible (4)	negligible (4)	low probability (3)	negligible (4)	moderate probability (2)	negligible (4)	moderate probability (2)	high probability / low impact (2)
Low Strength or Low Ductility Pipes	negligible (4)	negligible (4)	low probability (3)	low probability (3)	high probability (1)	low probability (3)	high probability (1)	high probability (1)
Non-Ductile Pipes	low probability (3)	low probability (3)	moderate probability (2)	low probability (3)	high probability (1)	moderate probability (2)	high probability (1)	high probability (1)
BUILDING STRUCTURES								
Modern Multistory	negligible (4)	negligible (4)		low probability (3)		low to moderate probability (3)		moderate probability (2)
Older Multi-level Brick/Masonry	negligible (4)	moderate probability (2)		high probability (1)		very high probability (1)		very high probability (1)
Residential	negligible (timber frame) (4) to low probability (brick) (3)	negligible (timber frame) (4) to moderate probability (brick); old brick chimneys break off (2)		low (timber frame) (3) to high probability (brick); old brick chimneys break off (1)		low (timber frame) (3) to very high probability (brick); old brick chimneys break off (1)		high to very high probability (1)
SERVICES								
power lines, lamp posts	negligible (4)	negligible (4)		low probability (3)		moderate probability (2)		high probability (1)
pipe bridges	negligible (4)	low probability (3)		moderate probability (2)		high probability (1)		high probability (1)
CIVIL STRUCTURES								
roads, rail	negligible (4)	negligible (4)	low probability (3)	negligible (4)	moderate probability (2)	low probability (3)	high probabaility (1)	high probability (1)
embankments	negligible (4)	low probability (3)	moderate probability (2)	low (3) to moderate (2) probability depending on embankment height	high probability (1)	moderate probability (2)	high probability (1)	High probability (1)
SPECIFIC INFRASTRUCTURE								
Auckland International Airport	negligible (4)	negligible (4)		low probability (3) Short shut-down period for repairs.		low (3) to moderate probability (2) Shut-down for repairs.		moderate probability (2). Shut-down for repairs.
Auckland Ports	negligible (modern) (4) to low probability (old) (3)	low (modern) (3) to moderate probability (old) (2)		moderate (modern) (2) to high probability (old) (1)		high probability (1)		very high probability (1)
Water Supply Dams, Waitakere and Hunua	low probability (3)	low (3) to moderate probability (2)		moderate (2) to high probability (1) Low risk of dambreak: severe impact potential.		high probability (1) Moderate risk of dambreak: severe impact potential.		not applicable

Effect Ratings System:
(1) High probability and/or severe impact potential
(2) moderate probability and/or moderate impact potential
(3) low probability and/or low impact potential
(4) negligible impact potential

Slope Classes:
Class A slopes 0 - 7°
Class B slopes 8 - 15°
Class C slopes 16 - 20°
Class D slopes > 20°

SECTION 3

VOLCANIC ERUPTION

REPORT 3.1

VOLCANIC IMPACT ASSESSMENT FOR THE AUCKLAND VOLCANIC FIELD

Prepared for

AUCKLAND REGIONAL COUNCIL

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2. Currently at CSIRO, Perth, Australia
3. Auckland Regional Council

(Abridged version of ARC Technical Publication Number 79, April 1997)

April 1997

SUMMARY

Auckland is a monogenetic volcanic field, covering an area of 360 km^2, in which activity has occurred from scattered vents during the past 140 000 years. There are 49 identified vents, although there is evidence that some adjacent vents may have been active in the same episode. By definition, monogenetic volcanoes erupt only in a single episode, after which the magma conduit is blocked by solidification. Subsequent eruptions occur from new pathways to the surface, and from different and unpredictable vent locations.

This report aims to identify the likely impacts within the Auckland region of future volcanic eruptions from the Auckland Volcanic Field. The effects of such eruptions on the buildings, main infrastructure, critical facilities, population, economic activities and natural features are considered.

Five different eruption scenarios have been developed. Their purpose is not to predict what the next eruption at Auckland will be like, but to identify some of the processes and effects that could be expected in a likely eruption. The parameters used in these scenario eruptions are based on evidence from the geological record of the Auckland Volcanic Field, plus observed eruptions at similar volcanoes overseas. However, a future Auckland eruption will not necessarily be similar to any of the scenario events, in sequence, size, duration, or vent location.

A full discussion of each of the scenarios can be found in ARC Technical Report, Number 79, April 1997. A summary of one of these scenarios (Scenario 3) is presented in this report.

Scenario 3 is a waterfront phreatomagmatic/magmatic eruption centred in the railyards, affecting the central business district, port, and residential areas. This particular scenario was selected for the Auckland Engineering Lifelines Project because it encompasses both phreatomagmatic and magmatic eruption styles.

Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk to life, and destroy near-vent structures in the scenario eruptions but the extent of these hazards (in a typical Auckland eruption) is mostly limited to within a few kilometres of the vent. Severe near-vent ground shaking accompanying volcanic earthquakes will also damage buildings, possibly also in areas not greatly damaged by eruption products. Apart from the evacuation of people and removal of transportable assets (if possible) there are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures.

Evacuation, where necessary to save lives in high-risk, near-vent (<5 km) areas (affected by lava flows, ballistic block impacts, pyroclastic surges), should be carried out before an eruption commences, and would have to be completed before the eruption peaks. Evacuation may involve in excess of 150 000 people. Elsewhere, later evacuation of people may became necessary in areas where loss of services (electricity, water supply, sewage) makes continuing habitation untenable.

The scenario impacts illustrate the vulnerability of urban areas where the deposition of only a few mm-cm of ash is sufficient to cause disruption of transportation, electricity, water, sewage and stormwater systems. Most systems, if affected only by thin tephra fall (<50 mm), can be restored within a few days to weeks after an eruption has ended.

Falls of volcanic ash can disrupt electricity supply depending on weather conditions, with power outages occurring if the ash is wet (i.e. conductive). Immediate ash removal is the best mitigation option to prevent widespread outages. Volcanic ash falls can cause severe damage to sewage and stormwater systems. The most effective mitigation measure to lessen the affects of ash falls is to reduce the input of ash into the system. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Water supplies are vulnerable to contamination by ash fall into storage lakes preventing their use, and to excessive water demand during

post-eruption ash clean-up operations. Water management plans will be required to manage excessive demands, and should include procedures to fill service reservoirs (if possible) on receipt of an ash fall warning. Information messages outlining water conservation measures will need to be broadcast to the public.

Urban areas in the region will be forced to undertake expensive and time-consuming clean-up operations as a consequence of any of the scenario eruptions. In each case there will be a need to develop coordinated community-wide ash-removal plans, which identify appropriate methods of ash removal, collection and disposal. The public will need to be adequately informed on how to deal with volcanic ash.

This eruption scenario/impact exercise has highlighted the value of prior emergency management planning that will identify likely impacts on community lifelines and strengthen the links between agencies that will have to respond to such events. This needs to be done well in advance of any volcanic activity.

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1.0 SCENARIO

1.1 INTRODUCTION

Auckland is New Zealand's largest urban centre with approximately one million inhabitants occupying the area surrounding the narrow isthmus between the Hauraki Gulf and Manukau Harbour. Auckland is New Zealand's major airport, seaport and commercial/industrial centre and the focus of one of the most rapidly growing areas of the country. Metropolitan Auckland has developed across the Auckland Volcanic Field (Fig. 1.2) in which small eruptions have occurred from 49 scattered vents during the past 140 000 years (Allen and Smith 1994). The most recent, and largest, eruptions formed Rangitoto Island which has grown within the last 800 years. The Auckland Volcanic Field is classified as active, and further eruptions can be expected.

The risk to Auckland from a volcanic eruption can be expressed by the relationship:

$$Risk = Hazard \times Vulnerability$$

in which the hazard from a future volcanic eruption is a combination of the probability of an eruption occurring in any given (say 100 year) period, plus the extent of damage from the eruption. Vulnerability is an expression of the effects of the eruption on people, buildings, infrastructure and economic activity. The probability of an eruption occurring in the Auckland Volcanic Field is quite low (cf. say Hawaii) and the extent of devastation is limited (cf. say a Taupo eruption), but the vulnerability is very high. Although the time of the next Auckland eruption cannot presently be determined, its effects can be assessed using knowledge gained from the studies of past eruptions in New Zealand and overseas.

This report uses geological, seismological and volcanological technical terms. Explanations for these terms can be found in the Glossary.

This report provides:

(a) a brief description of the history of the Auckland Volcanic Field and associated hazards;

(b) a description of one of five potential eruption scenarios in Auckland which were developed for the Auckland Regional Council (ARC Technical Publication Number 9, April 1997). The scenarios cover the range of expected eruption styles, and the differing landuse environments (residential, commercial and industrial) which could be affected by a future eruption. The five scenarios are:

Scenario 1 An offshore, surtseyan-style, phreatomagmatic eruption, centred at grid reference R11/730860, producing a smaller version of Rangitoto volcano.

Scenario 2 A phreatomagmatic eruption centred at R11/780780 in the Tamaki Estuary, affecting residential and industrial areas.

Scenario 3 A waterfront phreatomagmatic/magmatic eruption centred at R11/ 690824, affecting central business district, port, and residential areas.

Scenario 4 A magmatic eruption from a vent at the top (south) end of Queen Street, Auckland City (at R11/675812), affecting the central business district (CBD).

Scenario 5 A magmatic eruption from a vent at the intersection of Mt Albert/Mt Eden roads (at R11/671755), affecting residential and commercial areas.

Figure 1.1 shows the locations of the five eruption scenarios.

Only one scenario (Scenario 3) is discussed in this report, which is an abridged version of ARC Technical Publication Number 79, April 1997. This scenario was selected because it encompasses both phreatomagmatic and magmatic eruption styles, so that the effects of both can be discussed and compared.

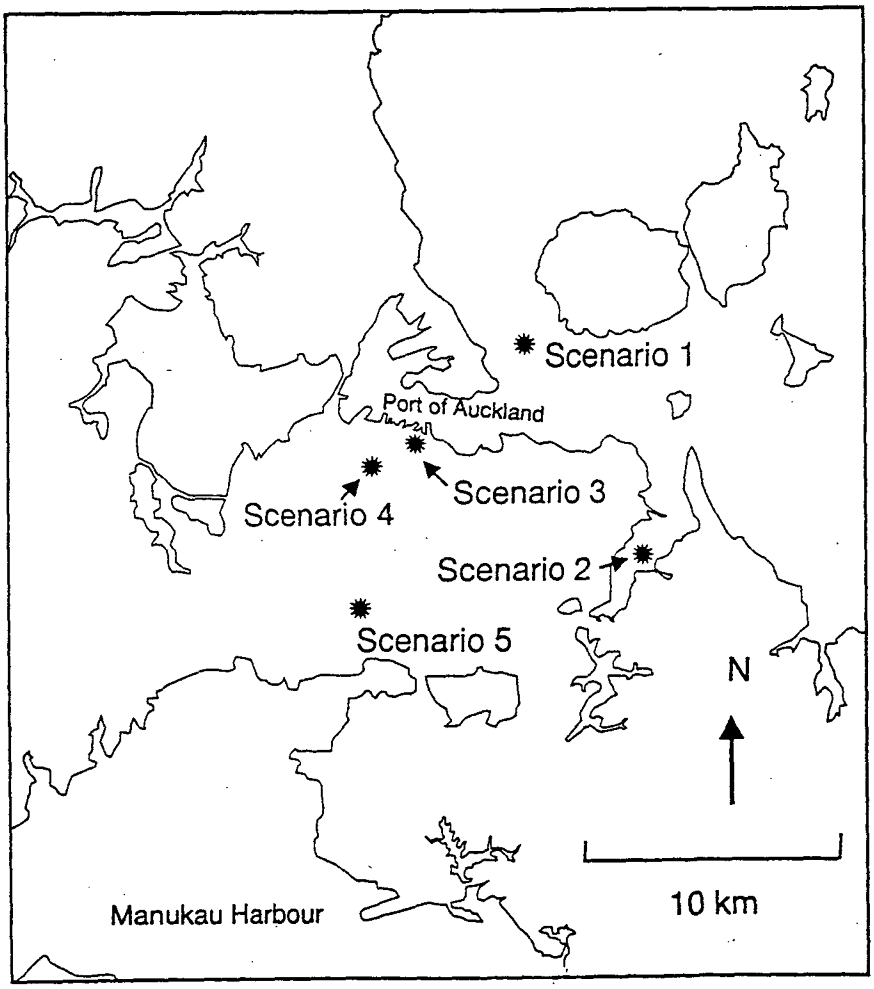

Figure 1.1: Map showing the location of the five eruption scenarios

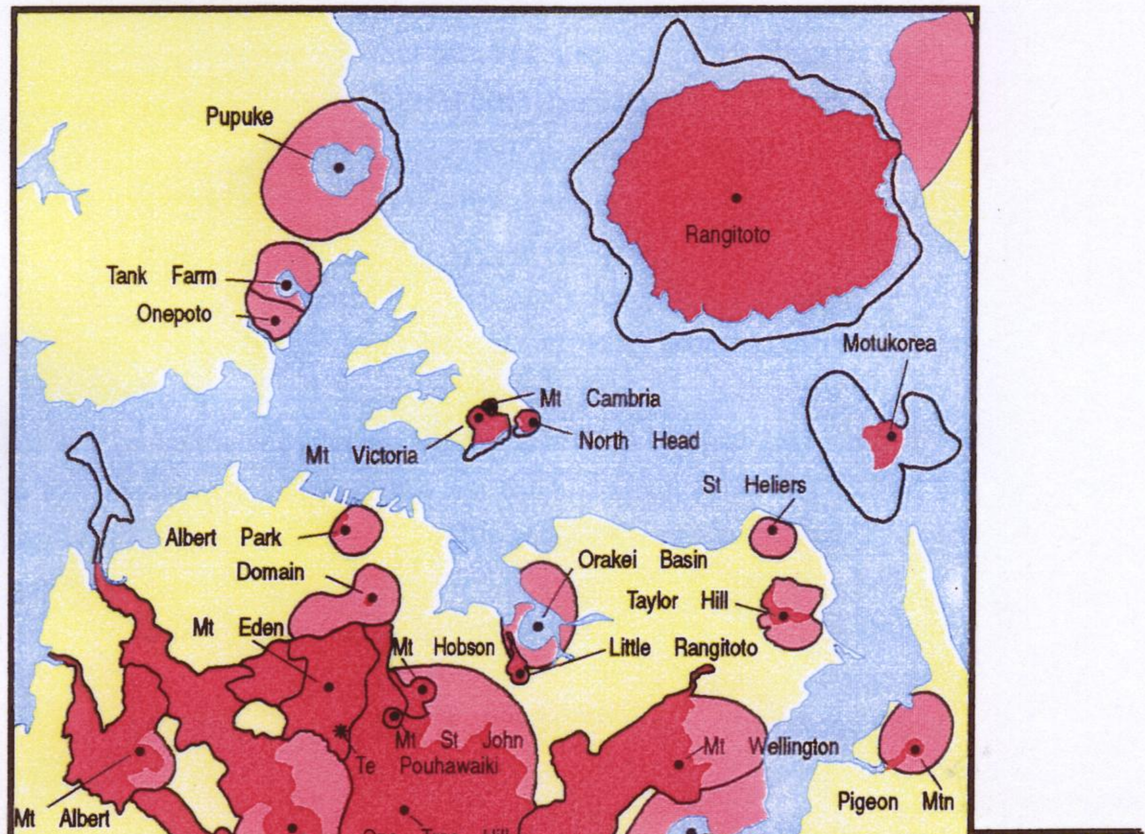

FIGURE 1.2: Map of Auckland Volcanic Field volcanoes, from Kermode 1992.

1.2 HISTORY OF THE AUCKLAND VOLCANIC FIELD

Auckland is a monogenetic volcanic field, covering an area of 360 km^2, in which activity has occurred from scattered vents during the past 140 000 years (Searle 1981, Kermode 1992). There are 49 identified vents (Fig. 1.2), although there is evidence that some adjacent vents may have been active in the same episode (Rout *et al.* 1993). By definition, monogenetic volcanoes erupt only in a single episode, after which the magma conduit is blocked by solidification. Subsequent eruptions occur from new pathways to the surface, and from different and unpredictable vent locations. Auckland volcanoes thus differ from others such as Ruapehu or White Island, where multiple eruptions occur from the same vent over thousands of years.

Determining the precise ages of past Auckland eruptions has been limited by the lack of material suitable for radiometric dating (see Allen and Smith 1994 for a summary of dating techniques and ages). The ages of some Auckland volcanoes are shown in Fig. 1.3, along with erupted volumes. Past eruptions have been usually small (volume < 0.1 km^3), although an apparent trend towards increasing size of eruption with time (Fig. 1.3) is noted by Smith and Allen (1993). The most recent eruption, which formed Rangitoto (2 km^3) at about 800 to 600 years ago, is also the largest. Twenty eruptions are known to have occurred in Auckland during the last 20 000 years, although 18 of these occurred between 20 000 and 10 000 years ago (Allen and Smith 1994). The considerable variation in length of recent apparent repose periods (see Fig. 1.3) means that meaningful probabilities of eruption occurrence in any century cannot be calculated (see Allen and Smith 1994).

The eruption history of the Auckland Volcanic Field, with past eruptions occurring at intervals of hundreds to thousands of years, means that there is no reason to believe that activity has ceased with the recent arrival of humanity. Future eruptions must be expected, occurring from new and apparently random vent locations within the Auckland Volcanic Field. The field may be in an early stage of its evolution, with future eruptions increasing in size and frequency (Allen and Smith 1994).

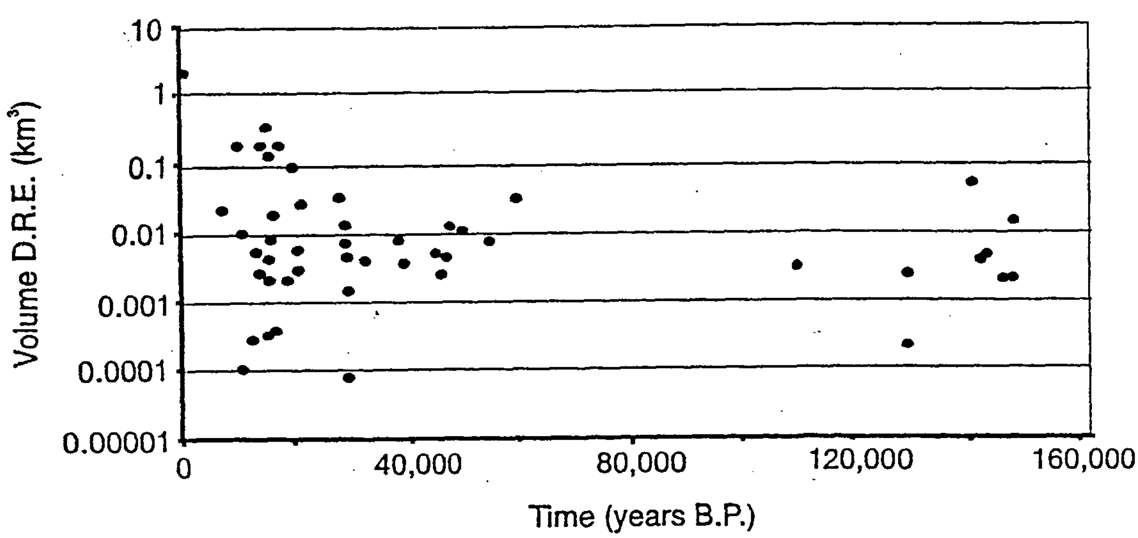

Figure 1.3: Volumes of Auckland volcanoes, and their ages. Note that all the larger eruptions (>0.1 km^3) have occurred in the last 20 000 years. From Allen and Smith (1994).

1.3 SCENARIO DEVELOPMENT

A scenario provides an imagined but logical sequence of events. Scenarios allow consideration of a range of possible events which may occur in the future. In developing the scenarios, a number of assumptions have been made as to their eruption size, their locations, durations, wind velocities at the time, and so on. The purpose of the scenarios is not to predict what the next eruption at Auckland will be like, but to identify some of the processes and effects that could be expected in a likely eruption. The parameters used in these scenario eruptions are based on evidence from the geological record of the Auckland Volcanic Field, plus observed eruptions at similar volcanoes overseas. However, a future Auckland eruption will not necessarily be similar to any of the scenario events, in sequence, size, duration, or vent location. Note that the effects of pyroclastic surges and tephra falls in the scenario eruptions are more widespread than those preserved in the geological record at Auckland. We have been influenced by the recent (1945, 1995, 1996) eruptions of Ruapehu (and other recently active volcanoes), where thin but socially- and economically-significant tephra falls have already been lost from the geological record of distal areas.

The scenarios do not include actions that might be taken by responding agencies (eg. police and civil defence). These are for the appropriate agency to determine, and are outside the scope of this report.

1.4 SCENARIO ERUPTION PARAMETERS

PRECURSORS

Seismicity in the upper crust (0-20 km depth) is a common precursor to volcanic eruptions. The Auckland Volcano-Seismic Network (Fig. 1.4), which is currently under development, is designed to detect such earthquakes. Cassidy *et al.* (1986) suggest that the ascent rate for basalt magma in the Auckland Volcanic Field may range from 1 to several tens of centimetres per second, from a source at 75-125 km depth. This implies that it may only take days to a few months for magma to reach the surface once upward movement is initiated.

There are few recorded observations of eruptions in monogenetic volcanic fields, and even fewer detailed accounts of the seismicity preceding such eruptions. The 1943 eruption of Paricutin volcano, Mexico (Yokoyama & de la Cruz-Reyna 1990), provides one of the best examples. The first instrumentally detected earthquake occurred 45 days before the eruption. Earthquakes were first felt two weeks prior to the outbreak of surface activity, and increased until the eruption occurred. Steam and gases were emitted 4.5 hours before the first magmatic ejecta reached the surface.

We have devised a general precursory seismic sequence for the Auckland Volcanic Field, and used it in each of the 5 eruption scenarios, modified to suit the different vent location of each scenario. This is (a) a result of lack of knowledge as to the actual precursory seismic sequences of previous Auckland eruptions (there being no evidence preserved); and (b) to illustrate that the same magma body generated at depth could erupt in very different ways, determined by vent location, near-surface geology, and topography. However, the use of a general precursory seismic sequence does not indicate that we expect the next eruption to follow this pattern. Eruptions may follow only a short precursory sequence (days) or longer periods (weeks).

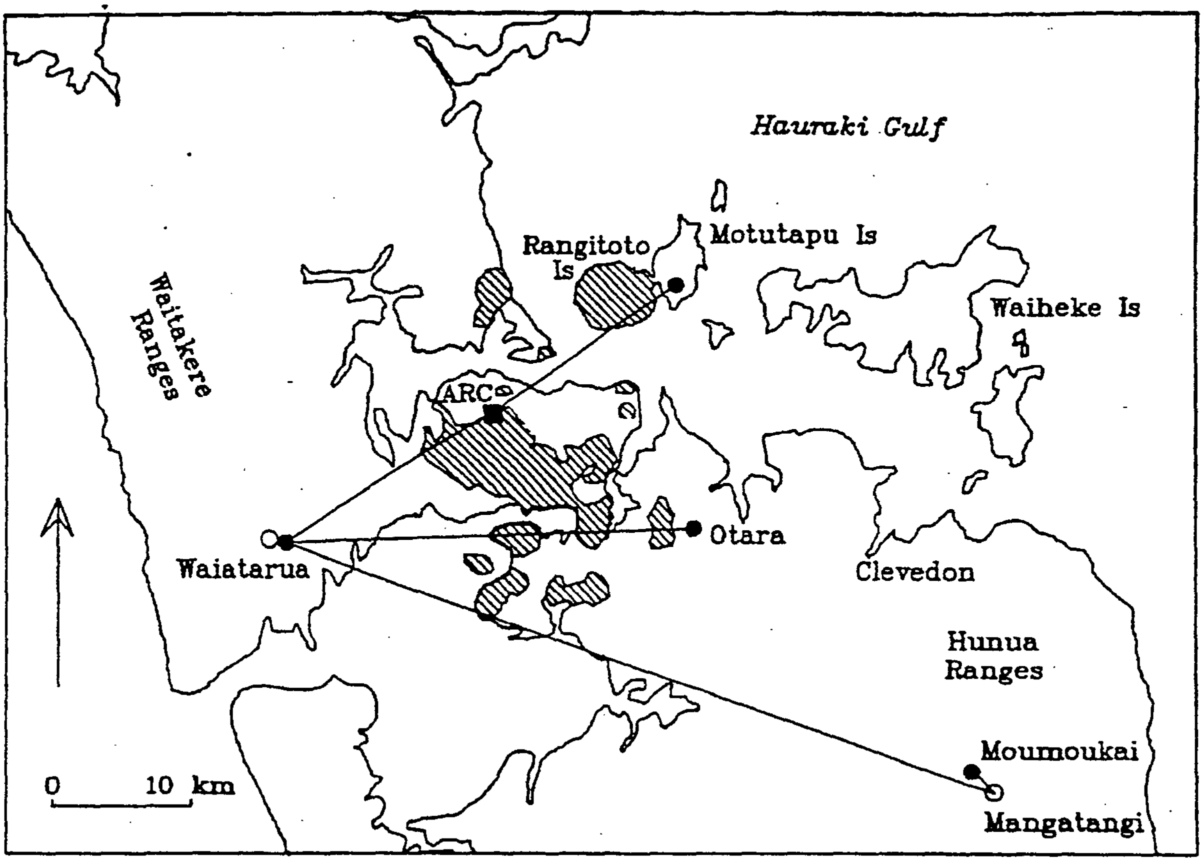

Figure 1.4: The Auckland Volcano-Seismic Network. Otara (OTAz), Motutapu (MTAz), Waiatarua (WTAz) and Moumoukai (MKAz) seismometers (solid circles) are telemetered via relay sites (open circles) to the Auckland Regional Council. The Auckland volcanic field is hatched

ERUPTION DYNAMICS

The style of eruptions in the Auckland Volcanic Field is largely controlled by whether the vent is on-land or within the sea, and by the near-surface occurrence of water-saturated sediments. Past eruptions have covered a range from phreatomagmatic ("wet"), caused by explosive interaction of magma and external water (see below), to purely magmatic ("dry") in which involvement of external water is not significant.

During the course of an eruption, changes in the water/magma ratio (see below) may lead to changes in the style of the activity. These changes may be either "short-term" oscillations in eruption style, or a long term evolution towards a "drier" or "wetter" eruption. Evidence for changes in style during an eruption are seen in many of the eruption deposits in the Auckland Volcanic Field (Searle 1981 and Kermode 1992), and have been well documented at Crater Hill (Houghton *et al.* 1996).

PHREATOMAGMATIC ERUPTIONS

Phreatomagmatic ("wet") eruptions in the Auckland Volcanic Field involve the interaction of high temperature basaltic magma and external water (which may be surface water or groundwater). Phreatomagmatic eruptions are complex and dependent on a set of interrelated factors including: (a) the magma supply rate and physical properties (temperature, gas content, viscosity etc); (b) the supply rate and pressure (depth) of available external water; (c) vent geometry and structure; and (d) basement geology. The key feature in phreatomagmatic eruptions is the rapid heating of liquid water to magmatic temperatures (~1000°C). At low confining pressures, magmatic heating causes water to flash into steam, so that the water phase volume increases by up to 6000 times (at 1b atmospheric pressure). This explosive expansion of the water phase enhances fragmentation of the basaltic magma and adjacent country rock. Fragmentation very efficiently transfers the heat energy of the magma into kinetic energy driving the steam explosions. Efficiency of the explosive heat exchange process is related to the ratio of water to magma (Fig. 1.5), with the highest efficiency at a water:magma ratio of ~0.3, (Wohletz 1983, Wohletz and Sheridan 1983). Efficiency falls off at higher or lower water:magma ratios.

Phreatomagmatic explosions can occur in a number of situations including: (a) when rising magma encounters shallow ground water or surface water, (b) when vent wall rocks containing abundant groundwater collapse onto the magma column, (c) when retreat of a magma column allows rapid inflow of groundwater into the vent.

Phreatomagmatic explosions commonly produce rapidly rising, steam-rich vertical eruption columns surrounded by ground-hugging turbulent mixtures of steam and solid ejecta that flow out laterally from the base of the eruption column. Such lateral flows are termed "base surges" (Moore 1967). Surges range from wet and cool, to dry and hot. Initial velocities can be as high as 100 ms^{-1} at the vent, and surges can flow at velocities of 15 to 30 ms^{-1} (55 to 100 km/hr) out over 3 km from the vent (Moore *et al.* 1966). Historic examples of phreatomagmatic eruptions producing base surges the 1957 Capelinhos eruptions (Azores) in which surges travelled up to 2 km from the vent (Waters & Fisher 1971), the 1965 Taal eruption (Philippines) in which surges travelled 6 km from the vent (Moore 1967) and the 1977 eruptions at Ukinrek Maars (Alaska) where surges reached 3 km from the vent (Self *et al.* 1980). In the Auckland Volcanic Field preserved surge deposits are found up to 1 km from vents but would have almost certainly been deposited beyond that distance. Near-vent, where deposits are significantly thick (>0.2 m) surges are non-survivable and will destroy all but strongly-constructed structures. Surge thickness, density and speed will decrease towards the limits of flow, but will still prove fatal to people in the open, and will damage weakly-constructed buildings. Within the Auckland Volcanic Field, a 5 km radius is assumed to be a minimum safe distance to avoid the impacts of surges.

The fragmentation associated with phreatomagmatic eruptions produces a high proportion of fine material (ash and lapilli). Steam condensation in the eruption plume commonly produces ash rainout and promotes aggregation of ash into small clusters and accretionary lapilli. In the 1977 eruptions at Ukinrek Maars, the ash plume rose in excess of 6 km and fine ash fell up to 125 km from the vent (Self *et al.* 1980). The 1963 Surtsey eruption produced an ash plume to 12-15 km altitude and ash fell to >20 km downwind (Thorarinsson 1965, 1969).

A range of crater landforms is produced by phreatomagmatic eruptions, reflecting the dynamics of the eruption, and principally the ratio of explosion energy to ejecta mass (this parameter is sometimes termed "eruption violence"). The greater the energy content of a (subaerial) explosion, the greater the eruption velocities produced, and the more widely ejecta is dispersed. Three main crater types are maars, tuff rings and tuff cones, in order of decreasing energy content of eruption. **Maars** are usually vertical-walled volcanic craters that have been cut (largely by collapse) into pre-eruption country rocks, and are surrounded by low ejecta rims. **Tuff rings** are constructional craters that lie mostly on or above the pre-eruption surface. The crater rims usually dip at a low angle both outwards and inwards. **Tuff cones** (including scoria cones) have smaller craters than tuff rings and higher rims, with steeply dipping beds produced by the deposition of most ejecta close to the vent.

MAGMATIC (DRY) ERUPTIONS

"Dry" eruptions of basaltic magma in Auckland Volcanic Field exhibit styles of activity termed hawaiian and strombolian. Both types of eruption are driven by the escape of magmatic gases from the venting lava. Hawaiian activity is characterised by the continuous and voluminous discharge of highly fluid lavas, often with gas-driven "fire fountaining" of scoria to hundreds of metres above the vent. Strombolian eruptions are characterised by a series of discrete explosions as large gas bubbles burst through the magma surface at intervals between 0.1 s to several hours (Blackburn *et al.* 1976). Both types of eruption commonly produce scoria cones, along with lava flows.

Wood (1980) summarises observations of 48 basaltic cone-forming eruptions. The eruptions usually start along a fissure, with initial weak venting of gases followed by intense eruption of scoria. Eruption usually becomes concentrated at one or more locations along the fissure. The near-continuous explosions can produce fire fountaining of incandescent lava to 200 -500 m in height. High accumulation rates of material falling back to ground often produces fountain-fed lava flows. Scoria cones are the most visible result of these eruptions and reach near final heights within a few days. The cone usually represents the least significant fraction of material produced, with lava flows and pyroclastic fall deposits (tephra) the dominant products. Lava flows are commonly fed by lava tubes at the base of the cones. Alternatively lava can flow from a breach in the cone when lava ponds in the vent. With time, explosions become less frequent and lava effusion becomes the main activity. The mean duration of observed cone-forming eruptions is 30 days.

Blackburn *et al.* (1976) describe the dynamics of strombolian explosive eruptions. Observations of the 1973 Heimaey (Iceland) eruption showed that large clasts (>20 cm) follow ballistic trajectories from the vent; intermediate-sized clasts (5-20 cm) are commonly released from the eruption column at 100-500 m heights; small particles (0.1-5 cm) are carried up 200-1000 m in the convecting eruption plume, with finer material (<1 mm) reaching heights of 6-10 km (Self *et al.* 1974). Subsequent dispersal is influenced by wind velocity. Most of the coarse material is deposited on or near the vent, but a small proportion of fine material can be deposited hundreds of kilometres downwind.

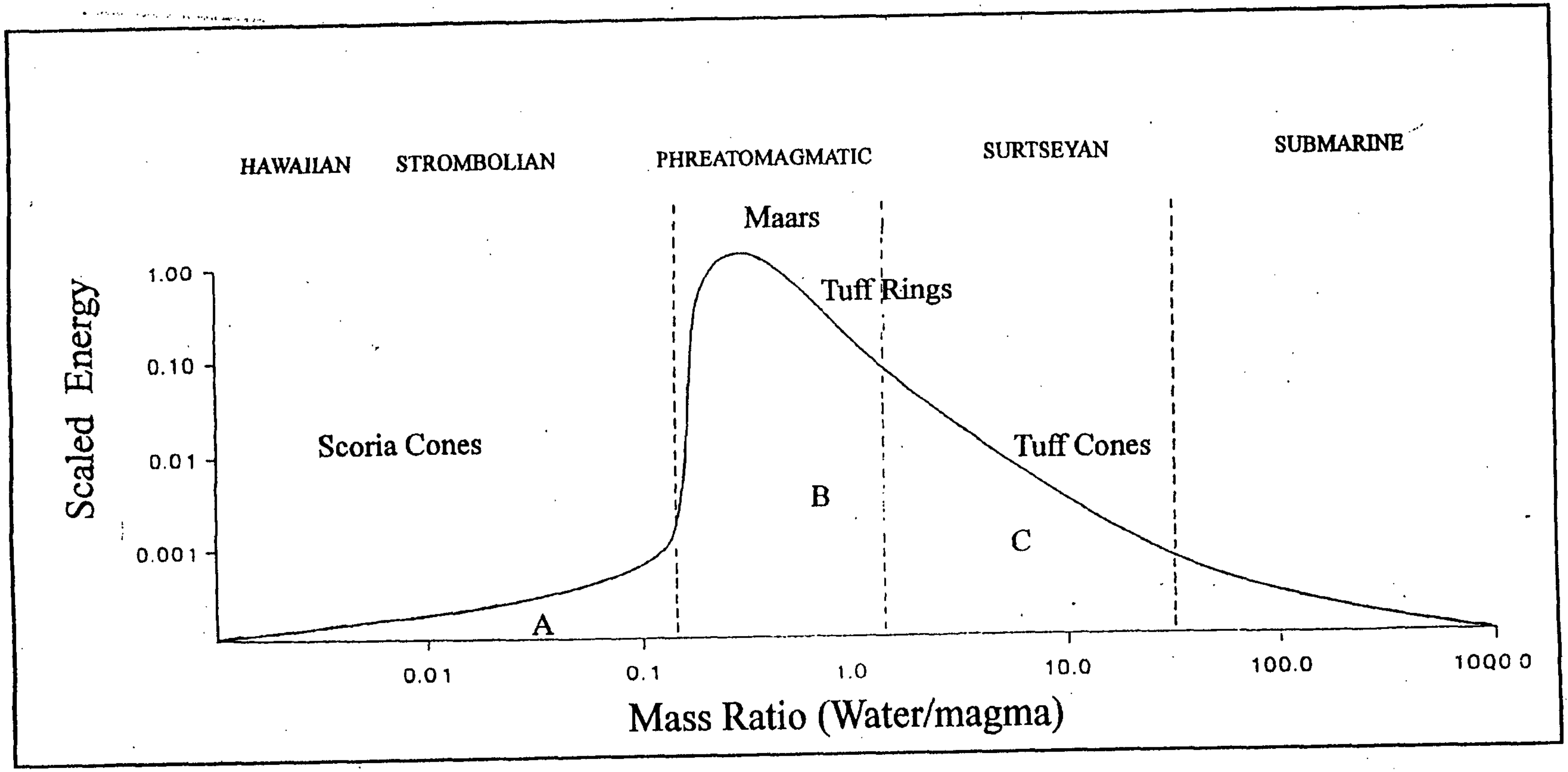

Figure 1.5: **Plot cf explosive energy (scaled to maximum yield) against water/magma mass ratios for volcanic eruptions. the sharp rise in the curve within the surtseyan field marks the onset of dynamic mixing between magma and water. from Wohletz (1983)**

WIND DIRECTION

The wind direction in Auckland is variable (Fig. 1.6) but the predominant directions are from the west and southwest. In modelling tephra fall distribution for each scenario eruption the ASHFALL program (Hurst 1994) has been used, with the following wind speed profile with elevation.

Elevation (km)	Wind Speed (ms^{-1})
1	9
2	11
3	12
4	13
5	14
6	16
7	17

Wind directions for each scenario have been chosen to produce tephra fall patterns desired or required for the scenario brief and/or the subsequent impact study (e.g. we have not been constrained by the most frequently-occurring wind directions).

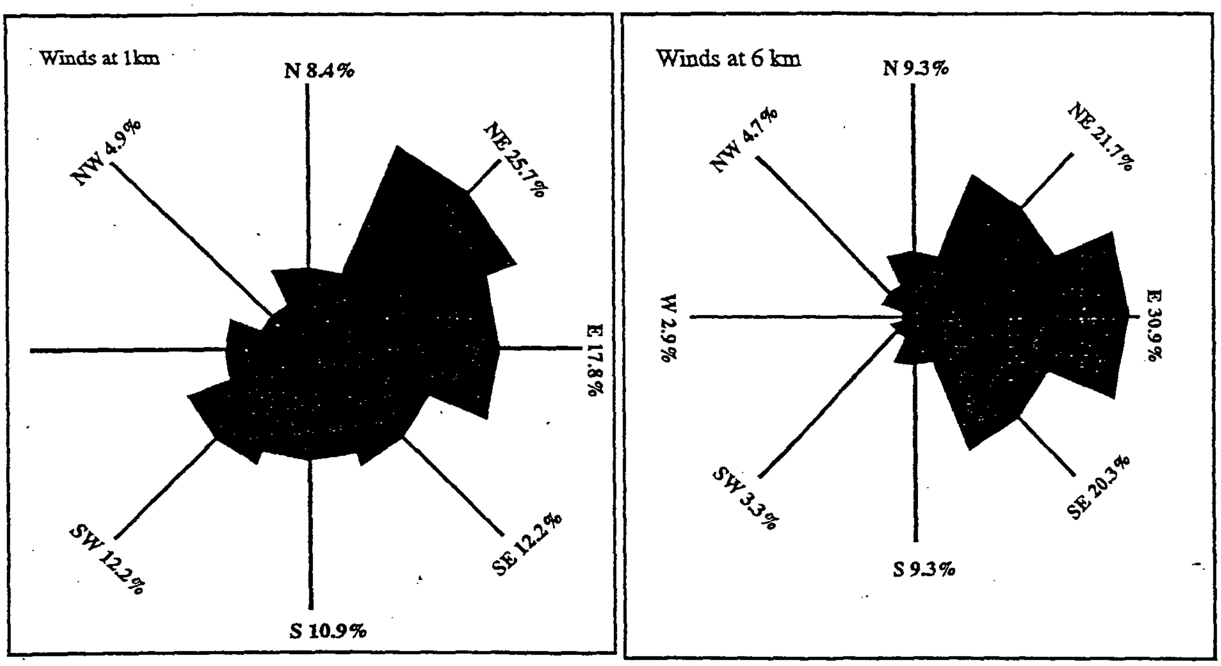

Figure 1.6: The frequency of wind directions at 1 and 6 km above Auckland airport

SCENARIO 3

Vent location:	Auckland Rail Yards, downtown Auckland City (R11/690824)
Magma type:	Basalt
Underlying country rock:	Waitemata Group flysch (sandstones and mudstones)
Erupted volume:	Tephra - 10^7 m^3; lava - 10^8 m^3.

In this CBD and port/residential waterfront-located phreatomagmatic/magmatic eruption scenario, the first instrumentally-recorded high-frequency earthquake is set at -25 days (25 days before the start of eruptive activity). For scenario 3, the eruption dynamics and products are in part modelled on the 1957/58 Capelinhos eruption in the Azores (Machado *et al.* 1962), and on the eruption which produced Rangitoto Island. Vent location is shown in Fig. 1.7.

CHRONOLOGY OF THE SCENARIO 3 ERUPTION

Day 1(-25) A M_L 5.1 high frequency tectonic earthquake occurs at ~100 km depth beneath Auckland. It is recorded by the Auckland Volcano-Seismic Network (AVSN - Fig. 1.4), and by most North Island stations of the National Seismic Network, although only weakly felt in the Auckland area.

Day 6 (-20) Two high-frequency earthquakes (M_L 2.5 and 3.2) are recorded by the AVSN, with first arrivals on the Motutapu (MTAz) instrument; sequentially later at the Otara (OTAz), Waiatarua (WTAz) and Moumoukai (MKAz) stations. These events are not felt, and are regarded as aftershocks of the M_L 5.1 event 5 days earlier. No action is taken.

Day 8 (-18) Four high-frequency earthquakes (M_L 2.4 to 2.9) are recorded by the AVSN, with sequential arrival times on MTAz, OTAz, WTAz and MKAz seismo-graphs, similar to those of Day 6. GNS is contacted at 1800 h and the recent seismic events are discussed. ARC deploys a smoked-paper portable seismograph at North Head during the evening.

Day 9 (-17) GNS staff travel to Auckland and install a portable seismometer at Kauri Point. Five high-frequency earthquakes similar to those of the previous days are recorded by the Auckland net instruments. **Scientific Alert Level 1 is declared**[1], as a result of the unusual seismicity.

Day 10 (-16) Five high-frequency earthquakes (M_L 3.0 to 3.2) are recorded by the AVSN and portable seismographs; the largest event is weakly felt across central Auckland. Analysis of these (and some of the earlier) events indicates they are approximately located beneath the Auckland City-Devonport area, at 30-40 km depths. A further portable seismometer is installed at Cornwall Park (with a very low gain setting as the site is very noisy).

Day 16 (-10) Two high-frequency earthquakes (both M_L 3.1) are recorded by the AVSN and portable seismographs.

Day 19 (-7) 25 high-frequency earthquakes (M_L 2.4 to 3.7) are recorded by the AVSN and portable seismographs. Locations are similar to the earlier events, with possible shallowing to ~10-20 km depths. Two apparent long-period small earthquakes are poorly recorded. **Scientific Alert Level 2 is declared,** after recognition of the apparent shallowing of epicentres and the possible occurrence of long-period events. A portable EARSS seismograph (replacement) is installed at North Head, although the site is very noisy

[1]See Appendix 1 for description of the Science Alert levels.

and the instrument gain has to be set at very low level. A RSAM tremor monitoring system is installed on the volcano-seismic network at the ARC Building recording centre.

Day 20 (-6) 10 high-frequency earthquakes (M_L 2.3 to 3.9) are recorded by the Auckland volcano-seismic network. The best-located events appear to originate at about 15 km depth.

Day 21(-5) 8 high-frequency earthquakes (M_L 2.4 to 3.7), and 4 long period earthquakes are recorded by the volcano-seismic network. Refinement of the seismic analysis shows that most of the well-recorded high-frequency shallower events of the last 12 days have been located within a 3 km diameter area centred between Devonport and the Auckland Central Business District. A tilt-levelling site and tide gauge are installed in the Container Wharf area, with the initial tilt survey carried out during the night.

Day 22 (-4) 150 high-frequency earthquakes (M_L 2.2 to 4.1) and 10 long period volcanic earthquakes are recorded by the volcano-seismic network and portable seismographs; the two largest high-frequency events are most strongly felt by people in the Devonport-CBD area. The high-frequency events are estimated to be centred at 5-10 km depths. Some minor shaking damage (cracking of facades, plastered walls, and a few windows) occurs in older buildings within the epicentral area, with some items falling from shelves. Felt intensities are MM III to V. Low-frequency volcanic tremor (1-2 Hz) appears on MTAz, OTAz and adjacent portable seismographs, occurring as short bursts of 30-60s duration over a two hour period from 1600h. The **Scientific Alert Level** remains at 2 (e.g. 2+ ?) although the further shallowing of epicentres and the occurrence of volcanic tremor is recognised as indicating an increased probability of an eruption actually occurring. A further tilt-levelling site is hastily installed at North Head.

Day 23 (-3) 45 high-frequency earthquakes are recorded by the volcano-seismic network; 25 of these earthquakes are felt (M_L 3.9 to 4.3), including 5 locally audible. 60 long-period volcanic earthquakes are recorded. Bursts of low-frequency tremor are occurring more often, with increasing amplitudes, and the appearance of higher frequency spectra. Relevelling of the tilt-level sites finds no significant tilt, but initial data from the crude tide gauge at the Container Wharf suggests that some uplift may be occurring here.

Day 24 (-2) 30 high-frequency earthquakes are recorded by the volcano-seismic network seismographs; 4 of these earthquakes were felt (M_L 3.8 to 4.1) but seismicity is generally less than on the previous few days. Tremor levels and numbers of long-period events are also lower than on the previous day. No inflation is detected by relevelling of tilt sites.

Day 25 (-1) High-frequency earthquakes increase dramatically to over 1100 events instrumentally recorded in the 24 hrs prior to 0800h today. At least 200 of these events are felt (M_L 3.8 to 4.6), with widespread minor shaking damage to buildings in the Devonport-CBD epicentral area. Near-continuous volcanic tremor, with mixed low and higher frequencies, starts at 0300h, overloading MTAz and the local portable seismographs. Discrete level changes of the Container Wharf tide gauge appear to accompany some of the larger felt earthquakes, which are heard as sharp bangs. Sulphurous gas smells are detected by scientists working in the Mechanics Bay area. **Scientific Alert Level 3 is declared at 1200h** as an eruption appears imminent. Felt earthquakes continue throughout the day and into the night.

Day 26 (0) Eruption.

0400h Seismic activity (felt and instrumentally recorded) peaks around this time, before decreasing again. Continuous volcanic tremor with mixed low to high frequency spectra, is accompanied by large (M_L 4-4.5) high frequency earthquakes occurring at 0.5 to 3 minute intervals. Shaking damage occurs to buildings and structures in the CBD and Wharf area. Ground cracking is observed in the Auckland Rail Yards-Container Wharf area around R11/690824, where continuous ground shaking is being felt.

0600h Ground shaking intensifies, causing severe damage to local buildings and structures. Ground cracks widen and coalesce into a 300 m long zone of branching fissures, partially collapsing structures which are undermined. Steam appears from five vents along the fissure. Steam discharge rates steadily increase, accompanied by detectable volcanic gas emission with strong smell of SO_2. Wind is blowing from SW carrying the steam/gas plume NE towards Devonport at low elevations.

0804h The eruption begins with initial small explosions throwing mostly lithic ejecta ~100 m into the air in vertically-directed dark plumes. Explosions rapidly increase in violence and ejected volume, and spread along the 300 m long fissure. Volcanic tremor levels remain very high but discrete sharp-onset high-frequency large earthquakes are decreasing, being replaced by volcanic earthquakes which accompany the larger jetting eruptions. Some of the larger explosions generate visible shock waves associated with loud detonations. Some large windows are broken by overpressures out to 2 km from the fissure. The eruption column is convecting to 2-3 km elevation above the active area, expanding into a large steam cloud drifting downwind over the Harbour and towards Devonport. **Scientific Alert Level 4 is declared.**

0840h Explosions are now larger and occurring more frequently, with the eruption column rising to 8 km, spreading into an expanding eruption cloud carried to NE and E by winds at this elevation. The eruption fissure has extended 200 m NE into the harbour and sea water is flooding into the fissure which is being continually enlarged and deepened by removal of material. With widening of the fissure, explosions are becoming more divergent, and steam-rich small base-surges are spreading from base of the eruption column, carrying mixed lithic material with a minor component of basaltic magma. These surges travel out to 1 km across the low-lying areas adjacent to the wharves, and into the harbour (Fig. 1.7). Ash and scoria is falling out of the eruption cloud across the main harbour channel and Devonport. Ballistic clasts up to metre-size are falling out to 2 km from the vent; those falling on buildings and structures causing considerable damage including the starting of fires. Smoke from burning buildings contributes to the eruption column. Frequent lightning pulses within the eruption column are causing some interference with radio-linked communications including the radio-telemetered seismographs.

0900h The explosions continue to grow in size as the eruption intensifies. The larger explosions throw massive plumes to >1 km above the surface. Lateral components of these explosions send spear-headed plumes out to 400 m horizontally, where they collapse to generate locally-directed primary base-surges, some of which flow into restricted sectors of the Parnell and CBD areas as well as out into the harbour. However, these primary surges are overridden by larger and faster moving base-surges formed by bulk collapse of the vertical eruption columns. These secondary surges destroy all the Mechanics Bay wharf structures, and travel 2-3 km to north across the harbour to the Devonport shoreline (Fig. 1.7) where lesser damage occurs. Somewhat controlled by the rising topography to south of the vent, the surges travel 1-2 km in this

direction, where they infill the flat area to south of the vent and destroy, bury or damage all structures. Strongly-constructed large buildings remain standing, but are damaged by sand blasting and breakage of glass doors and windows, and partly buried. The surges cause considerable damage inside the buildings they enter. Steam/gas cloud turbulence causes considerable further damage beyond the surge limits. Heavy tephra fall is now occurring across Devonport, Rangitoto, Orakei, Mission Bay and St Heliers (Fig. 1.8). The large surges passing into the harbour drive large waves (~4-6 m amplitude) northward towards Northcote, Takapuna and Devonport, where they flood onto the beaches causing considerable damage to near shore structures and roads. The largest explosions are accompanied by strongly felt earthquakes, the largest of M_L 4.6, with shaking causing further damage to structures. **Scientific Alert level 5 is declared.**

0930h Discrete eruptions become increasingly frequent and are becoming concentrated into a single main vent being excavated in the centre of the rail yards. Some collapse of the vent walls is occurring, enlarging the crater to ~500 m diameter, with collapsed material ejected in the explosions. Almost continuous large explosions and base-surges are accompanied by the most intense seismic activity of the entire eruption episode. The enlarging eruption column rises to 8-10 km in a decreasing W wind. Large ejecta in the column are visibly incandescent for several hundred metres above the surface. The eruption cloud expands at high elevation (~10 km) over Devonport-Mission Bay as the wind continues to decrease, with fallout of mm-cm size ash and scoria clasts, and some larger bombs, commencing in these areas.

1100h Activity continues with only slight fluctuations in intensity while the wind dies. Heavy tephra fall (>1 cm accumulation) is now occurring in the whole CBD, Devonport area (including Northcote and Takapuna), and the eastern suburbs (Fig. 1.8), with total darkness beneath the eruption cloud. Base surges continue to devastate and then bury large areas, with ~1 m thick surge deposits now extending out to 3 km from the vent (Fig. 1.16). Beyond this surge-devastated zone, 5-10 cm thick wet tephra fall loadings are causing partial collapse of some weakly-constructed flat-roofed buildings. Surges which flowed into the harbour have partly infilled the <20 m deep, 1 km wide channel between the wharf area and Devonport, while thick rafts of floating scoria have covered the entire channel.

1300h Wind direction is veering to the WNW and freshening, so that scoria and ash is commencing to fall towards the south in the Newmarket, Remuera, Ellerslie and Mt Wellington areas. The eruptions continue during the day and into the night, building a low tuff ring rampart at about 500 m distance around the vent, completely burying the previously flat area at foot of the Parnell and Albert Park hills.

Day 27 (+1) Eruptions diminish during the early morning and only minor activity occurs during this day. Voluminous clouds of volcanic gas and steam pour from the crater, with occasional minor ash emissions.

During the next 3 months similar but somewhat smaller phreatomagmatic eruptions occur frequently. The eruption of 5×10^7 m^3 of tephra has built a 1 km diameter, 50 m high tuff-ring (Fig. 1.7) with shape and structure rather similar to the Orakei Basin (Allen *et al.* 1996). Areas within 5 km downwind of the crater are affected by >5 cm thick tephra falls, depending on wind directions at time of the larger eruptions. Emission of a continuous gas plume causes considerable gas and acid rain problems in downwind areas during attempts at tephra clearing operations.

Day 156 Strong seismic activity recommences with a vigorous swarm of M_L 2.0-3.6 high-frequency shallow events with sharp onsets, occurring at several hundred per day over three days. These events are located in a linear zone extending from 1 to 4 km SSW of

the new crater (Fig. 1.9). Ground cracking occurs in two subparallel alignments on each margin of the seismic zone, which subsides by up to 0.4 m during the swarm. Buildings located within and adjacent to the seismic zone, and which had survived the thick tephra fall, suffer considerable shaking damage, some collapsing. Roads are blocked by collapsed material and displacement cracks.

Day 159 Hawaiian/strombolian-style eruptions commence as low (10 m height) explosive fire fountaining within the new crater. Gas clouds (including SO_2) spread across central Auckland as fire fountaining increases in height to 200 m. Large (~0.6 m) incandescent bombs are falling out to 500 m from the vent. Most of the ejecta consists of 1 to 50 cm scoria clasts and this is being deposited around the vent (where a small scoria cone is forming) and in a fallout apron extending out 1 km downwind to the NE. A small amount of fine material is being convected up to 5 km and drifts to the NE. Volcanic gas clouds are extending over a wider area, with SO_2 gas becoming noticeable in Devonport. The largest explosions are accompanied by strongly felt earthquakes, the largest of M_L 4.6. A small lava flow emerges from the base of the newly forming scoria cone and flows across the floor of the tuff-ring crater. Fire fountaining continues with fluctuating intensity, as the largest fire fountains reach 300 m above the vent and the cone grows in height. The eruption column becomes more collimated and rises to 8 km, with fine ash being carried across Rangitoto Island. Wind changes to the west, carrying gas clouds, scoria and fine ash over the eastern suburbs (Orakei, Mission Bay and Glen Innes areas).

Day 170 The scoria cone has grown to 100 m height and often contains a lava lake. Lava flows from the cone, as strombolian and hawaiian eruptions continue with fire fountaining frequently to 200-300 m height. Lava flows and intercalated scoria deposits have partly filled the new tuff ring crater, and lava has flowed into the harbour from new vents which have broken out on the north side of the tuff ring. These flows threaten to block the channel to shipping. Vigorous strombolian eruptions continue, with downwind effects as previously described......

Day 200 The scoria cone continues to grow, reaching 140 m in height, and scoria and lavas have now entirely filled the tuff ring crater and are spilling over the lower northern sides (Fig. 1.9). As the cone increases in height, lava outbreaks are more frequently occurring from its base, and lava tunnels carry voluminous flows into the harbour to north. White clouds of hydrochloric acid aerosols (laze) are produced where lava flows into the sea. No shipping has entered Auckland Harbour since the eruption commenced 6 months earlier.

Day 250 Lava eruptions continue without break, most flowing out to the north, as a substantial lava shield is being constructed (Fig. 1.9). Occasional explosive eruptions generate eruption columns to 500-1000 m, and minor tephra falls occur downwind. Some littoral explosions have been occurring on the northern edge of the lava shield, where the inflowing lavas have trapped sea water. These littoral explosions have thrown hot ejecta to a few hundred metres from the "rootless" vents, and discouraged attempts to slow northward progress of the lava flow by pumping water on it from nearby boats.

Day 295 Lava shield growth has extended across the harbour channel to the Devonport Naval Base area, blocking the channel with lava.

Day 360++ Continuing lava outpouring builds a smaller version of Rangitoto cone. Fire fountaining and lava overflow occur, and a massive lava shield now joins the Parnell hills to Devonport. The previous Waitemata Harbour is now a lake, dammed behind the new lava cone. Heavy winter and spring rainfalls are causing a slow rise in

Waitemata lake level, flooding onto shorelines. Plans are being made to cut a new drainage channel to the sea through the Takapuna area.

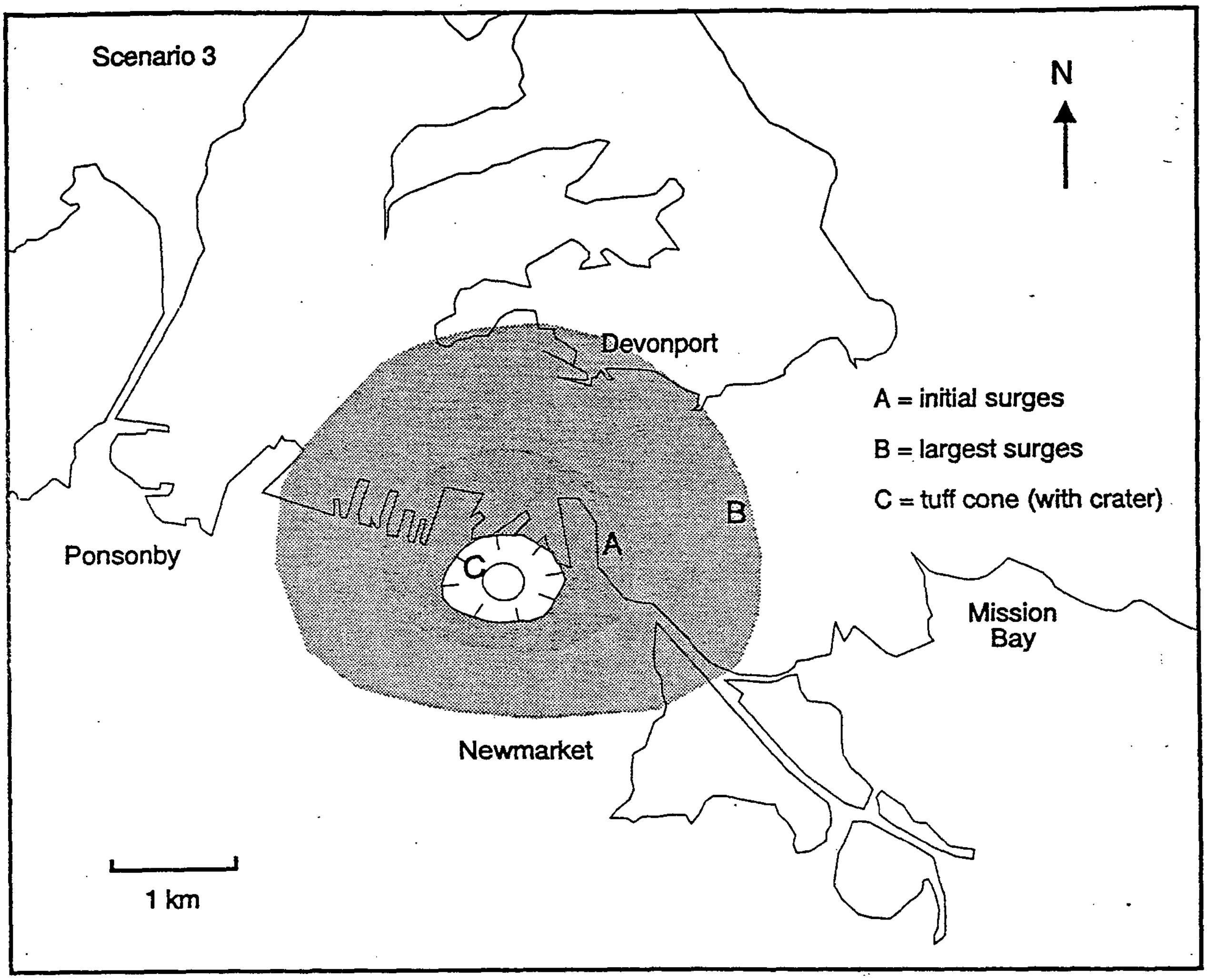

Figure 1.7: **Vent location and extent of initial, and largest, base-surges (stippled) during early stage of the Scenario 3 eruption. The tuff cone is also shown.**

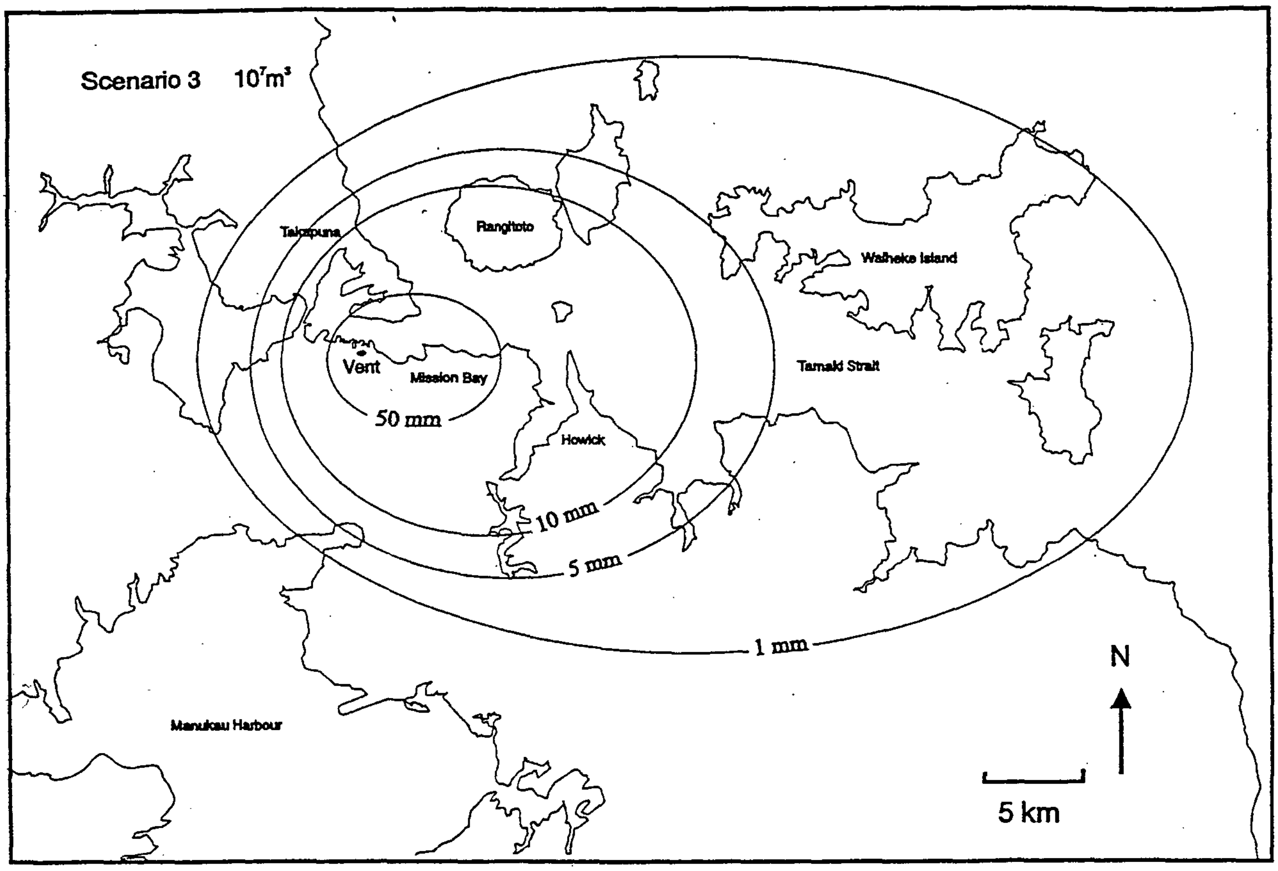

Figure 1.8: **Tephra fall distribution (10^7 m^3) resulting from the Scenario 3 eruption**

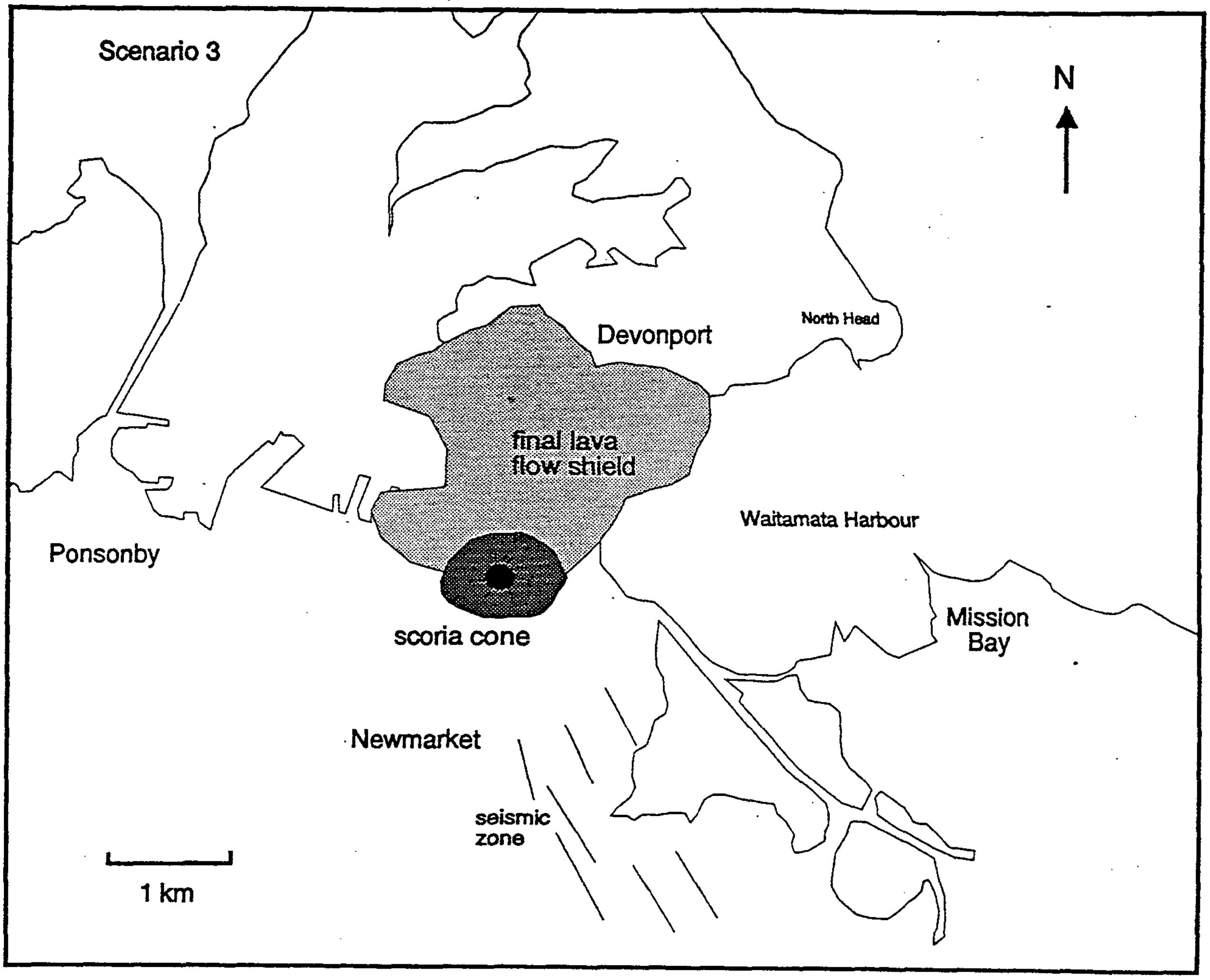

Figure 1.9: **Scoria cone and lava shield construction during the final stage of the Scenario 3 eruption. Zone of precusory seismicity and ground cracking is also shown**

PHOTOGRAPHS TO ILLUSTRATE SCENARIO 3

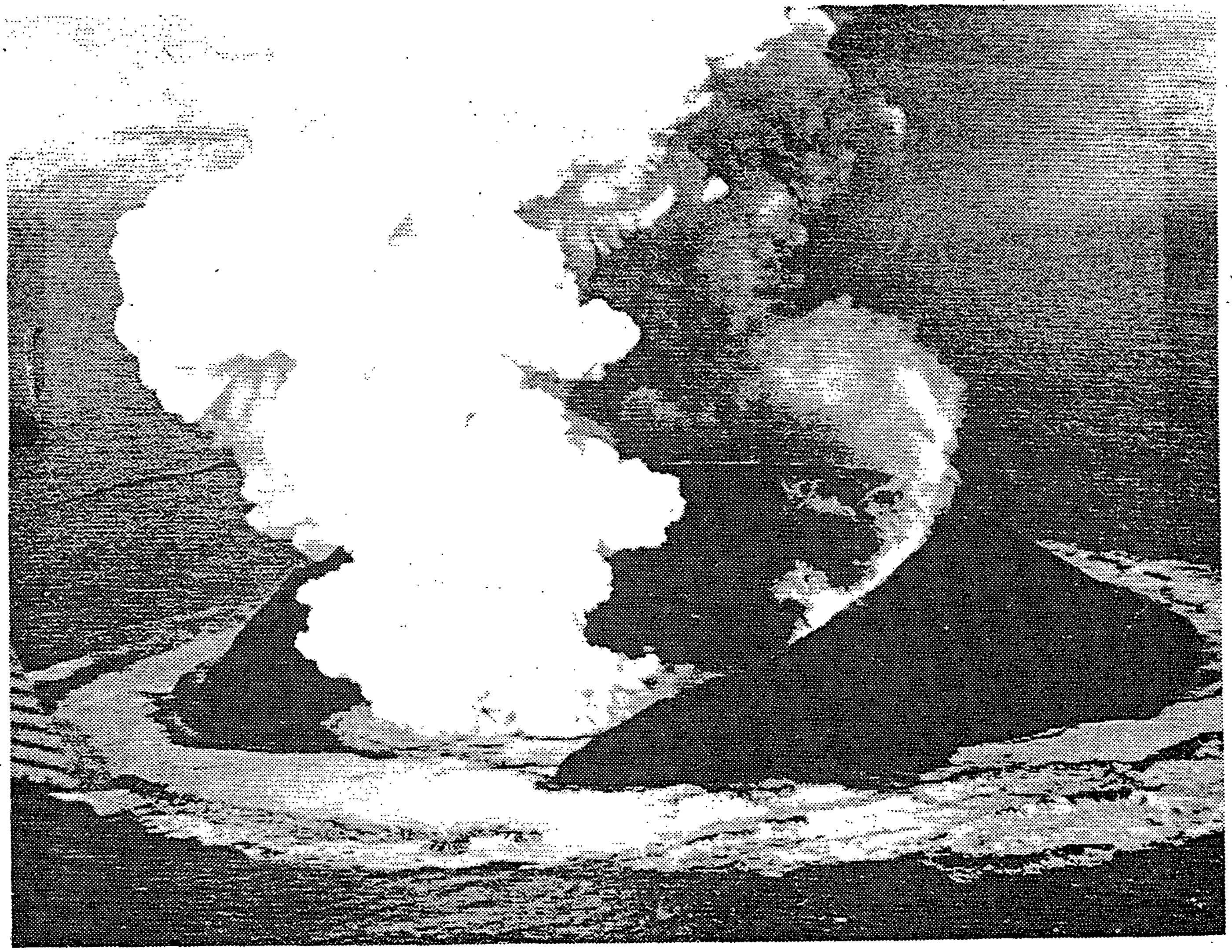

Figure 1.10: The tuff cone of Surtsey, Iceland, viewed from the air on November 30, 1963. The eruption began 16 days earlier. (Photograph courtesy of S. Thorarinsson and Cassell & Company)

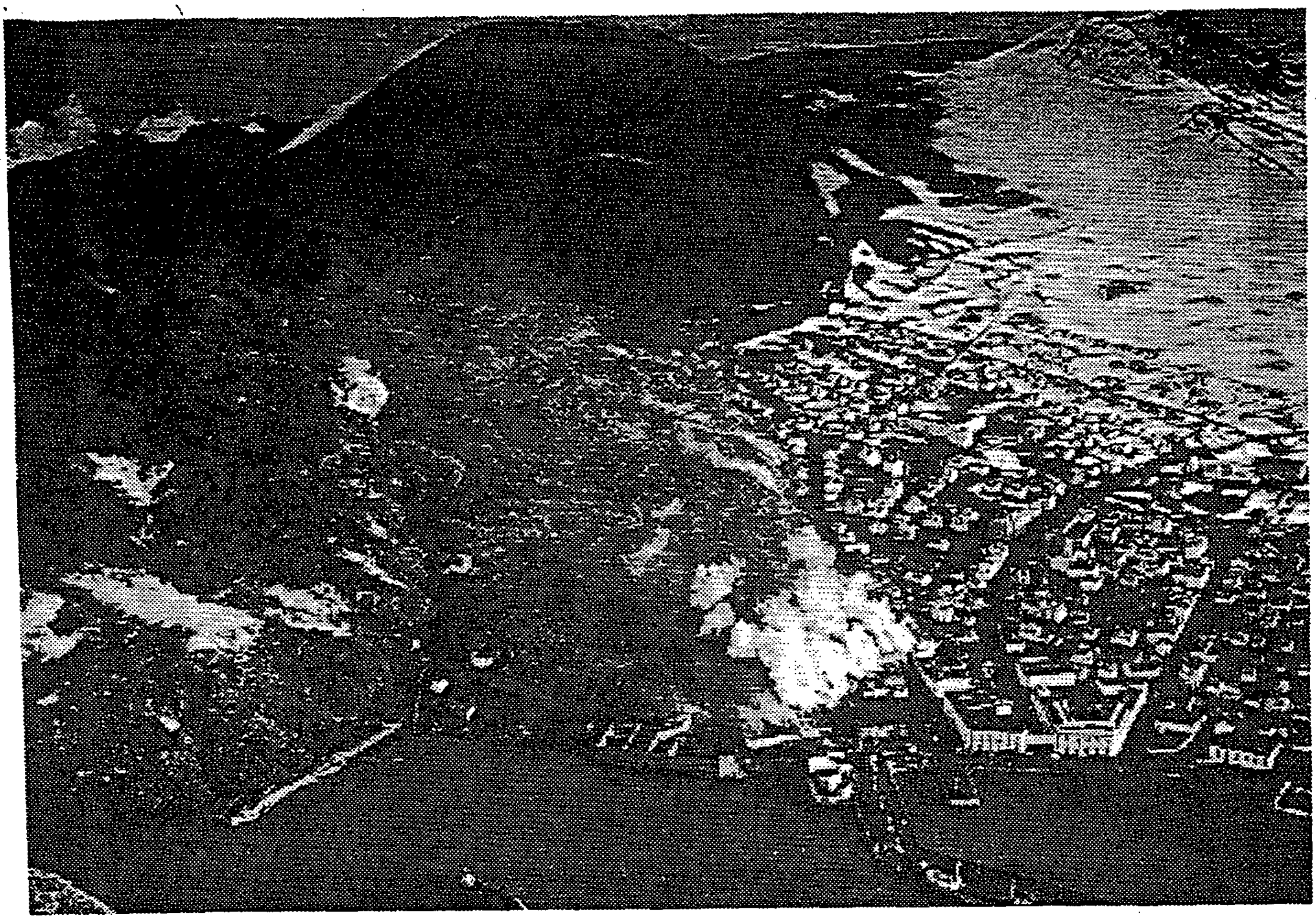

Figure 1.11: An aerial view looking across the fishing port of Vestmannaeyjar on the island of Heimaey, Iceland, partly covered by tephra and lava from the 1973 eruption. Note the newly formed scoria cone at the top of the picture. (Photography by S. Einarsson and courtesy of T. Einarsson)

2.0 IMPACT OF SCENARIO ON KEY 'LIFELINES'

the following section identifies the likely impacts of Scenario 3 on key Auckland Lifelines. Because there are few, if any, analogous examples of volcanic eruptions occurring within, or immediately adjacent to, a modern city, our assessment of the likely impacts is somewhat imaginative, and undoubtedly incomplete. Further, information on the infrastructure and facilities of the Auckland region has been obtained from many sources and covers general items only (i.e. first order infrastructure) and therefore detail is lacking. More detailed infrastructure (or higher order) and many topics about specific damage are beyond the expertise of the authors and outside the scope of the report. This report should not be viewed as the final word on the impacts of future eruptions at Auckland. Rather, it should be the starting point for more detailed studies, by the organisations concerned, of potential eruption effects on the population, communications, water and energy supplies, transport and other industries of the Auckland region.

2.1 ELECTRICITY SUPPLY AND RETICULATION

Most electricity used in the Auckland area is produced by the Electricity Corporation of New Zealand Ltd (ECNZ) and Contact Energy Ltd generating facilities (located outside the Auckland Volcanic Field), and distributed by the national grid operated by Transpower Ltd. The grid high voltage lines feed into a number of Auckland region substations (see Fig. 2.1) operated by Transpower Ltd, and then onto Mercury Energy Ltd and Power New Zealand Ltd local substations for distribution to customers. These utilities maintain the local distribution systems.

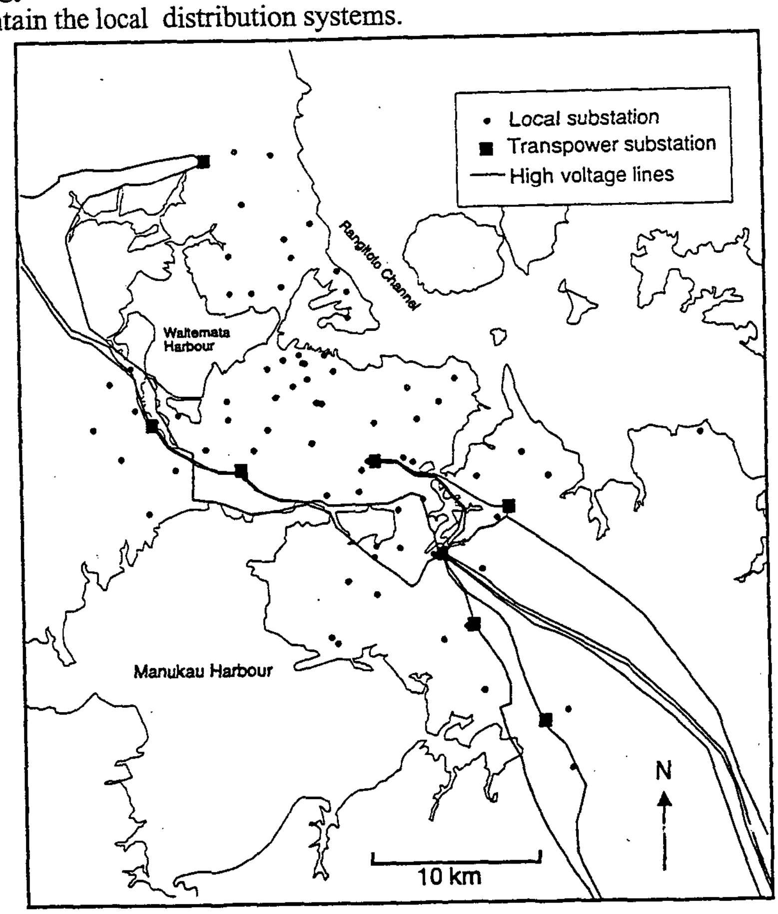

Figure 2.1: **Electricity distribution substations and high-voltage lines within the Auckland area. (Compiled from information supplied by Transpower Ltd, Mercury Energy Ltd and Power NZ Ltd)**

Falls of volcanic ash (tephra) can disrupt electricity supply over wide areas in several. Heavy accumulations of ash on tree limbs can break them onto local distribution lines, shorting-out or breaking the lines. Damp or wet ash-coatings on insulators will induce flashovers. Low-voltage systems are more vulnerable than higher-voltage systems due to the smaller weathersheds on low-voltage insulators. Light rainfalls post-eruption are more likely to induce flashovers than are heavy rainfalls, which will tend to remove ash coatings from insulators. The abrasive nature of ash will cause damage to mechanically moving parts, such as switches and cooling fans. Most tephra-fall induced power outages are of short duration unless the falls are exceptionally thick, or other volcanic hazards prevent clean-up operations. Immediate ash removal is the best mitigation procedure to prevent widespread outages resulting from tephra-falls.

Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk of damage to electricity installations in the affected areas, but the extent of these hazards (in typical Auckland eruptions) is mostly limited to within a few kilometres of the erupting vent. Severe near-vent ground shaking accompanying volcanic earthquakes (and any associated faulting as in Scenario 3) will also topple power poles and rupture underground services, possibly in areas not greatly damaged by eruption products. There are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures. Corrosion of metal surfaces will result from acid rain formed from the release of volcanic gases, notably SO_2 and HCl.

The consequences of loss of electricity supply are widespread, and many other public utilities (e.g. water supply pumps, radio and telecommunication facilities) will be inoperative without alternative power supplies (batteries and generators) available.

ELECTRICITY SUPPLY AND RETICULATION
Scenario 3

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig 1.9)	Moderate-high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back tree branches, repair lines
	South Auckland, Waiheke Island (< 5 mm thick)	Low-moderate risk of outage if ash is wet. Low risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
Lava flows	CBD and Devonport (see fig.1.8)	Destruction within flow area	N/A
Surges	1.5-3 km from vent (see fig.1.7)	Destruction of all above ground installations	N/A
Ground shaking/ faulting	To 5 km SSW from vent (see fig.1.8)	Toppled power poles, broken lines, ruptured underground services.	N/A
Lightning strikes	out to 10 km from vent.	High risk of damage and outage.	N/A
Acid Rain	up to 10 km downwind.	Moderate to minor corrosion, effect decreasing with distance from the vent.	Washing of transformer bushings and other substation insulators.

2.2 GAS SUPPLY AND RETICULATION

Natural gas is piped from the Maui gas field to the Auckland area by the Natural Gas Corporation Ltd. The pipes are usually buried to more than 0.7 m depth. Automatic shutdown equipment at points along the pipeline is designed to cut off the gas supply if the pipe is ruptured. Gas is supplied to the Enerco Gas Ltd local supply company. A trunk pipeline distributes gas throughout the city, into several branch mains (Fig. 2.2). Gas pressure is reduced at pressure reducing stations for local supply.

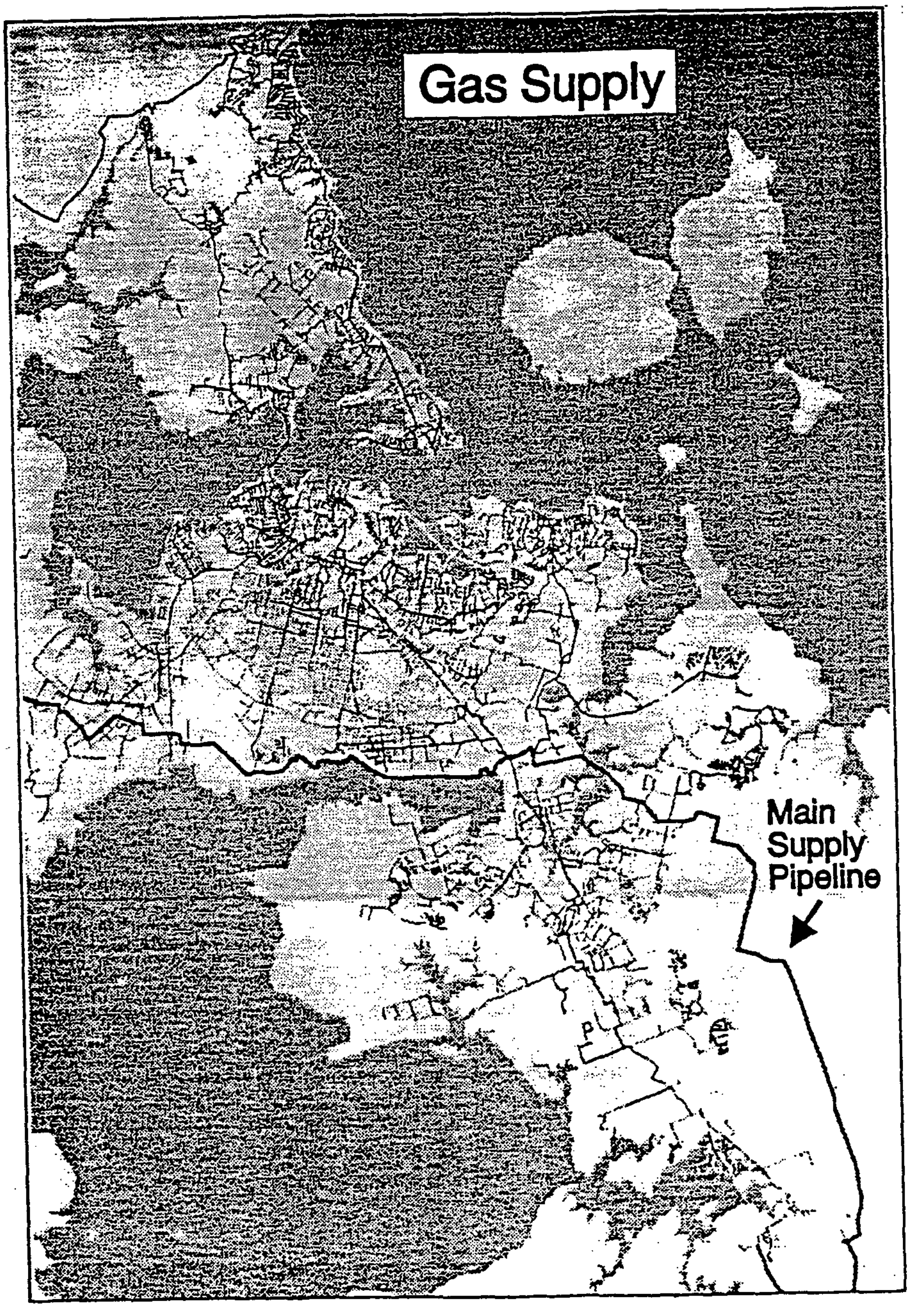

Figure 2.2: Gas distribution in Auckland (map supplied by Enerco Gas Ltd)

Most gas pipes are located below-ground and are thus protected from the direct effects of tephra falls, pyroclastic surges, lava flows and the affects of acid rain. Above-ground, pumping stations, pressure reduction facilities, pipeline bridge crossings and gas meters at consumer's sites are vulnerable to damage from a range of volcanic hazards. Any line installations (Fig. 2.2) above ground would be severely damaged by surges. Severe ground deformation would rupture gas pipes near vents prior to the eruption commencing, and during eruptions in areas of associated faulting. Any damage to facilities or fracture of pipelines may cause ignition of residual gas, even if gas reticulation has been previously shut down.

GAS SUPPLY AND RETICULATION
Scenario 3

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Surges and ballistic clasts	Within surge zone centred on Mechanics Bay vent area (see fig.1.7).	Damage to above-ground gas distribution and metering facilities	Cut off gas supply
Lava flows	Within surge-affected area (see fig.1.8)	Complete destruction of any facilities which survived surges	Cut off gas supply
Ground deformation and faulting	Near-vent, and in Newmarket-Remuera seismic zone to SSW (see fig.1.8)	Fracture of pipelines, before and during the lengthy eruption episode	Cut off gas supply

2.3 WATER SUPPLY AND RETICULATION

Auckland's reticulated water is derived from four main areas: 1) Waitakere Ranges, 2) Onehunga groundwater source, 3) Hays Creek and 4) Hunua Ranges (Fig. 2.3 and Table 2.1). A small stand-alone underground system is also used in Papatoetoe.

Table 2.1: Auckland's main water supplies

Sources	Type	Treatment	% of Auckland Supply
Waitakere Ranges	5 dams	Waitakere, Huia and Nihotupu Filter Stations	31 %
Onehunga	3 wells/ 1 borehole	Onehunga Filter Station	5 %
Hays Creek	1 dam	Hunua Gorge Filter Station	3 %
Hunua Ranges	4 dams	Ardmore Filter Station	61 %

Dams in the Waitakere and Hunua ranges supply 95% of the reticulated water supply (Fig. 2.3). Water is treated at a number of filter stations and supplied by a series of large water mains to 57 service reservoirs. Gravity is the main means of moving water from the filter stations but 20 pumping stations are used where gravity is insufficient. The service reservoirs provide a "buffer" capacity to meet daily demand and have sufficient storage for two and a half days of average demand on the whole system. Reservoirs that supply discrete areas are normally operated between 75-100% full, and others between 50-100% full. Gravity is utilised to supply most areas from the service reservoirs, through local council operated distribution networks. Service reservoirs are completely enclosed except for mesh-covered ventilators. The bulk water supply system is monitored from the Watercare Operations Centre in Onehunga. Water quality is also monitored to ensure that water meets Drinking Water Standards.

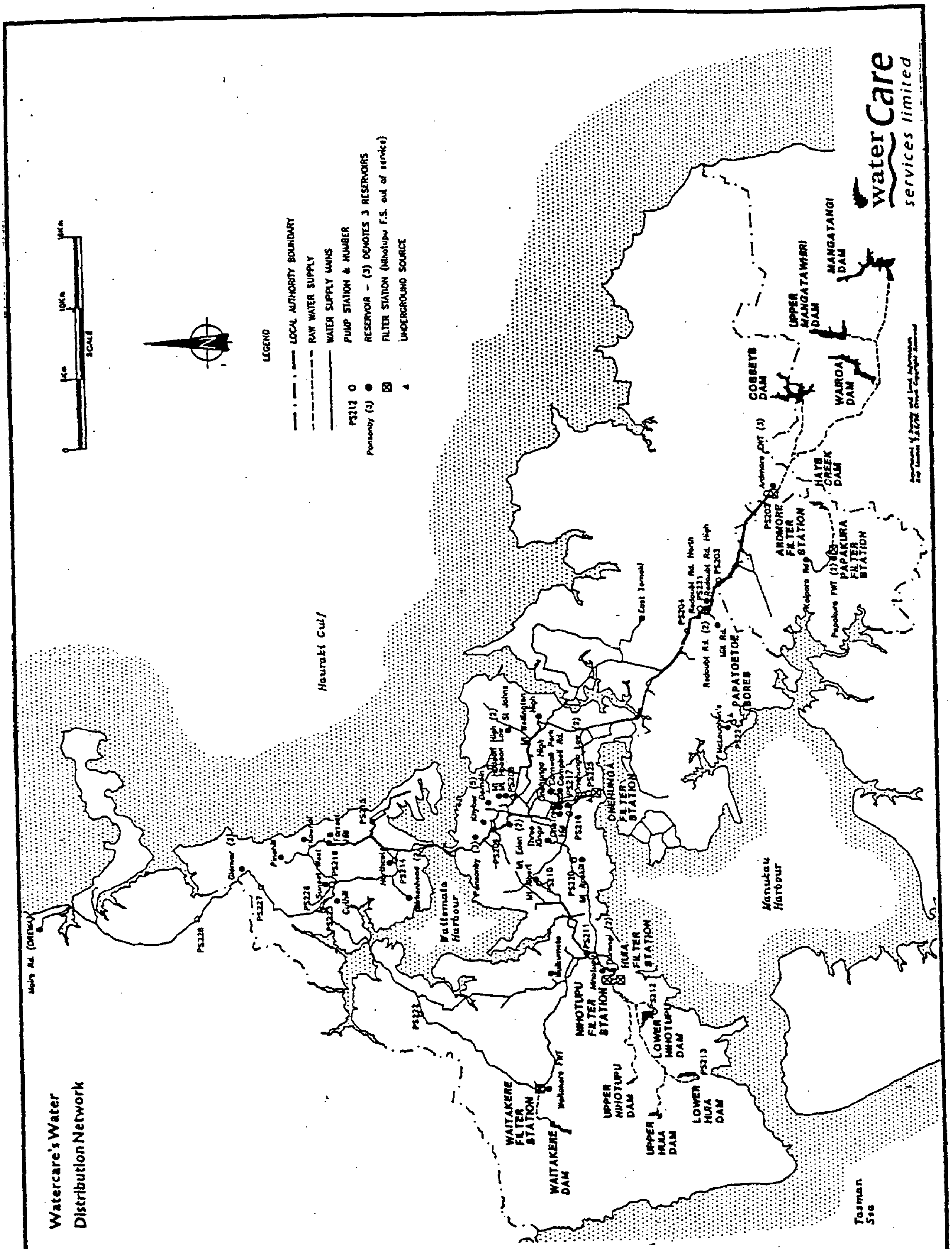

Figure 2.3: **Water reticulation system in the Auckland region (Supplied by Watercare Services Ltd)**

Contamination of Auckland's stream-lake-fed reticulated water supplies is possible from even relatively small tephra-producing eruptions, and is likely to restrict or prevent water intake from these sources for some time during and after an eruption episode. It is at just this time that increased demand for water can be expected for ash and acid rain clean-up operations.

Both turbidity and acidity of storage lakes will increase with tephra infall, but these parameters are likely to return to normal levels within a few days-weeks after tephra-falls cease and suspended ash settles out of the water column. However, intense rainfalls will wash further ash into lakes from their catchments, and ash-laden stormwater inflows can continue for months after an eruption has ended. Filter beds at the lake water treatment stations could be blocked by high loadings of suspended ash, and water intake at the treatment stations would likely be stopped until the lakes had cleared. Hazardous changes in lake water chemistry induced by toxic trace elements (including selenium, mercury, arsenic, fluorine and boron) contained in condensates on infalling ash are possible but unlikely due to the dilution and buffering properties of the relatively large volumes of lake water.

Water supply installations in near-vent areas directly affected by lava flows, ballistic blocks and pyroclastic surges will be destroyed. Water supply pipes in areas of severe ground deformation and/or faulting will be broken. Heat from lava flows can pressurise water remaining in underlying shallow buried pipes, possibly causing local explosions.

In outlying areas without reticulated water supply, household tank water may be collected from roof catchments. Within tephra-fall areas, downpipes should be disconnected from storage tanks so that ash is not washed into the tanks, and only reconnected after ash has been removed from roofs and gutters.

WATER SUPPLY AND RETICULATION
Scenario 3

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall (direct)	North Shore, central and eastern suburbs (5-50 mm thick, see fig.1.9)	Low - moderate risk to reservoirs from ash infiltration	Cover reservoir ventilators, monitor water quality
	South Auckland, Waiheke Island (< 5 mm thick)	Low risk to reservoirs from ash infiltration. Contamination of roof/tank supplies.	Cover reservoir ventilators, monitor water quality. Disconnect roof/tank pipes
(indirect)	all ash fall and acid rain areas	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures
Ground shaking/ faulting	Near-vent and 5 km to SSW (see fig.1.8)	Pipe breakage	N/A

2.4 WASTEWATER RETICULATION AND TREATMENT

Auckland's wastewater system consists of a network of pipes, tunnels, seven major interceptors, 60 pumping stations and a treatment plant (Fig. 2.4). Sewage is collected from local council operated pipe networks, and passes to the bulk wastewater system operated by Watercare Services Ltd. Sewage and stormwater is combined in a part of the system (e.g. Orakei interceptor), which services much of the inner city. Overloads sometimes occur when the volume entering the system exceeds the capacity of the pipes and pumping stations. Overloads are usually a result of high rainfall, prolonged power outage or equipment failure. A sophisticated remote surveillance system monitors the status of pump stations and warns of equipment failure and overflows. The wastewater treatment plant at Mangere uses both primary and secondary treatment methods.

Tephra-falls will cause serious problems to Auckland's sewage and stormwater systems over a wide area. Ash which falls on roads, roofs, and other impervious areas, is easily washed into the stormwater system by rain, or during cleanup operations. [In some overseas eruptions, minor amounts of ash have been cleared from stormwater basins and pipelines by vacuum suction or high pressure water jets]. Ash will enter the sewage system via illegal connections, manholes, gully traps, or where the sewage and stormwater systems are combined (central Auckland). The density of ash is usually too high for a significant amount to remain in suspension at the water velocities normal in the sewer and stormwater pipes, so that ash will readily accumulate to block pipes and channels and lead to surface ponding. Finer ash may remain in suspension and be transported to the sewage treatment plant. Sewage pumps may be abrasion-damaged by ash-laden sewage, or fail due to loss of electricity (see above). Failure will result in the banking up of sewage in urban areas. The removal of ash from sewage and stormwater systems will be a time consuming and costly exercise.

Ash-laden sewage which enters the Mangere treatment plant will overload the solid-removal equipment at the pretreatment and primary treatment stages. Milliscreens, mechanical grit/sludge removal mechanisms and other equipment that comes into contact with ash-laden sewage are likely to be rapidly worn and/or damaged. Ash falling directly into sedimentation tanks will add to the volume of solid material that will eventually have to be removed. Ash entering secondary treatment facilities, such as oxidation ponds and biofilters will reduce or halt the oxidation process until such time as the ash settles out or is removed. The ash may affect the acidity or toxicity level of the effluent to an extent that bacteria growth is damaged or lost. Release of untreated sewage will result from failure of the plant and/or its deliberate shutdown to avoid further damage.

Lava flows and thick pyroclastic surge deposits will block existing stormwater reticulation in affected areas, and significantly change local topography, leading to local ponding of surface waters. Heat from lava flows can pressurise water remaining in underlying shallow buried pipes, causing local explosions. (Septic tanks have been exploded in Iceland!) Ground deformation and faulting will break existing sewage and stormwater pipes. All these hazards are restricted to near-vent areas.

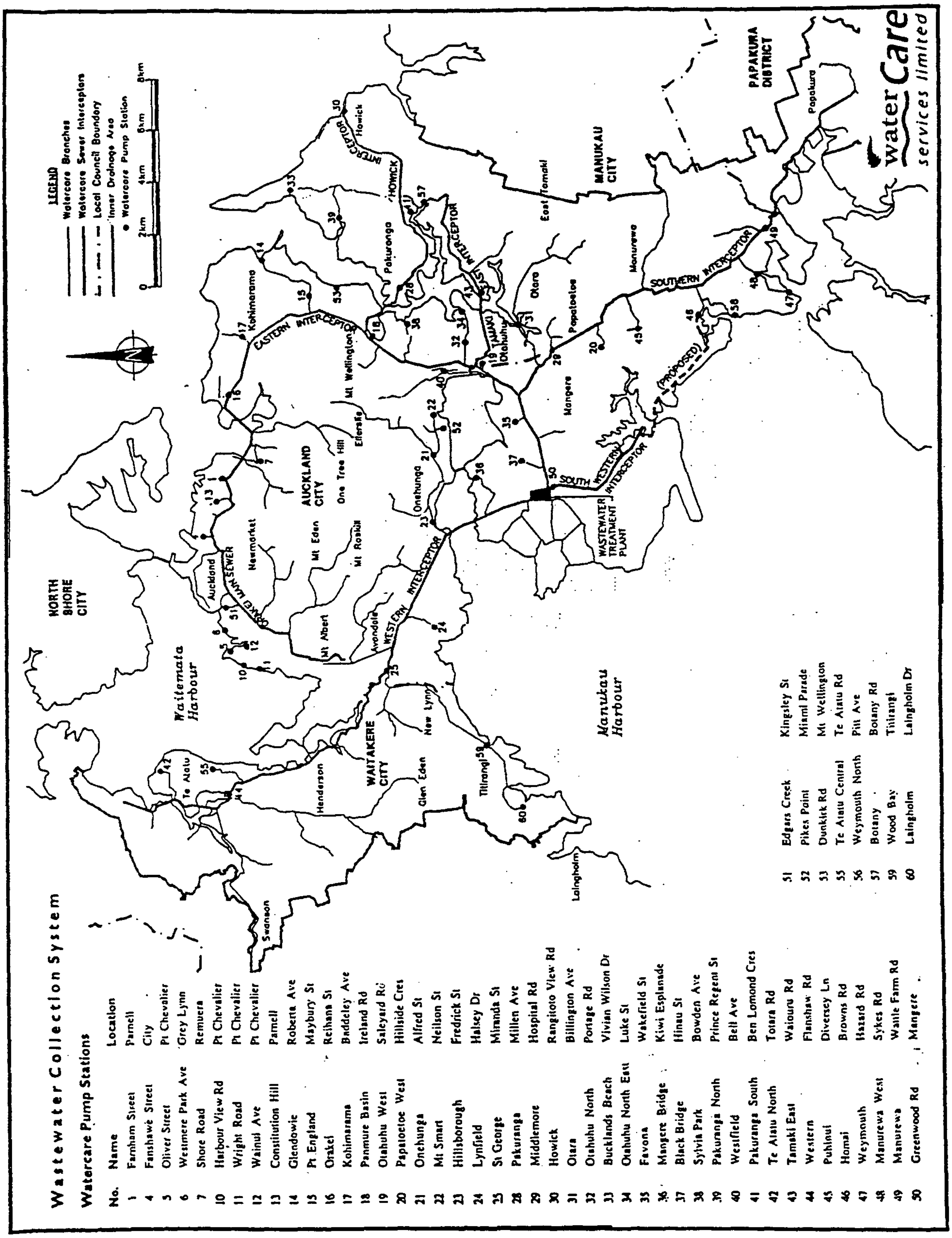

Figure 2.4: **The wastewater collection system in the Auckland region. (supplied by Watercare Services Ltd)**

WASTE WATER RETICULATION AND TREATMENT
Scenario 3

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig. 1.9)	High-moderate risk to stormwater/sewerage system, potential risk to treatment plant.	Minimise input of ash to reticulation systems, monitor sewage for ash contamination
	South Auckland, Waiheke Island (<5 mm thick)	Low - moderate risk to stormwater/sewerage system (as above)	Minimise input of ash
Ground shaking/ faulting	Near-vent and 5 km to SSW (see fig.1.8)	Pipe breakage	N/A

2.5 TELECOMMUNICATIONS

The telecommunication networks provide local and external telephone links in the region. There are a number of telecommunication providers in the Auckland area. For the purposes of this report information has only been sourced from Telecom NZ Ltd. Local lines are connected to local telephone exchanges which are in turn linked to microwave repeater radio stations (nodal points) by underground copper or fibre cables. The microwave radio stations transmit and receive calls to and from neighbouring stations. A number of microwave stations are also the sites of VHF and cellular telephone stations. The telecommunications network in the Auckland is shown in Figure 2.5.

Broadcast radio and television facilities in the Auckland region are provided by state and private organisations, with local stations and nationwide networks originating from studios within and outside the region. Radio and television transmitter sites are located about the city, with some microwave network links to outside areas sharing common facilities. We have not considered impacts on local broadcasting stations which would be affected by the scenario eruptions because emergency management broadcasting can be continued from stations outside the affected areas.

Communications will be severely disrupted during an eruption in Auckland, resulting from interference to radio waves due to disturbed atmospheric electrical conditions, overloading of telecommunication systems due to increased demand, direct damage to communications facilities by eruption products or lightning strikes, indirect impacts resulting from disruption to electricity supplies or transportation of technicians (preventing operations or maintenance). Ash entering telephone exchanges can cause damage to electrical and mechanical systems and general damage to buildings. Exchanges have battery-generator power backup systems to enable continued operation in the event of loss of electricity supply. Generators are housed in the exchange buildings, but rely on external air intakes to air filters. Clogging of these filters by ash would result in failure of the generator, followed by exhaustion of the battery capacity after a few hours demand.

Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk of damage to communication installations in the affected areas, but the extent of these hazards (in typical Auckland eruptions) is mostly limited to within a few kilometres of the erupting vent. Severe near-vent ground shaking accompanying volcanic earthquakes (and any associated faulting as in Scenario 3) will also topple poles and rupture underground services, possibly in areas not greatly damaged by eruption products. There are few or no mitigation options available to counteract any of

these near-vent hazards, which apply to all structures. Corrosion of metal surfaces will result from acid rain formed from the release of volcanic gases, notably SO_2 and HCl.

Loss of communications will make disaster management extremely difficult before, during and after an eruption.

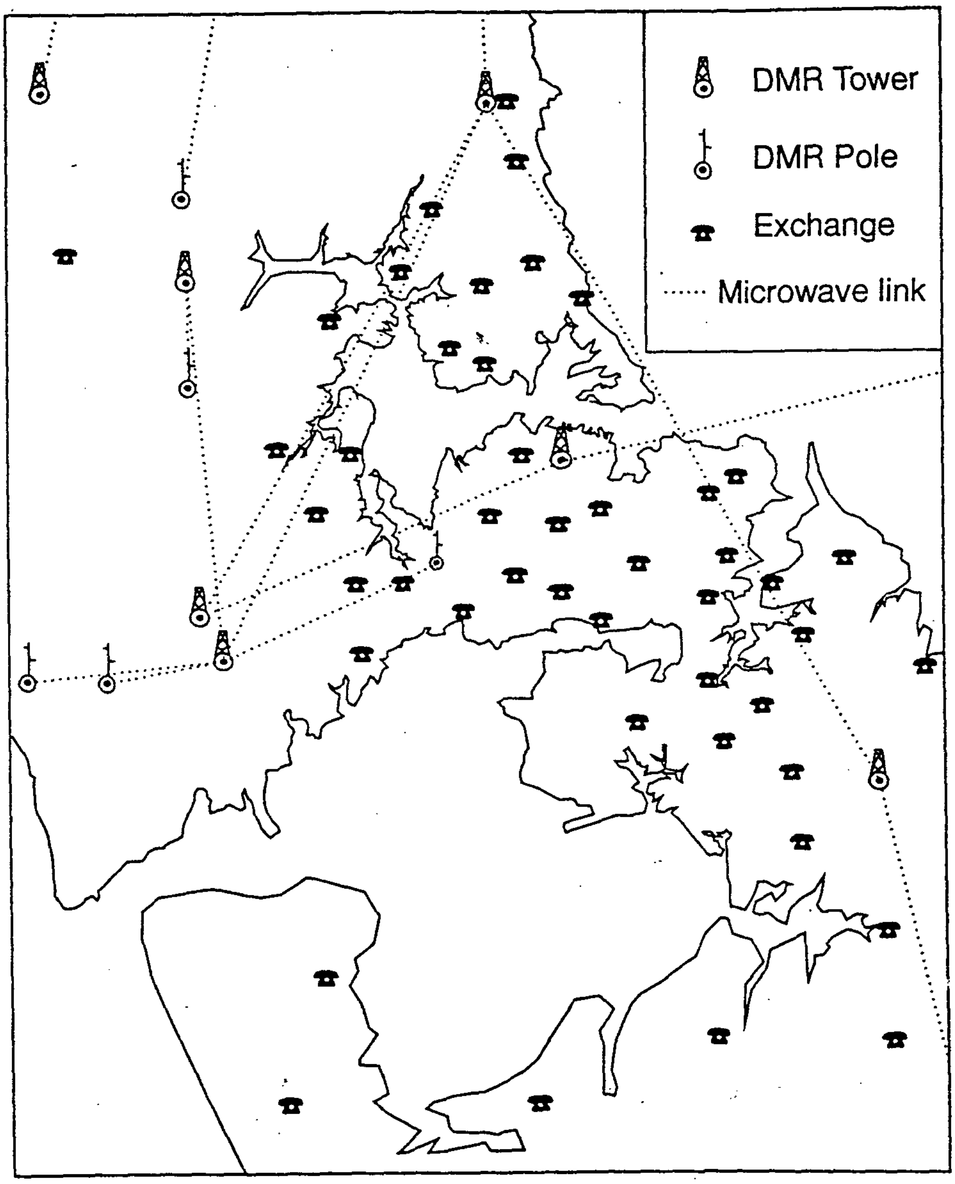

Figure 2.5: The telecommunications network in the Auckland region (supplied by Telecom NZ Ltd). (DMR refers to Digital Microwave Repeater)

TELECOMMUNICATIONS
Scenario 3

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Exchanges			
Tephra-fall	Within 10 mm isopach (see fig.1.9)	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash
	outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Seal exchanges, fit internal air-conditioning, remove ash
Acid Rain	up to 10 km downwind from vent (see fig.1.7)	Risk of minor to moderate corrosion,decreasing away from the vent.	Washing of exterior of buildings.
Lines/cables			
Tephra-fall	within 50 mm isopach (see fig.1.9)	Moderate risk of line collapse if ash builds up.	Rainfall, hosing or air blasting to remove ash.
Surges (and lava flows)	Out to 3 km from vent (see fig.1.7)	Destruction of poles and lines.	N/A
Ballistic clasts	Out to 2 km from vent	Area also devastated by surges	N/A
Lightning	Out to 10 km downwind from vent	Pole fires and transformer explosions	N/A
Ground shaking/ faulting	Near-vent and 5 km to SSW (see fig.1.8)	Cable breakage	N/A
Microwave towers			
Tephra	Within 10 mm isopach (see fig.1.9)	Low to moderate risk of disruption and damage if exchanges are sealed	Remove ash immediately.
	Outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Remove ash immediately.
Lightning	Out to 10 km downwind from vent	Strikes on towers	N/A

2.6 CRITICAL FACILITY BUILDINGS (HOSPITALS, CIVIL DEFENCE HQ, FIRE HQ, POLICE HQ)

For the purpose of this report, critical facilities are defined as buildings associated with emergency and essential services required during an emergency. A large number of buildings may be included in this category (e.g. hospitals, fire and police stations, civil defence facilities, contractor's yards, ambulance stations etc.). The consequence of disruption to their use will vary depending on their importance to the operation of the emergency management system as a whole. Auckland has a range of critical facilities, of varying importance and only a few are discussed here (i.e. main hospitals, Regional Police, Fire and Ambulance headquarters, City Council Civil Defence headquarters and Regional Civil Defence headquarters).

Critical facility buildings are extremely vulnerable to disruptions of the "lifelines" which provide the services and linkages which allow them to operate. Electricity is required for lighting, ventilation, boiler operations, water heating, freezers/coolers, kitchens, medical services, lifts and security. Water supply is usually required for satisfactory operation of hot and cold water systems, fire hoses and sprinklers, kitchens and laboratories. Communication facilities are critical for the operation of the emergency management organisations (civil defence, police, fire) and require continued electricity supply. Many buildings have back-up systems (e.g. electrical generators, water tanks) to provide limited supplies of these services in the event of loss of main (or primary) services

Tephra can cause direct damage to buildings and building services in several ways; overloading roofs to cause collapse (in excess of 100 mm of wet tephra), soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials.

Lava flows, ballistic clast impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk of damage to critical facilities in the eruption-affected areas, but the extent of these hazards is mostly limited to within a few kilometres of the vent. Severe near-vent ground shaking accompanying volcanic earthquakes (and any associated faulting as in Scenario 3) will also damage buildings, possibly in areas not greatly damaged by eruption products. Apart from the evacuation of people (and removal of plant), there are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures (except for example, alternative or duplicate facilities which may be set up outside the affected area in advance). Corrosion of metal surfaces will result from acid rain formed from the release of volcanic gases, notably SO_2 and HCl.

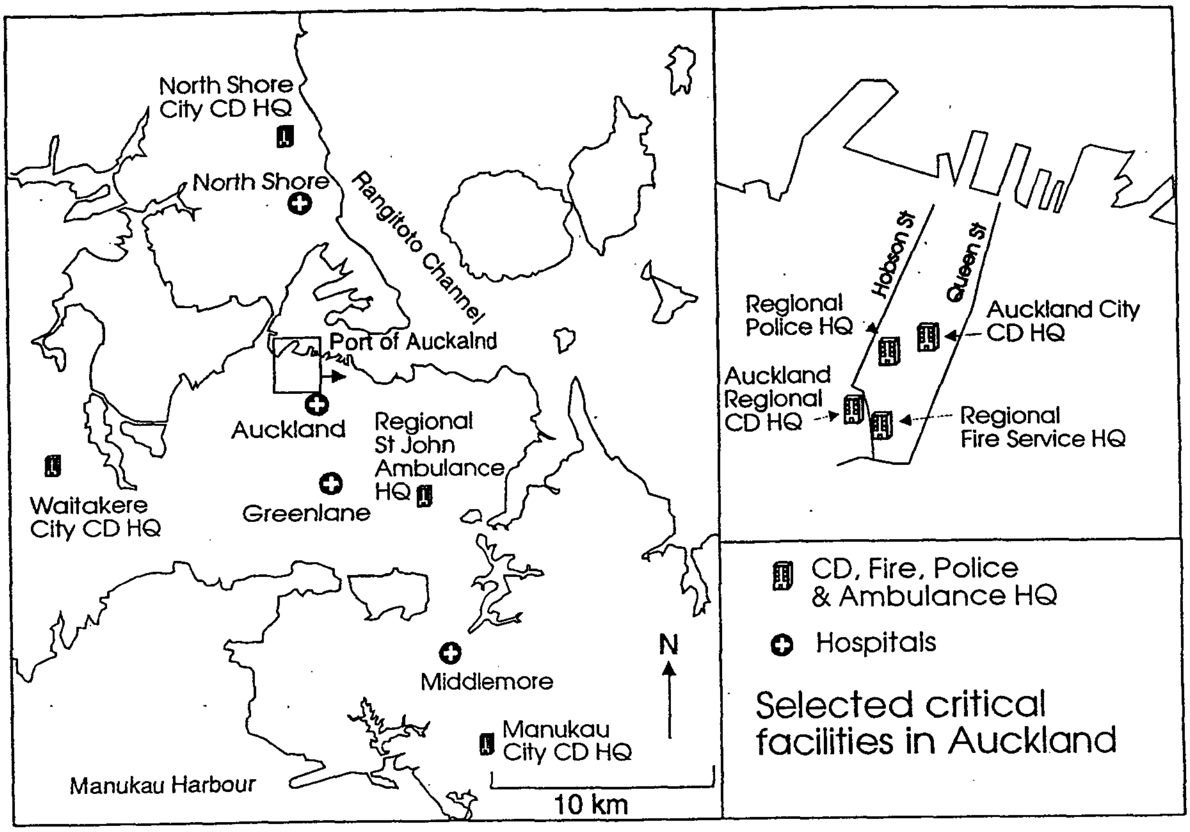

Figure 2.6: Locations of critical facility buildings mentioned in the text

CRITICAL FACILITY BUILDINGS
Scenario 3

Type of facility	Location	Basic risk to service	Mitigation strategies
Hospitals		*Tephra falls*	
	North Shore Greenlane Middlemore	10mm 30mm 5mm	<50mm, seal against ash, use internal air conditioning, local clean up
	Auckland	60mm tephra and peripheral to surge zone	evacuate
Auckland City and regional CD HQ		50mm tephra and peripheral to surge zone	evacuate
Auckland Central Police HQ		50mm tephra and peripheral to surge zone	evacuate
Auckland Central Fire HQ		50mm tephra and peripheral to surge zone	evacuate

2.7 POPULATION

The Auckland region contains more than one million inhabitants occupying the area surrounding the narrow isthmus between the Hauraki Gulf and Manukau Harbour. The entire population of the region will be affected in some way by an eruption from the Auckland Volcanic Field. Most people will experience tephra fall and some loss of services, but a significant number of people will face evacuation from the potential near-vent area. Evacuation will be deemed necessary by the controlling authorities if a perceived risk to human life reaches unacceptable levels. Within the Auckland Volcanic Field, a 5 km radius around the vent is assumed to be a minimum safe distance to avoid the impacts of surges and ballistic clasts which can be expected to feature in the early, explosive phases, of an impending eruption. The population living within a range of distances from each scenario eruption vent is given in Table 2.2.

Table 2.2: Population within a given radius of Scenario 3

	Scenario 3
Grid reference	6482400 2669000
1 km	2 688[m]
2 km	12 102[m]
5 km	105 096[a]
10 km	368 004[a]

m = S meshblock populations contained with the given radius (1991 census).
a = S area unit populations contained with the given radius (1991 census).

Note: Populations are calculated using the Department of Statistics CD-Rom census database (Supermap 2). A meshblock or area unit is only selected where the arc covers or passes through the centroid of the area. Meshblocks are the smallest geographic units in which data is collected by the Department of Statistics. They vary in size from a city block (or part of) to extensive tracts of rural land. Urban meshblocks generally contain between 150 to 200 people while rural meshblocks have fewer (100 to 150) and some have no population. Meshblocks can only be used in the above calculations when there are less than c. 500 within a given radius. Area units are the next larger statistical unit, made up of an aggregation of meshblocks and are used for population calculations at larger radii. Area units general have a population of between 3 000 to 5 000.

EVACUATION

The principal function of evacuation is to ensure that people move from a place of relative danger to a place of relative safety via a route that is itself free from significant danger. The destination as well as the route must be considered in the plan. There needs to be careful coordination of the timing and conduct of an evacuation and this must be done in association with agencies who are assessing risk and ordering the evacuation, as well as those responsible for receiving evacuees. Evacuation of near-vent areas must be completed prior to the eruption if possible. When precursory seismicity and deformation is severe, some voluntary self-evacuation of the near-vent area is likely to occur (as at Rabaul in 1994), before compulsory evacuation is required.

Post-eruption evacuation may also become necessary in areas where people have survived tephra fall without difficulty, but in which the long term loss of normal services such as water and food supply, electricity, and waste disposal, have made continued habitation untenable.

If the evacuation of a hazardous zone is to proceed in an orderly manner it is essential that people know where to go, and what route to take. Unless the risk to life is immediate and obvious, people will be

reluctant to leave their homes. Assurance must be given that the evacuated area will remain off limits to unauthorised people.

New Zealanders' experience of large scale evacuations is minimal, and the logistical and social problems associated with such an action would probably be very substantial. People forced to move are likely to feel demoralized and dysfunctional, and physical and mental health problems may occur at a higher rate than normal. This will depend on the severity of the disaster, and the personal situation of the evacuees.

Evacuations usually involve three types of movement:

1. Self-evacuation where people move out in their own vehicles to stay with friends/relatives. Such self-evacuations may be voluntary, and often precede any compulsory evacuation.

2. Movement of people who do not own or have access to private vehicles;

3. Movement of people with special needs, e.g. hospitals, disabled persons, jails

PUBLIC HEALTH ASPECTS

Residents outside the compulsory evacuation zone may have to contend with significant thickness of tephra (up to 50 mm). Fresh tephra and aerosols act as an irritant on the upper and lower respiratory tracts and eyes but is non-toxic. Respiratory problems will result from the inhalation of fine ash, but will be more acute in patients with existing respiratory disorders. Eye problems will include foreign material in eyes, corneal abrasion and conjunctivitis. During periods of ashfall the best precaution is to stay indoors. Where it is necessary to move outside, a protective filter mask should be worn. If such a mask if unobtainable, wet cloth over the mouth and nose will prevent inhalation of the ash.

POPULATION
Scenario 3

Area	Action/Mitigation
5 km radius around vent (see fig.1.7)	Evacuation (~105 000 people)
Orakei, Remuera Newmarket, Mount Eden Grey Lynn, Ponsonby Auckland Central Northcote, Devonport	Take with you: essential medicines, toilet items; important documents; transistor radio and torch; extra clothing. Before leaving: consider your pets and animals, turn off water, electricity, gas and heating oil at the mains; secure premises. When you reach safety: listen to your radio for further instructions, including registration requirements.
Tephra fall	
North Shore, central and eastern suburbs (5 - 50 mm thick, see fig.1.9) South Auckland, Waiheke Island (<5 mm thick)	Take shelter. Listen to the radio for advice and information, stay indoors, close windows and doors, do not run air-conditioning or clothes dryers with outside connection, if outside seek shelter; use a mask or handkerchief for breathing , do not drive unless you have to, but if you must drive, drive slowly as ashfall will reduce visibility, keep pets indoors.

2.8 ROAD AND RAIL TRANSPORTATION FACILITIES

State Highways provide access to the city from north and south (Fig. 2.7). All road transport must pass through the narrow isthmus between the Hauraki Gulf and Manukau Harbour. Within the region much of the state highway system comprises multi-lane motorways. Within the city a number of arterial routes link various suburbs. The North Shore and Auckland City are linked by the eight-lane Auckland Harbour Bridge, as well as an upper harbour bridge and road links to the northwest.

The railway system serving Auckland comprises three lines (Fig. 2.7). The North Island Main Trunk line enters Auckland from the south serving the Port of Auckland. Inter-city passenger and commuter services also utilize this line and commuter services operate on the eastern and western lines.

Reduced visibility on roads will be experienced over wide areas during and after ash falls. Dry fine ash is readily raised in billowing clouds by passing vehicles and will present an ongoing hazard. Wet fine ash can turn to mud causing vehicle traction problems. Thick (>100 mm) ashfall deposits will absorb a considerable amount of water before being washed away. Thin ash deposits (<2 mm) will generally be moved to the shoulder of roads by traffic, but will remain there. Greater thicknesses of ash will need to be physically removed from road surfaces by scraping, brushing and washing.

Lava flows will block roads over which they flow, and lava removal or road rerouting will present major problems after an eruption has ended. Thick surge deposits will also bury roads in near-vent areas. Severe ground deformation and/or faulting can make roads temporarily impassable by road surface cracking and building collapse onto the roadway. Most such effects will only occur in near-vent areas which will be devastated by other effects of the eruption.

Problems arising as a consequence of closure of roads include lack of access for emergency services, stranding of travellers, disruptions to food supplies, and economic impacts on businesses in the affected areas. Where ash-covered roads remain open, speed restrictions will need to be introduced to ensure traffic safety on roads in reduced visibility, and to reduce dust problems in adjacent communities.

Ash entering vehicle engines and transmissions will cause wear on moving parts, reducing their life. In most cases severe damage will only result from excessive vehicle use in an ash-affected environment. The most common effect of ashfall on vehicles is blockage of air filters leading to overheating and stopping of motors. The abrasive ash can also damage vehicle brakes, exterior fittings, paintwork and windows.

Acid rain and gas clouds (including "laze") will cause greatly increased corrosion of vehicles.

Rail lines and rail transportation will be affected in a similar manner to road transportation, but rail is usually the ground transport system least affected by tephra fall. Near-vent severe ground deformation and cracking will cut rail lines, which will also be buried beneath thick surge deposits and lava flows). In distal areas, ashfall less than ~10 mm thick can be quickly cleared from rail tracks, and train running resumed. Problems with ash clouds stirred up by train passage restrict operating speeds, cause operator vision and breathing problems, and can affect diesel locomotive motors and transmissions (as happened during the 1980 Mt St Helens eruptions). Light rain on ashfall has led to extensive short-circuiting of electrically-operated signal equipment in overseas eruptions.

ROAD AND RAIL TRANSPORTATION FACILITIES
Scenario 3.

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Roads			
Tephra	Within 50 mm isopach (see fig.1.9)	Roads closed until ash cleared.	Remove ash from road surface
	Between 50 and 5 mm isopachs	High risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
	Outside 5 mm isopach	Reduced visibility and traction problems (if wet).	Remove ash from road surface
Surges and lava flows	Out to 2 km from vent (see fig.1.7)	Roads buried	N/A
Vehicles	Within 10 mm isopach (see fig.1.9)	Moderate - high risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
	Between 10 and 1 mm isopachs	Low - moderate risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
Railways			
Tephra	Within 5 mm isopach (see fig.1.9)	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from lines, reduce speeds,provide face masks, increased locomotive maintenance
Surges and lava flows	Out to 2 km from vent (see fig.1.9)	Lines buried	N/A.

2.9 PORT FACILITIES AND SHIPPING

The port of Auckland is the region's main sea port, loading the largest value of goods per year of any New Zealand port. The main port facilities are located on the southern shore of the Waitemata Harbour, between St Mary's Bay and Judges Bay, with other shipping facilities and wharfs at Devonport and Birkenhead on the north shore of Waitemata Harbour. There are also wharf facilities at Onehunga on the Manukau Harbour.

Auckland port facilities and shipping are affected by tephra falls, tsunamis, surges and lava flows in the various eruption scenarios. Where relatively thin, tephra falls will produce temporary primary and secondary impacts on port operations by affecting staff availability, road and rail access (see above), power supplies and communications, as well as availability of freight (which will probably be largely diverted to other ports). Rafts of scoria will temporarily block sea access in parts of the harbour, although these rafts should rapidly clear after eruption has ceased. Small may cause some damage as

small vessels (yachts) are thrown against wharf structures by wave action. Larger waves, generated early in the Scenario 3 eruption, would cause considerable damage to ships and wharfs in the Devonport area. All the main port facilities are destroyed by pyroclastic surges and lava flows later in the Scenario - 3 eruption, which also causes major topographic modifications to harbour morphology as lava flows block the entrance to the Waitemata Harbour.

PORT FACILITIES AND SHIPPING
Scenario 3

Type of hazard	Nature of impact	Basic risk to service	Mitigation strategies
Tephra	>50 mm fall on main port area (see fig.1.9)	High risk of disruption, but insignificant cf. later destruction	Cease operation, cover vulnerable machinery, remove ships
	~1 mm fall on Onehunga (see fig.1.9)	Moderate risk of temporary disruption, low risk of damage to port machinery	Cease operation, cover vulnerable machinery, initiate clean-up operations
Tsunamis	Affect Devonport	Damage to wharf facilities (insignificant cf. later destruction	Prior removal of equipment
Surges and tuff cone growth	Hot wet surges from proximal vent (see fig.1.7)	Destruction and burial of main wharf area and Devonport, infilling of shipping channel	Prior removal of equipment
Lava flows	Further burial of wharf areas (see fig.1.8)	blockage of Waitemata harbour entrance	N/A

2.10 AIRPORT FACILITIES AND AIR TRANSPORTATION

Auckland International Airport (at Mangere) is the main international airport in New Zealand and is the only airport in the Auckland region to have scheduled passenger services. Scheduled domestic flights account for 65 % of air traffic, international 16 % and the remaining 18 % general aviation (defined as all flights other than regular scheduled flights by domestic and international airlines). Other Auckland region airports affected by the scenario eruptions are located at Ardmore, RNZAF Base Auckland (Whenuapai and Hobsonville) and Dairy Flat, with smaller airfields at Drury and on Waiheke Island. Airport locations are shown in Figure 2.7.

Air transportation is particularly vulnerable to moderate-large tephra eruptions (as recently demonstrated during the Ruapehu 1995 and 1996 eruptions), with airports being closed by <1 mm thick tephra falls, and large airspace volumes being closed to avoid actual (or suspected) ash clouds which can cause failure of aircraft engines in flight. The Civil Aviation Authority (CAA) will restrict air-space during eruptive episodes because of drifting ash and the sulphur dioxide haze, resulting in cancellation of flights and re-routing of others away from the exclusion zones. The restrictions precluded aircraft flying in cloud or at night within these zones due to the inablity of aircraft radar to detect ash clouds. As the exclusion zones changed constantly regular briefings for pilots are required and the re-routing adds extra distance to flights, increasing fuel costs and flight times.

Acid rain and gas clouds carried downwind during and after eruptions will present a continuing corrosion hazard to exposed aircraft and airport communication/electronic facilities.

There may be possible interference to radio communications and radar affecting traffic control (see Section 2.6).

AIRPORT FACILITIES AND AIR TRANSPORTATION
Scenario 3

Type of hazard	Airports affected	Basic risk to service	Mitigation strategies
Ash clouds	All Auckland airports	Downwind airspace closed during eruption	Track ash clouds and avoid
Tephra falls (see fig. 1.9)	Trace at all major Auckland airports,~2 mm at Waiheke	Airports closed until ash removed from runways and installations	Clean up after eruption
Acid rain and gas	All Auckland airports, subject to wind direction	Corrosion of aircraft and airport (communication) installations	Avoid aircraft exposure, clean up after acid rain/gas events

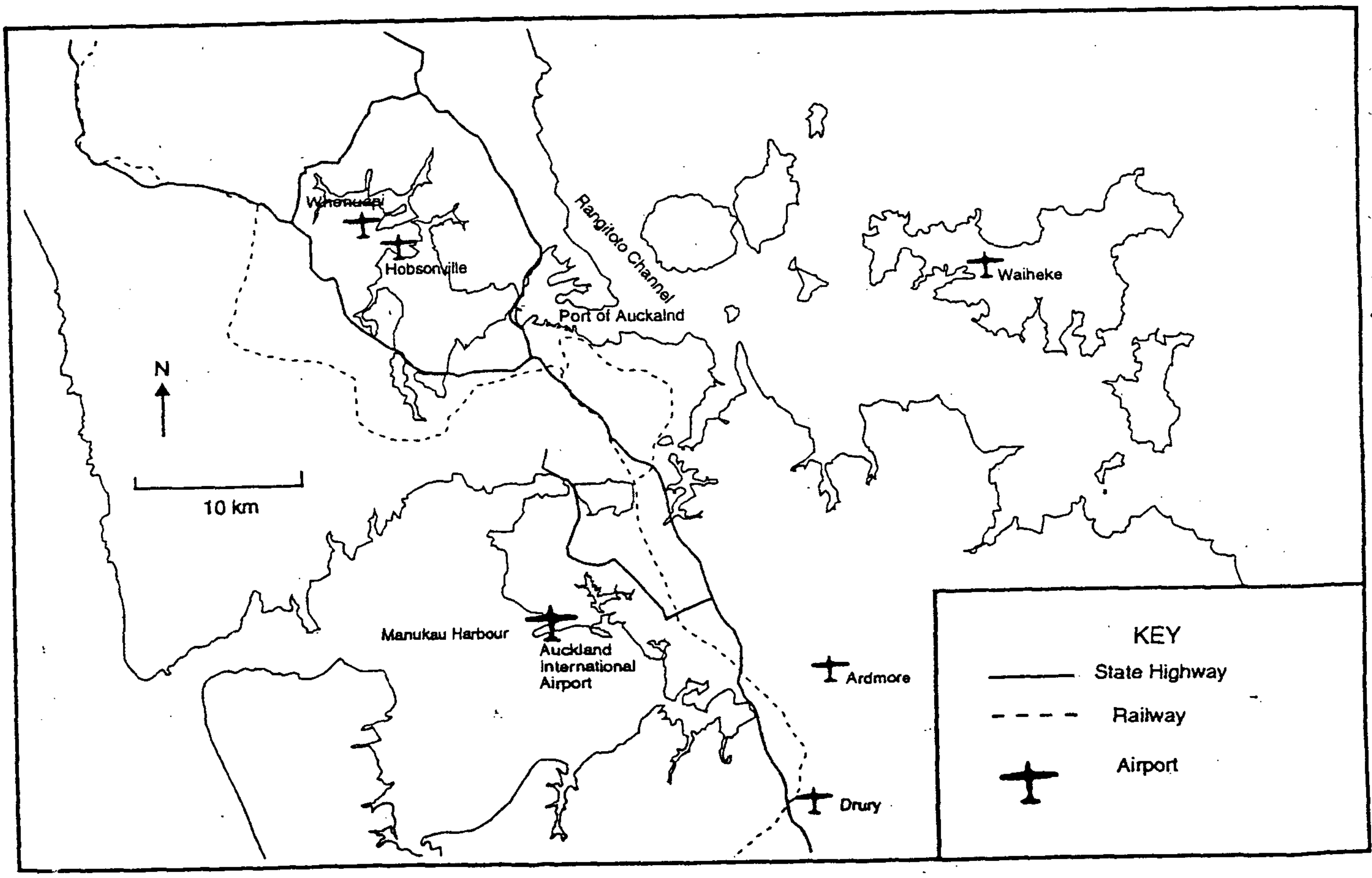

Figure 2.7: Main transportation routes and airport locations in the Auckland region

2.11 OTHER IMPACTS

A volcanic eruption which occurs within or adjacent to a major city will impact on all aspects of urban - life. All the possible impacts in this study have not been considered, in part because of the higher level of detail needed which is beyond the scope of the report (e.g. locations of petrol stations and hazardous chemical stores), but also because there are no closely analogous eruptions which have occurred within a modern city. Some impacts not considered are the effects of pyroclastic surges and lava flows on (a) petroleum storage tank farms, and petrol and LPG and CNG service stations; and (b) hazardous and inflammable chemical stores (destruction of which could produce widespread secondary effects). Other factors not considered include the difficulty of reliably identifying the end of an eruption episode (so that rebuilding could commence), and the closely-related downstream economic effects which would follow an eruption (loss of business confidence, loss of market, loss of staff, loss of access to supplies, insurance availability and premium loadings etc). An assessment of economic effects should be considered as part of a comprehensive risk assessment.

2.12 CONCLUSIONS

- Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk to life, and destroy near-vent structures in the scenario eruption-affected areas, but the extent of these hazards (in a typical Auckland eruption) is mostly limited to within a few kilometres of the vent. Severe near-vent ground shaking accompanying volcanic earthquakes will also damage buildings, possibly also in areas not greatly damaged by eruption products. Apart from the evacuation of people and removal of transportable assets (<5 km) (if possible) there are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures.

- Evacuation, where necessary to save lives in high-risk, near-vent areas (affected by lava flows, ballistic block impacts, pyroclastic surges), should be carried out before an eruption commences, and would have to be completed before the eruption peaks. Elsewhere, later evacuation of people may became necessary in areas where loss of services (electricity, water supply, sewage) makes continuing habitation untenable.

- The various scenario impacts illustrate the vulnerability of urban areas where the deposition of a few mm-cm of ash is sufficient to cause disruption of transportation, electricity, water, sewage and stormwater systems. Most systems, if affected only by thin tephra fall (<50 mm), can be restored within a few days to weeks.

- Falls of volcanic ash can disrupt electricity supply. Weather conditions will influence how falling ash adheres to insulating surfaces, with power outages occurring if the ash is wet (i.e. conductive). Low voltage systems are more vulnerable than higher voltage systems due to smaller weather sheds on insulators. Most outages are usually of short duration. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent widespread outages.

- Volcanic ash falls can cause severe damage to sewage and stormwater systems. The most effective mitigation measure to lessen the affects of ash falls is to reduce the input of ash into the system. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Bypassing and/or shutting down parts of the plant may need to be considered to reduce the likelihood of damage.

- Water supplies are vulnerable to contamination by ash fall into storage lakes preventing their use, and to excessive water demand during post-eruption ash clean-up operations. Water management plans will be required to manage excessive demands and should include

procedures to fill service reservoirs (if possible) on receipt of an ash fall warning, when appropriate public information messages outlining water conservation measures should also be broadcast. There is also a need to retain a fire fighting potential.

- Urban areas in the region will be forced to undertake expensive and time-consuming clean-up operations as a consequence of any of the scenario eruptions. In each case there will be a need to develop coordinated community-wide ash-removal plans, which identify appropriate methods of ash removal, collection and disposal. The public will need to be adequately informed on how to deal with volcanic ash.

- Relatively long term effects on people, animal and vegetation health, and on corrosion/deterioration of metallic and other materials may result from volcanic gas clouds (notably SO_2 and HCl) and acid rain carried downwind from vent areas. Release of volcanic gases may continue long after eruptive activity has ceased.

- This eruption scenario/impact exercise has highlighted the value of emergency management planning that will identify likely impacts on community lifelines and strengthen the links between agencies that will have to respond to such events. This needs to be done well in advance of any volcanic activity. Emergency managers need to agree on the early and proactive responses to warnings.

- The social and economic impacts of an eruption in Auckland will be determined not only by direct physical consequences but by the interaction of social, cultural and institutional processes that can amplify and attenuate the public response. Consideration of social and economic impacts must therefore be incorporated in comprehensive hazard management.

- The time required for the community to recover from a volcanic eruption depends on the extent of the impacts and the amount of assistance available. Physical, economic and social recovery planning can reduce this period and minimise ongoing social and economic effects.

APPENDIX 1 SCIENTIFIC ALERT LEVELS

Volcano surveillance in the Auckland Volcanic Field is carried out by the ARC in conjunction with the Institute of Geological & Nuclear Sciences (GNS) and University of Auckland. Monitoring enables the background or normal state of the volcano to be determined. Departures from the normal state indicate the onset of an eruptive episode.

As detailed in the National Civil Defence Plan the volcanic field is assigned a Scientific Alert Level by GNS, denoting its **current status.** The scientific alert system is based on a 6-stage classification (Table 4.1) where the lowest level is 0 (dormancy) and the highest level is 5 (large scale hazardous eruption in progress). The New Zealand system has two parallel tables one for **frequently active cone volcanoes** and the other for **reawakening volcanoes**. The Auckland Volcanic Field is classified as a reawakening volcano for the purposes of setting scientific alert levels. GNS will adjust the alert level based on observations from the surveillance programme and notify the Regional Council, Ministry of Civil Defence, and the media (as per the National Civil Defence Plan).

A move from Alert Level 0 to Alert Level 1 does not necessarily signal imminent volcanic activity. Alert Level 1, simply means that indications of unrest have been detected by the scientific community and is being evaluated. Level 2 is confirmation that the apparent unrest is volcanic in origin and indicates that an eruption may occur in the future. Level 3 indicates the commence of minor steam eruptions and high increasing trends of unrest indicators suggesting a real possibility of a hazardous eruption. Level 4 signals the eruption of new magma and a hazardous local eruption is in progress, with a large scale eruption possible. Level 5 indicates a large hazardous eruption in progress with a significant risk over a wide area.

SCIENTIFIC ALERT LEVELS

Frequently Active Cone Volcanoes			Reawakening Volcanoes	
White Island, Tongariro-Ngauruhoe, Ruapehu		SCIENTIFIC ALERT	Kermadecs, Northland, Auckland, Mayor Island, Rotorua, Okataina, Taupo, Taranaki	
Volcano Status	**Indicative Phenomena**	**LEVEL**	**Indicative Phenomena**	**Volcano Status**
Uusal dormant, or quiescent state	Typical background surface activity; seismicity, deformation and heat flow at low levels.	0	Typical background surface activity; deformation, seismicity, and heat flow at low levels.	Usual dormant, or quiescent state.
Signs of volcano unrest	Departure from typical background surface activity.	1	Apparent seismic, geodetic, thermal or other unrest indicators.	Initial signs of possible volcano unrest. No eruption threat.
Minor eruptive activity	Onset of eruptive activity, accompanied by changes to monitored indicators.	2	Increase in number or intensity of unrest indicators (seismicity, deformation, heat flow etc).	Confirmation of volcano unrest. Eruption threat.
Significant local eruption in progress	Increased vigour of ongoing activity and monitored indicators. Significant effects on volcano, possible effects beyond.	3	Minor steam eruptions. High increasing trends of unrest indicators, significant effects on volcano, possible beyond.	Minor eruptions commenced. Real possibility of hazardous eruptions.
Hazardous local eruption in progress	Significant change to ongoing activity and monitoring indicators. Effects beyond volcano.	4	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.	Hazardous local eruption in progress. Large scale eruption now possible.
Large hazardous eruption in progress	Destruction with major damage beyond volcano. *Significant risk* over wider areas.	5	Destruction with major damage beyond active volcano. Significant risk over wider areas.	Large hazardous volcanic eruption in progress.

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GLOSSARY

Accretionary lapilli	More or less spherical masses of weakly-cemented ash.
Aerosols	Solid particles or liquid droplets which are dispersed in gas (ie air).
Ash	Fine pyroclastic material under 2 mm in diameter.
Ashfall	Rain of airborne volcanic ash from an eruption cloud.
AVSN	Auckland Volcano-Seismic Network
Ballistic clast	A block or bomb explosively ejected from the vent and which **(block or bomb)** travels on a ballistic trajectory
Basalt	Dark-coloured, fine-grained volcanic rock of mafic composition (>53% SiO_2).
Base surge	Volcanic density current that moves laterally outwards as a dilute, turbulent mixture of hot gas (steam), water and solid ejecta.
Block	Pyroclast larger than 64 mm that was solid when ejected.
Bomb	Pyroclast larger than 64 mm that was partly or wholly fluid when ejected.
CBD	Central Business District
Clast	An individual constituent, grain or fragment of rock (see pyroclast).
Conduit	A passage that magma moves through.
Convected airfall	Airfall particles that were initially carried upwards by the convecting eruption column.
Crater	A basin-like, rimmed structure from which volcanic material is ejected.
D.R.E.	Dense-rock equivalent. The volume of rock erupted after all pore space caused by vesiculation and fracturing has been subtracted. This calculation is used to determine the volume of magma that reached the surface during an eruption.
Earthquake	Sudden motion of trembling in the earth caused by the abrupt release of accumulated strain.
Ejecta	Material thrown out by a volcano.
Eruption column	Column of volcanic gases and solid particles rising into the atmosphere, initially driven by gas pressure and later thermal convection.
Eruption cloud	Cloud of volcanic gas and other pyroclastic fragments.

Fault	Fracture or zone of fractures along which displacement takes place or has taken place in the past.
Felt intensity	A measure of earthquake ground shaking based on the effects on structures and people at specific locations. There is an outwardly decreasing range of intensities for a single earthquake.
Fissure	Long, narrow crack or vent along which an eruption takes place.
Flysch	A marine sedimentary facies characterised by bedded sandstones and mudstone.
Hawaiian eruption	An eruption characterised by the continuous and voluminous discharge of highly fluid lavas, often with gas-driven "fire-fountaining" of scoria to hundreds of metres above the vent.
H_2O	Water.
Hz	Hertz (measure of wave frequency; 1 Hz is 1 cycle per second)
Isopach	Line on a map drawn through points of equal thickness of a designated rock unit.
Lapilli	Pyroclasts between 2 and 64 mm in size.
Lava	Molten extrusive rock on the earth's surface; also the rock that solidified from it.
Lithic	Fragment of previously formed rock, not magmatic at time of eruption.
Maar	A low-relief, vertical-walled volcanic crater that has been cut (largely by collapse) into pre-eruption country-rock and surrounded by a low ejecta rim.
Magma	Molten rock within the earth.
Magmatic	Pertaining to or derived from magma.
Monogenetic	Resulting from one process of formation; developing at one place and time.
Phreatomagmatic	A volcanic explosion that ejects both magmatic material and steam formed by the contact of magma with groundwater or shallow surface water.
Pyroclast	Individual particle ejected during an eruption.
Radiometric dating	Calculating an age in years for geological materials by measuring the presence of radioactive elements (i.e. carbon-14, potassium 40/argon 40).
Scoria	Vesicular, coarse-grained pyroclasts, usually of basaltic or andesitic composition.
Seismicity	The rate and location of earthquakes in an area.

Seismograph	A device for recording seismic waves (produced by earthquakes).
Seismometer	The sensor part of a seismograph.
SO_2	Sulphur dioxide (gas)
Spatter	Accumulation of fluid pyroclasts around a vent.
Strombolian	Type of eruption characterized by discrete explosions ejecting basaltic magma.
Surge	Volcanic density current pulse that moves laterally outwards as a dilute, turbulent mixture of hot gas (steam), water and solid ejecta.
Surtseyan	Type of eruption which occurs when basaltic magma is erupted in shallow-moderate water depths, producing violent steam explosions ejecting highly fragmented clasts.
Tephra	Collective term used for volcanic material, regardless of size, explosively ejected from a vent through the air.
Tuff cone	A cone with smaller crater and higher rim than a tuff ring, with steeply dipping beds produced by the deposition of ejecta close to the vent..
Tuff ring	A constructional crater that lies mostly on or above the pre-eruption surface. The crater rim usually dips at a low angle both outwards and inwards
Turbidity	The state, condition or quality of opaqueness or reduced clarity of a fluid (water), due to the presence of suspended matter.
Viscosity	The property of a substance to offer internal resistance to flow.

REPORT 3.2

AUCKLAND VOLCANIC IMPACT ASSESSMENT - DISTANT ERUPTION SCENARIOS

Prepared for

AUCKLAND REGIONAL COUNCIL

By

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EXECUTIVE SUMMARY

The city of Auckland is built on a basaltic volcanic field which may have been active as recent as 1400 A.D. However, the Auckland Region faces an additional volcanic threat from several large central North Island volcanic centres that are located 140 - 280 km to the south and south-east. To date the threat of inundation by ash and aerosols from distant volcanic sources has not yet been fully considered in any regional or local authority hazard assessment and 'lifelines' planning.

This report considers the direct and indirect impacts of distant eruptions on Auckland, with emphasis on the effects to various types of services (underground, overground, overhead and critical facilities). Scenarios are developed to consider eruptions from both a large andesitic cone volcano (i.e. Egmont) and rhyolitic caldera complex (i.e. Okataina Volcanic Centre).

The impact of a distant eruption will be uniformly widespread across the entire Auckland Region and contrasts with the relatively localised impact of hazards generated from an eruption within the Auckland Volcanic Field. The type of hazards potentially affecting Auckland following a distant eruption are ash falls and aerosols. The impacts from the two scenarios illustrate the vulnerability of urban areas which receive only a few mm-cm of ash but sufficient to cause disruption of transportation, electricity, water, sewage and stormwater systems. Different management strategies are required to deal with the two hazard types compared to the more diverse range of hazards potentially generated during a local Auckland eruption.

Every volcanic impact likely to be experienced in Auckland will also occur in greater severity in adjacent regions closer to the source area. Substantial resources (i.e. heavy equipment & expertise) needed for the clean-up operations may be required in more seriously affected proximal areas. Temporary relocation of such resources will inevitably delay 'lifelines' recovery in Auckland. In addition, there is likely to be further strain on food, water, construction material supplies and other equipment as other more seriously affected communities from outside the region look to Auckland for help.

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1.0 INTRODUCTION

The city of Auckland is built on a basaltic volcanic field which may have been active as recent as 1400 A.D. The volcanic hazards associated with this field have been reported on by Nairn *et al.* (1996). However, the Auckland Region faces an additional volcanic threat from several large central North Island volcanic centres that are located 140 - 280 km to the south and south-east. Tephra (ash) layers originating from these eruptive centres are numerous and widespread in the Auckland Region and have primary thicknesses ranging from 1 mm to > 60 cm. Only the rhyolitic deposits representing moderate to large magnitude eruptive events are thick enough to be preserved in the geological record as discrete layers. Rhyolitic ignimbrites up to 9 m thick are also documented but are extremely infrequent. The frequent occurrence of these rhyolitic ash beds preserved in the Auckland Region demonstrate the necessity to consider their potential impact in any regional natural hazard assessment (Newnham *et al.* in press). To date the threat of inundation by ash and aerosols from distant volcanic sources has not yet been fully considered in any regional or local authority hazard assessment and 'lifelines' planning.

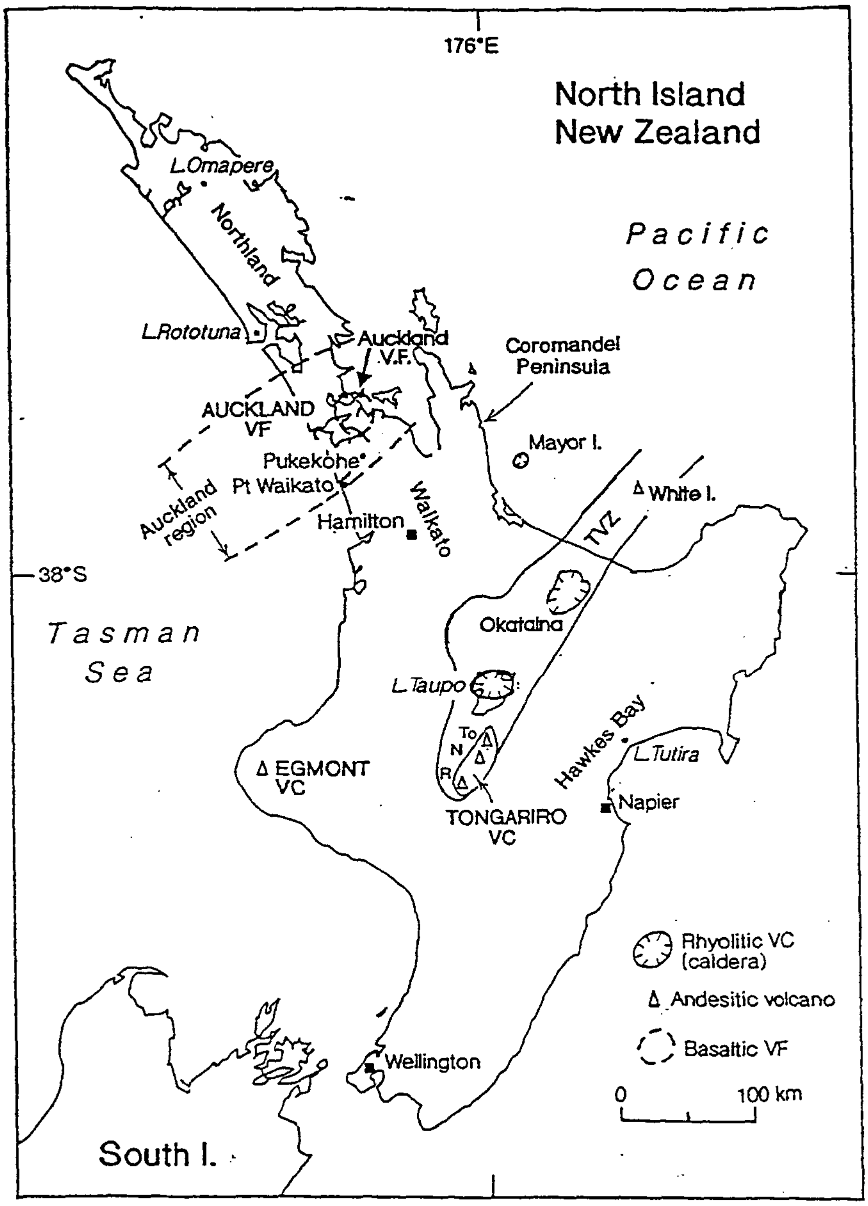
2.0 SCOPE OF THIS REPORT

This report considers the direct and indirect impacts of distant eruptions on Auckland, with emphasis on the effects to various types of services (underground, overground, overhead and critical facilities). Scenarios are developed to consider eruptions from both a large andesitic cone volcano (i.e. Egmont) and rhyolitic caldera complex (i.e. Okataina Volcanic Centre).

3.0 DISTANT VOLCANIC HAZARD TO AUCKLAND

In the central North Island there are two major volcano types: (i) andesitic cones and (ii) rhyolitic calderas (Wilson *et al.* 1995). Activity at cone volcanoes (i.e. Egmont, Tongariro, Ngauruhoe, Ruapehu and White Island) are typically characterised by a succession of small to moderate sized eruptions occurring, on average, every 50 to 300 years from approximately the same vent area over a long period of time. Activity at caldera volcanoes, on the other hand (i.e. Taupo, Okataina and Mayor Island), is characterised by far less frequent (on average every 1000 - 2000 years), moderate to exceptionally large sized eruptions. These eruptions are capable of generating large volumes of material that can be distributed over exceptionally large areas many hundreds of kilometres downwind.

Figure 1: **Locations of the active volcanic centres in the central North Island and the Auckland region (Modified from Newnham *et al.* (in Press))**



The impact of a distant eruption will be uniformly widespread across the entire Auckland Region and contrasts with the relatively localised impact of hazards generated from an eruption within the Auckland Volcanic Field (Nairn *et al.* 1996). The type of hazards potentially affecting Auckland following a distant eruption are ash falls and aerosols (fine liquid droplets, usually H_2SO_4 and/or HCl). Different management strategies will therefore be required to deal with these two hazard types compared to the more diverse range of hazards potentially generated during a local Auckland eruption.

Every volcanic impact likely to be experienced in Auckland will also occur in greater severity in adjacent regions closer to the source area. Substantial resources (i.e. heavy equipment & expertise) needed for the clean-up operations may be required in more seriously affected proximal areas. Temporary relocation of such resources will inevitably delay 'lifelines' recovery in Auckland. In addition, there is likely to be further strain on food, water, construction material supplies and other equipment as other more seriously affected communities from outside the region look to Auckland for help.

4.0 IMPACTS OF ASH FALLS AND AEROSOLS ON "LIFELINES"

4.1 IMPACT ZONES

The impact of ash fall on people, structures, equipment and agriculture depends largely on its thickness. Five levels of uncompacted ash thickness are given below (compiled from data presented by Blong 1984, Johnston & Nairn 1993, Johnston *et al.* (in press)).

4.2 AEROSOLS AND <1 mm ASH THICKNESS

- Will act as an irritant to lungs and eyes;
- Airports will close due to the potential damage to aircraft;
- Possible minor damage to vehicles, houses and equipment caused by fine abrasive ash;
- Possible contamination of water supplies, particularly roof-fed tank supplies;
- Dust (or mud) affects road visibility and traction.

4.3 1-5 mm ASH THICKNESS

Effects that occur with < 1 mm of ash will be amplified, plus:

- Some livestock may be affected but most will not be unduly stressed but may suffer from lack of feed, wear on teeth, and possible contamination of water supplies.

- Minor damage to houses will occur if fine ash enters buildings, soiling interiors, blocking air-conditioning filters etc.

- Electricity may be cut; ash shorting occurs at substations if the ash is wet and therefore conductive. Low voltage systems more vulnerable than high.

- Water supplies may be cut or limited due to failure of electricity to pumps.

- Contamination of water supplies by chemical leachates may occur.

- High water-usage will result from ash clean-up operations.

- Roads may need to be clear to reduce the dust nuisance and prevent storm-water systems may become blocked.

- Sewage systems may be blocked by ash, or disrupted by loss of electrical supplies.
- Damage to electrical equipment and machinery may occur.

4.4 5-100 mm ASH THICKNESS

Effects that occur with < 5 mm of ash will be amplified, plus:

- Ash will affect vegetation, causing burial of pasture and low plants. Foliage may be stripped off some trees but most trees will survive.
- Most pastures will be killed by over 50 mm of ash.
- Major ash removal operations in urban areas.
- Most buildings will support the ash load but weaker roof structures may collapse at 100 mm ash thickness, particularly if wet.
- Road transport may be halted due to the build up of ash on roads. Cars still working may soon stop due to clogging of air-filters.
- Rail transport may be forced to stop due to signal failure bought on by short circuiting if ash becomes wet.

4.5 100-300 mm ASH THICKNESS

Effects that occur with < 100 mm of ash will be amplified, plus:

- Buildings that are not cleared of ash will run the risk of roof collapse, especially large flat roofed structures and if ash becomes wet.
- Severe damage to trees, stripping of foliage and breaking of branches.
- Loss of electrical reticulation due to falling tree branches and shorting of power lines.
- > 300 mm ash thickness
- Effects that occur with < 300 mm will be amplified, plus:
- Heavy kill of vegetation.
- Complete burial of soil horizon.
- Livestock and other animals killed or heavily distressed.
- Kill of aquatic life in lakes and rivers.
- Major collapse of roofs due to ash loading.
- Loading and possible breakage of power and telephone lines.

- Roads unusable until cleared.

SCENARIO 1

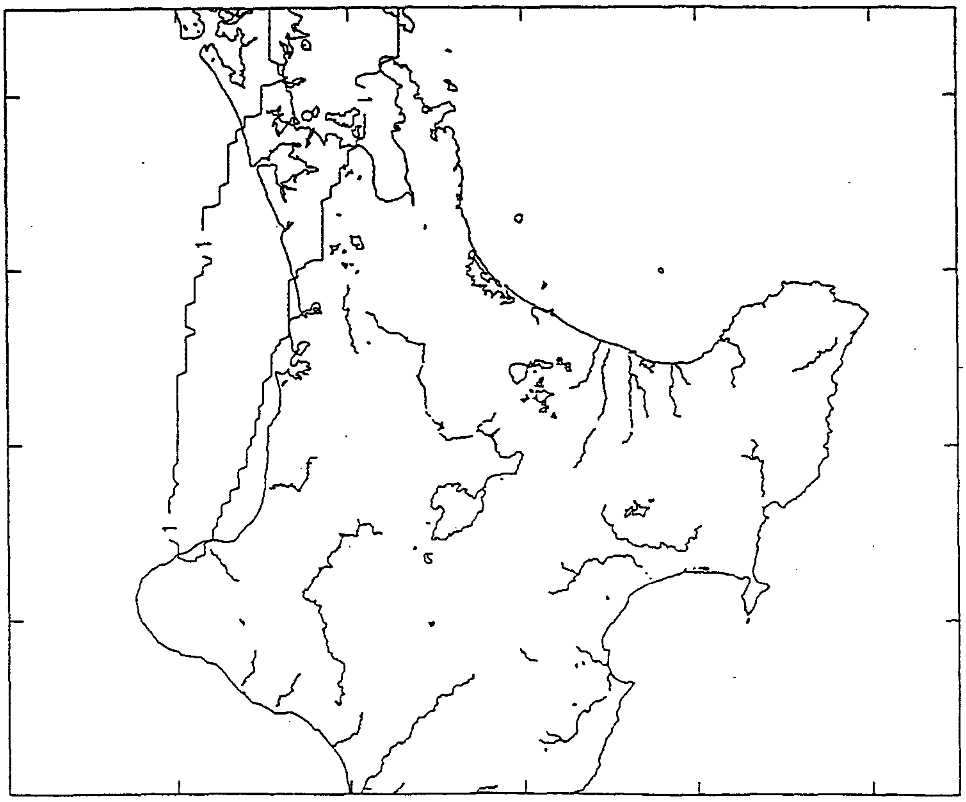
Our first scenario is based on a moderate magnitude eruption (c. 0.1 km^3) sourced from Egmont volcano. Ruapehu, Ngauruhoe and Tongariro are also capable of producing eruption of this type. In modelling ash fall distribution for this scenario the ASHFALL program (Hurst 1994) was used assuming a southerly wind direction.

After several months of precursory activity the climactic eruption begins with the development of a 14 km high eruption column around 9 am. Southerly winds of 70 km/h begin to disperse the volcanic ash and aerosols in a northerly direction towards Auckland. Ash begins to fall throughout the Auckland Region four hours later. By the following morning ash falls have ceased and the region is covered by a 1 mm thick mantle of ash.

Table 1: Summary of scenario 1 parameters

Given Conditions	Scenario 1	Outcome	Auckland
Volcano	Egmont volcano	Ash thickness	1 mm
Magma type	Andesite	Ash condition	Mildly acidic, initial dry, wet after 24 hours.
Magma volume	0.1 km^3		
Precursors	3 months		
Eruption dynamics	Sub-plinian	Other hazards	Aerosols
Wind direction	Southerly		
Wind velocity	70 km/hour		

Figure 2 **Tephra distribution (0.1 km^3) resulting from Scenario 1 eruption, modelled using the ASHFALL Program. Thickness in millimetres**



SCENARIO 2

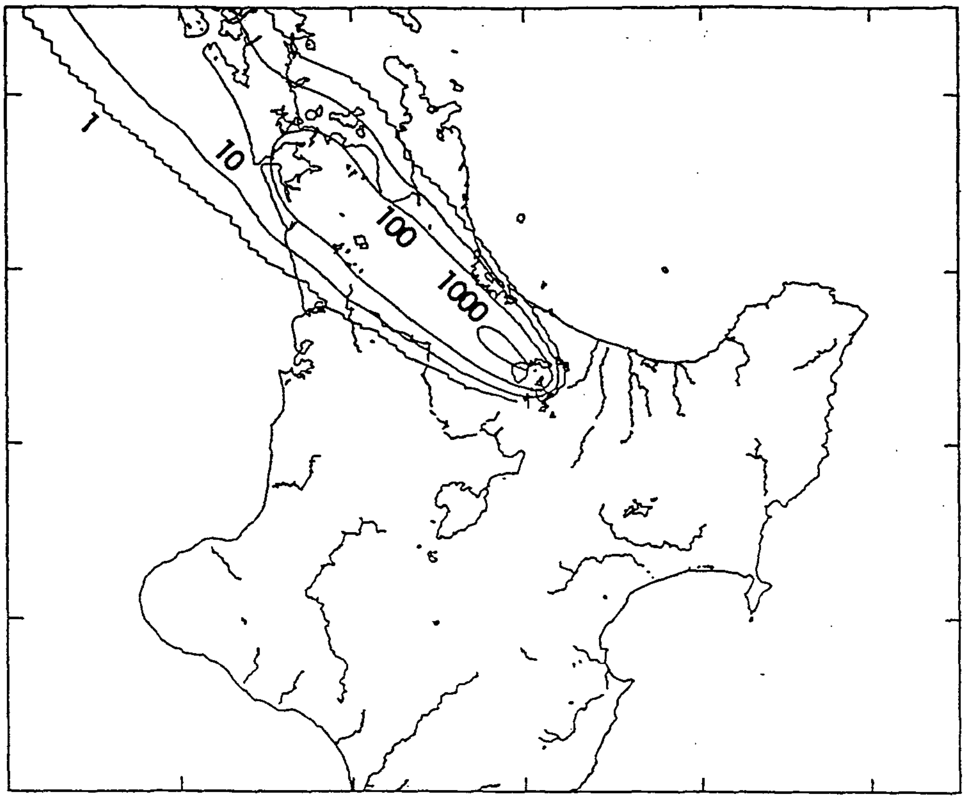
Scenario 2 is a Pinatubo-sized (4 km^3) eruption from the Okataina Volcanic Centre, c.220 km southeast of Auckland. Mayor Island and Taupo are also capable of producing an eruption of this type. There has been no historic rhyolite eruption observed in detail in which to base this scenario on. The 1991 eruption of Pinatubo, although dacitic in composition, provides a useful model for the sequence of events leading to a rhyolite eruption from Okataina Volcanic Centre (Nairn 1992). In modelling ash fall distribution the ASHFALL program (Hurst 1994) was used assuming a southeasterly wind direction.

After twelve months of precursory activity the climactic eruption begins with the development of a 40 km high eruption column around 9 am (based on Johnston & Nairn 1993). Southeast winds of 70 km/h begin to spread the ash and aerosol cloud in a northwest direction towards Auckland. Ash begins to fall throughout the Auckland Region three hours later accumulating at a rate of 1 cm/hour over the following ten hours. From the onset of the ash fall there is total darkness. By the following morning ash falls have ceased and the region is covered by 10 cm mantle of ash.

Table 2: Summary of scenario 2 parameters

Given Conditions	Scenario 2	Outcome	Auckland
Volcano	Okataina Volcanic Centre	Ash thickness	100 mm
Magma type	Rhyolite	Rate of ash fall	10 mm/hour
Magma volume	4 km^3	Ash condition	Mildly acidic, initially dry,
Precursors	12 months		wet/damp after 24 hours
Eruption dynamics	Plinian		Aerosols
Wind direction	Southeast	Other hazards	
Wind velocity	70 km/hour		

Figure 3: **Tephra distribution (4 km^3) resulting from Scenario 2 eruption, modelled using the ASHFALL program. Thickness in millimetres**



5.0 IMPACT OF SCENARIOS ON KEY 'LIFELINES'

The following section discuss the impacts of the two eruption scenarios on key Auckland 'lifelines'.

5.1 ELECTRICITY SUPPLY AND RETICULATION

The deposition of volcanic ash disrupt electricity supply over wide areas in several ways. Heavy accumulations of ash on tree limbs can break them onto local distribution lines, shorting-out or breaking the lines. Damp or wet ash-coatings on insulators will induce flashovers. Low-voltage systems are more vulnerable than higher-voltage systems due to the smaller weathersheds on low-voltage insulators. Light rainfalls post-eruption are more likely to induce flashovers than are heavy rainfalls, which will tend to remove ash coatings from insulators. The abrasive nature of ash will cause damage to mechanically moving parts, such as switches and cooling fans.

The consequences of loss of electricity supply are widespread, and many other public utilities (e.g. water supply pumps, radio and telecommunication facilities) will be inoperative for the duration of the power loss unless local backup power supplies (batteries and generators) are available.

SCENARIO

Scenario/ ash thickness	Basic risk to service	Mitigation strategies
1 (1 mm)	Low risk of outage if ash is wet. Negligible risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
2 (100 mm)	Moderate-high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back tree branches, repair lines.

5.2 GAS SUPPLY AND RETICULATION

Most gas pipes are located below-ground and thus protected from the direct effects of ash falls. Above-ground pumping stations, pressure reduction facilities, pipeline bridge crossings and gas meters at consumer's sites are vulnerable to damage.

SCENARIO

Scenario/ ash thickness	Basic risk to service	Mitigation strategies
1 (1mm)	Negligible	n/a
2 (100 mm)	Low-moderate risk to above ground facilities	Removal of ash from above-ground facilities

5.3 WATER SUPPLY AND RETICULATION

Contamination of Auckland's stream-lake-fed reticulated water supplies is possible from even relatively small ash falls, and is likely to restrict or prevent water intake from these sources for some time during and after an eruption episode. It is at just this time that increased demand for water can be expected for ash and acid rain clean-up operations.

Both turbidity and acidity of storage lakes will increase with ash falls, but these parameters are likely to return to normal levels within a few days-weeks after ash falls cease and suspended ash settles out of the water column. However, intense rainfalls will wash further ash into lakes from their catchments, and ash-laden storm inflows can continue for months after an eruption has ended. Filter beds at the lake water treatment stations could be blocked by high loadings of suspended-ash, and water intake at the treatment stations would likely be stopped until the lakes had cleared. Hazardous changes in lake water chemistry induced by toxic trace elements (including selenium, mercury, arsenic, fluorine and boron) contained in condensates on infalling ash are possible but unlikely due to the dilution and buffering properties of the relatively large volumes of lake water.

In outlying areas without reticulated water supply, household tank water may be collected from roof catchments. Within ash fall areas, downpipes should be disconnected from storage tanks so that ash is not washed into the tanks, and only reconnected after ash has been washed from roofs and gutters.

SCENARIO

Scenario/ ash thickness		Basic risk to service	Mitigation strategies
1 (1 mm)	ash fall (direct)	Negligible risk to service reservoirs from ash infiltration	n/a
	(indirect)	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures
2 (100 mm)	ash fall (direct)	Moderate-high risk to service reservoirs from elevated acidity, increased turbidity and ash infiltration of treatment plant	Cover ventilators, monitor water quality
	(indirect)	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures

5.4 WASTEWATER RETICULATION AND TREATMENT

Ash falls will cause serious problems to Auckland's sewage and stormwater systems over a wide area. Ash which falls on roads, roofs, and other impervious areas, is easily washed into the stormwater system by rain, or during cleanup operations. Ash will enter the sewage system via illegal connections, manholes, gully traps, or where the sewage and stormwater systems are inter-connected (central Auckland). The density of ash is usually too high for a significant amount to remain in suspension at the water velocities normal in the sewer and stormwater pipes, so that ash will readily accumulate to block pipes and channels and lead to surface ponding. Finer ash may remain in suspension and be transported to the sewage treatment plant. Sewage pumps may be abrasion-damaged by ash-laden sewage, or fail due to loss of electricity (see above). Failure will result in the banking up of sewage in

urban areas. The removal of ash from sewage and stormwater systems will be a time consuming and costly exercise.

Ash-laden sewage which enters the Mangere treatment plant will overload the solid-removal equipment at the pretreatment and primary treatment stages. Milliscreens, mechanical grit/sludge removal mechanisms and other equipment that comes into contact with ash-laden sewage are likely to be rapidly worn and/or damaged. Ash falling directly into sedimentation tanks will add to the volume of solid material that will eventually have to be removed. Ash entering secondary treatment facilities, such as oxidation ponds and biofilters will reduce or halt the oxidation process until such time as the ash settles out or is removed. The ash may affect the acidity or toxicity level of the effluent to an extent that bacteria growth is damaged or lost. Release of untreated sewage will result from failure of the plant and/or its deliberate shutdown to avoid further damage.

SCENARIO

Scenario/ ash thickness	Basic risk to service	Mitigation strategies
1 (1 mm)	Low risk of stormwater and/or sewerage systems blockage, potential risk to treatment plant equipment and processes.	Minimise input of ash to reticulation system, monitor sewage for ash contamination.
2 (100 mm)	High-moderate risk of stormwater/sewerage system blockage, potential risk to treatment plant equipment and processes.	Minimise input of ash to reticulation system, monitor sewage for ash contamination.

5.5 TELECOMMUNICATIONS

Communications will be severely disrupted during an ash fall on Auckland resulting from the possible interference to radio waves due to disturbed atmospheric electrical conditions, overloading of telecommunication systems due to increased demand, direct damage to communications facilities by ash, indirect impacts resulting from disruption to electricity supplies or transportation of communication workers (preventing operations or maintenance). Ash entering telephone exchanges may cause damage to electrical and mechanical systems and general damage to buildings. Exchanges have battery-generator power backup systems to enable continued operation in the event of loss of electricity supply. Generators are housed in the exchange buildings, but rely on external air intakes to air filters. Clogging of these filters by ash would result in failure of the generator, followed by exhaustion of the battery capacity after a few hours demand.

Loss of communications will make disaster management extremely difficult before, during and after an eruption.

SCENARIO

Scenario/ ash thickness		Basic risk to service	Mitigation strategies
1 (1 mm)	Exchanges	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash
	Microwave towers	Low to moderate risk of disruption and damage if exchanges are sealed	Remove ash immediately
2 (100 mm)	Exchanges	Moderate to high risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash
	Microwave towers	Moderate to high risk of disruption and damage if exchanges are sealed	Remove ash immediately

5.6 CRITICAL FACILITY BUILDINGS (HOSPITALS, CIVIL DEFENCE HQ, FIRE HQ, POLICE HQ)

These are buildings associated with essential services required during an emergency. A large number of buildings may be included in this category (e.g. hospitals, fire and police stations, civil defence facilities, schools etc.). The consequence of disruption to their use will vary depending on their importance to the operation of the emergency management system as a whole.

Critical facility buildings (for example hospitals) are extremely vulnerable to disruptions of the "lifelines" which provide the services and linkages which allow them to operate. Electricity is generally required for lighting, ventilation, boiler operations, water heating, freezers/coolers, kitchens, medical services, lifts and security. Water supply is usually required for satisfactory operation of hot and cold water systems, fire hoses and sprinklers, kitchens and laboratories. Communication facilities are critical for the operation of the emergency management organisations (civil defence, police, fire) and require continued electricity supply. Many buildings have back-up systems (e.g. electrical generators, water tanks) to provide limited supplies of these services in the event of loss of external services.

Ash falls can cause direct damage to buildings and building services in several ways; soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials. Overloading of roof strengths requires in excess of 100 mm of wet ash in most cases and is unlike to occur in either scenario.

5.7 ROAD AND RAIL TRANSPORTATION FACILITIES

Reduced visibility on roads will be experienced over wide areas during and after ash falls (both scenarios). Dry fine ash is readily raised in billowing clouds by passing vehicles and will present an ongoing hazard. Wet fine ash can turn to mud causing vehicle traction problems. Thin ash deposits (<2 mm) will generally be moved to the shoulder of roads by traffic, but will remain there. Greater thicknesses of ash will need to be physically removed from road surfaces by scraping, brushing and washing.

Problems arising as a consequence of closure of roads include lack of access for emergency services, stranding of travellers, disruption to food supplies, and economic impacts on businesses in the affected

areas. Where ash-covered roads remain open, speed restrictions will need to be introduced to ensure traffic safety on roads in conditions of reduced visibility, and to reduce dust problems in adjacent communities.

Ash entering vehicle engines and transmissions will cause wear on moving parts, reducing their life. In most cases severe damage will only result from excessive vehicle use in an ash-affected environment. The most common effect of ashfall on vehicles is blockage of air filters leading to overheating and stopping of motors. The abrasive ash can also damage vehicle brakes, exterior fittings, paintwork and windows.

Rail lines and rail transportation will be affected in a similar manner to road transportation,but rail is usually the ground transport system least affected by ash fall. Ash fall less than ~5 mm thick can easily be removed from rail tracks to quickly resume services. Problems with ash clouds stirred up by train passage restrict operating speeds, reduce operator vision and accentuate breathing problems, and can affect diesel locomotive motors and transmissions. During overseas eruptions light rain on ash fall greater than ~5 mm has led to extensive short-circuiting of electrically-operated signal equipment. Similar short-circuiting is likely to cause major operational difficulties for electric train services in the Auckland area in Scenario 2.

SCENARIO

Scenario/ ash thickness		Basic risk to service	Mitigation strategies
1 (1 mm)	Roads	Low risk of closure, but with reduced visibility.	n/a
	Vehicles	Low-moderate risk of damage, especially with frequent use.	Check air filters and lubricants often.
	Railways	Stirred up ash clouds cause visibility and operator health problems.	Reduce speeds if required, provide face masks, increased locomotive maintenance.
2 (100 mm)	Roads	High risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface.
	Vehicles	Moderate-high risk of damage, especially with frequent use.	Avoid non-essential use, change air-filters and lubricants often.
	Railways	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from, reduce speeds, provide face masks, increased locomotive maintenance.

5.8 PORT FACILITIES AND SHIPPING

Auckland port facilities and shipping are likely to be disrupted by ash falls and lead to temporary closure. Port operations may be additionally affected by secondary effects such as staff availability, road and rail access, power supplies and communications as well as, availability of freight (which will probably be largely diverted to other ports).

SCENARIO

Scenario/ ash thickness	Basic risk to service	Mitigation strategies
1 (1 mm)	Moderate risk of temporary disruption, low risk of damage	Temporarily cease operation, cover vulnerable machinery, initiate clean-up operations
2 (100 mm)	High risk of temporary disruption, moderate risk of damage	Cease operation, cover vulnerable machinery, remove ships, initiate clean-up operations

5.9 AIRPORT FACILITIES AND AIR TRANSPORTATION

Air transportation is particularly vulnerable to moderate-large eruptions (as recently demonstrated during the Ruapehu 1995 and 1996 eruptions), with airports being closed by <1 mm thick tephra falls, and large airspace volumes being closed to avoid actual (or suspected) ash and aerosol clouds which can cause failure of aircraft engines in flight.

SCENARIO

Scenario/ ash thickness	Type of hazard	Basic risk to service	Mitigation strategies
1 (1 mm)	Ash and aerosol clouds	Downwind airspace closed during eruptions	Track ash and aerosol clouds and avoid
	Ash falls	Airports closed until ash removed from runways and installations.	Clean up after eruption
2 (100 mm)	Ash and aerosol clouds	Downwind airspace closed during eruptions	Track ash and aerosol clouds and avoid
	Ash falls	Airports closed until ash removed from runways and installations (3 weeks before Auck. Int. is reopened to essential traffic)	Clean up after eruption

6.0 OTHER IMPACTS

6.1 PUBLIC HEALTH ASPECTS

Freshly fallen ash and aerosols are non toxic but act as irritants on the upper and lower respiratory tracts and eyes. Respiratory problems will result from inhalation and is likely to be more acute in patients with existing respiratory disorders. Eye problems will include foreign material in eyes, corneal abrasion and conjunctivitis. During periods of ashfall the best precaution is to stay indoors. Where it is necessary to move outside, a protective filter mask should be worn. If such a mask if unobtainable, wet cloth over the mouth and nose will prevent inhalation of the ash.

7.0 CONCLUSIONS

- The impact of a distant eruption will be uniformly widespread across the entire Auckland Region and contrasts with the relatively localised impact of hazards generated from an eruption within the Auckland Volcanic Field.

- The type of hazards potentially affecting Auckland following a distant eruption are ash falls and aerosols.

- Falls of volcanic ash can disrupt electricity supply. Weather conditions will influence how falling ash adheres to insulating surfaces, with power outages occurring if the ash is wet (i.e. conductive). Low voltage systems are more vulnerable than higher voltage systems due to smaller weather sheds on insulators. Most outages are usually of short duration. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent widespread outages.

- Volcanic ash falls can cause severe damage to sewage and stormwater systems. The most effective mitigation measure to lessen the affects of ash falls is to reduce the input of ash into the system. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Bypassing and/or shutting down parts of the plant may need to be considered to reduce the likelihood of damage.

- Water supplies are vulnerable to contamination by ash fall into storage lakes preventing their use, and to excessive demand during post-eruption ash clean-up operations. Water management plans are required to manage excessive demands and should include procedures to fill service reservoirs (if possible) on receipt of an ash fall warning, when appropriate public information messages outlining water conservation measures should also be broadcast. There is also a need to retain a fire fighting potential.

- The city will be forced to undertake expensive and time-consuming clean-up operations as a consequence of both of the scenario eruptions. In each case there will be a need to develop coordinated community-wide ash-removal plans, that identify appropriate methods of ash removal, collection and disposal. The public will need to be adequately informed on how to deal with volcanic ash.

- The impacts from the two scenarios illustrate the vulnerability of urban areas which receive only a few mm-cm of ash but sufficient to cause disruption of transportation, electricity, water, sewage and stormwater systems.

- The impact of a distant eruption on Auckland will be experienced in greater severity in adjacent regions closer to the source area. Substantial resources (i.e. heavy equipment & expertise)

needed for the clean-up operations may be required in more seriously affected proximal areas. Temporary relocation of such resources will inevitably delay 'lifelines' recovery in Auckland. In addition, there is likely to be further strain on food, water, construction material supplies and other equipment as other more seriously affected communities from outside the region look to Auckland for help.

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REPORT 3.3

REVIEW OF IMPACTS OF HISTORIC ERUPTIONS ON LIFELINES

Prepared for

AUCKLAND REGIONAL COUNCIL

By

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(Appendix A1 from Volcanic Impact Assessment for the Auckland Volcanic Field, ARC Technical Publication Number 79, April 1997)

CONTENTS

1.0 INTRODUCTION

A number of types of hazards result from volcanic eruptions. The most likely hazards in Auckland include pyroclastic falls (ash falls and projectiles), pyroclastic surges, lava flows, volcanic gases, volcanic earthquakes and atmospheric effects.

2.0 PYROCLASTIC FALL

Pyroclastic material is produced by three basic processes: (1) degassing of rising magma producing bubble growth and fragmentation, (2) explosive mixing of magma and water, (3) fragmentation of country rock during rapid expansion of steam and/or hot water (Heiken 1994).

2.1 Projectiles

Large fragments (blocks and bombs; > 64mm) follow ballistic trajectories and are termed projectiles. These fragments may land in a near-molten state and are capable of starting fires but rarely land more than 1-2 kilometres from a vent (Blong 1984). The impact of ballistic clasts will cause damage to buildings, with degree of damage dependent on projectile mass and velocity (Blong 1981, 1984). Clasts that are ejected hot have ability to ignite buildings. In the 1973 eruption of Heimay (Iceland) incandescent clasts ranging from 0.1 to 2m across were ejected and caused fires (Self *et al.* 1974).

2.2 Convected Air Fall

Finer material (ash, <2mm; and lapilli, 2-64 mm) is convected upwards in the eruption column (Self & Walker 1994) before settling out downwind to form pyroclastic fall deposits (tephra). Ash can be deposited to hundreds of kilometres from vent, making volcanic ash the product most likely to affect the largest area and the most people during an eruption.

A community's infrastructure ("lifelines") are vulnerable to disruption and damage from pyroclastic falls, with impact severity largely related to tephra thickness. Pyroclastic falls will not initially result in fatalities unless the fall is extremely heavy, or where victims are hit by projectiles (Baxter 1990). Falling ash is not toxic but will act as an irritant affecting eyes and throats. Deaths and injuries are more likely to result from secondary effects such as roof or veranda collapse, and falling branches or other accidents.

2.3 Impacts of Volcanic Ash on Transportation

Road Volcanic ash falling on roads can be extremely disruptive causing reduced visibility, traction problems and damage to vehicles, resulting in reduced speed limits or even road closures.

Reduction of visibility on roads is commonly reported during and after ash falls (see Table 2.1), and during heavy ash falls total darkness may result (Blong 1982). Dry ash is easily raised in clouds by passing vehicles and presents an ongoing hazard. Wet ash can turn to mud causing further problems to vehicle traction, as seen in and around Rabaul, after the 1994 eruption (Blong & McKee 1995). Ash fall deposits will absorb a considerable amount of water before being washed away. Thin ash (<5 mm) will generally be moved to the shoulder of roads by roadway traffic but will remain there. Greater thicknesses of ash will need to be physically removed.

Warrick et al. (1981) conclude from experience after the 1980 Mount St Helens eruption:

> "*Ash depth had little influence on the initial level of impacts on the transportation systems. On the other hand ash depth had direct influence on the length of recovery time for most transportation systems*".

In most cases vehicles remain operative during ash falls (i.e. Pinatubo 1991, Mt Spurr 1992, Rabaul 1994, Ruapehu 1995-1996). Fine dry ash can result clogging of air-filters, causing vehicles to over-heat. This was a main cause of vehicle strandings, in heavy ash fall areas, after the 18 May 1980 Mt St Helens eruption (Schuster 1981).

Ash entering the engine causes wear on moving parts, reducing their life. In most cases severe damage results from excessive use in an ash-rich environment. A number of ash-affected communities report keeping damage to a minimum by initiating preventive maintenance programmes (i.e. changing oil, oil filters, air-filters etc). The abrasive ash can also damage vehicle brakes, exterior fittings, paintwork and windows.

Table 2.1: Examples of ashfall impacts on road transport

Volcano and year	Road closures	Reduced visibility	Vehicle damage	Traction problems	Reference
Hudson 1991		*	*		Bitschene 1995
Mt St Helens 1980	*	*	*		Blong 1984, Warrick *et al.* 1981 Schuster 1981
Pinatubo 1991		*	*		Rudolfe 1995
Rabaul 1937	*		*	*	Johnson & Threlfall 1985
Rabaul 1994	*	*	*	*	Blong & McKee 1995, Finnimore *et al.* 1995
Ruapehu 1945		*	*		Johnston & Neall 1995
Ruapehu 1995	*	*	*	*	Houghton *et al.* 1996
Unzen 1990-1992		*			Yanagi *et al.* 1992

Secondary problems consequent on road closure will include loss of access for emergency services, stranding of travellers, disruptions to food supplies and economic impacts on businesses. Where roads remain open, speed restrictions may need to be introduced to ensure motorist safety on roads with reduced visibility.

Railways Rail transportation is vulnerable to volcanic ash, with disruptions caused by poor visibility and breathing problems for train crew. Trains will stir up fallen ash, affecting residents close to railway tracks. Light rain on fallen ash may lead to short-circuiting of signal equipment. Fine ash may enter engines causing wear on moving parts.

Blong (1984) describes a number of examples of disruption of rail services. The 18 May 1980 eruption of Mount St Helens severely disrupted rail services in eastern Washington (Warrick *et al.* 1981). In areas receiving ash, train crews reported almost zero visibility and train services were suspended. Operations resumed within 24 hours of the end of ash falls. Speed restrictions were put in place for the following nine days to combat the raising of dust clouds. Rain several days after the eruption caused

numerous short-circuits of track signals. Despite the problems, rail was the least disrupted of the transport systems.

Air Transport Air-transportation is extremely vulnerable to volcanic ash (Casadevall 1993, Miller 1994, Ziner 1994). Drifting volcanic ash can affect large volumes of air-space commonly resulting in its closure. Severe impacts can result from aircraft-ash encounters, with seven aircraft losing in-flight jet engine power over the past 15 years world-wide (Casadevall 1993). Luckily, to date, no aircraft have crashed as a consequence of such encounters. Even minor ashfalls on airports will render them inoperative and can damage aircraft and facilities (Labadie 1994). The removal and disposal of ash can be a time-consuming and costly operation.

Conclusions Ash falls will cause severe and widespread disruptions to transportation links over wide areas. Air-transport is the most widely affected sector due to closure of air-space and airports. Ash falls reduce visibility on roads and may damage vehicles. Falls of only a few millimetres frequently require time-consuming and expensive ash removal operations before roads and airports can re-open. Rail is commonly the least disrupted transport system.

2.4 Impacts of Volcanic Ash on Water Supplies

Contamination can take a number of forms resulting from physical and chemical changes in affected supplies. The most common contamination problem results from the suspension of ash in water (turbidity). Limits for potable water quality for turbidity are easily exceeded by suspended ash; high turbidity can interfere with the disinfecting process at water plants.

Freshly fallen ash readily releases soluble components (leachates), resulting in changes to local water chemistry. Leachates are sourced from surficial coatings of soluble components on individual ash grains and from the release of soluble elements and compounds from within grains (minerals or solid solution glass). The soluble coatings are derived from the interaction of ash particles with aerosols in the eruptive column. Aerosols are principally composed of sulphuric and hydrochloric acid droplets containing absorbed halide salts. The scavenging of aerosols by ash is most active close to the volcano (<50 km). This is indicated by observations that show the amounts of water-soluble material associated with ash falls decrease with increasing distance from source (Smith *et al.* 1983). The amount of available aerosols vary greatly between eruptions of similar volumes (Bernard & Rose 1990).

The flushing of soluble components from surfaces of ash particles is the main initial source of leachates. The most common leachates rinsed from freshly deposited ash are Cl, SO_4, Na, Ca, K, Mg, and F (Smith *et al.* 1982). Other elements reported but in lower concentrations are Mn, Zn, Ba, Se, Br, B, Al, Si, Cd, Pb, As, Cu and Fe. Most of these elements and compounds are naturally present in ground and surface water but become hazardous above certain concentrations. Finer ash deposits have larger surface areas per unit volume allowing them to carry more soluble ions (e.g. F) and moisture than coarser deposits. This is significant because smaller particles travel greater distances from the vent, thus extending the zone of possible contamination. The potential for chemical contamination of water supplies or pollution of rivers and lakes will depend on the ratio between the volume of water contaminated and amount of leachate delivered.

The release of Cl^- and SO_4^{2-} ions from water soluble salts in volcanic ash will lower the pH of water, possibly beyond the acceptable safe limits for potable water supply. Any changes in pH of surface and groundwater will be influenced by the buffering effect of soil. This is affected by the ability of soil to absorb pH changes (Hausenbuiller 1978).

Indirect impacts can result from ash causing physical damage to filters at intake structures and/or treatment plants, greater susceptibility to wear of plant, and interference with electrical equipment. Other indirect problems can occur as a result of increased water demand for clean-up by residents of communities affected by ash fall.

Historic examples of potable water supply contamination Contamination of water supplies has been reported subsequent to a number of historic eruptions. The most common problems were the result of unacceptable pH and turbidity levels (Blong 1984, Collins 1978, Le Guern *et al.* 1980, Wilmox 1959), but hazardous chemical changes have been reported in a few cases (Blong 1984; Collins 1978; Oskarsson 1980; Thorarinsson 1979). Excess fluorine is recognised as the most hazardous circumstance.

Conclusion Contamination of open water supplies is possible even from relatively small ash falls. Both turbidity and acidity will usually return to normal levels within a few hours to days unless ashfalls are prolonged. Adverse affects on covered water supplies are minimal. Hazardous changes in water chemistry are rare; except close to a volcano where small volumes of water (such as roof-fed water tanks, stock water troughs and shallow surface water bodies) can be contaminated by ash leaching to levels that exceed guidelines for potable water. Levels of contaminants in streams, rivers and lakes may also be elevated for short periods. Observations of historic eruptions show that concentrations of hazardous leachates in ash decrease with distance from the vent, and few examples of serious chemical contamination of potable water supplies exist. Excess fluorine is recognised as the most hazardous circumstance.

2.5 Impacts of Volcanic Ash on Sewage and Storm Water Systems

Sewage and stormwater systems are vulnerable to damage from volcanic ash falls (White *et al.* 1980, Day & Fisher 1981, F.E.M.A. 1984, Schuster 1981, Warrick *et al.* 1981; Blong 1984), which may include; blockage of pipes, damage to pumps and other machinery and interference with sewage treatment processes.

Ash falls can cause serious problems to urban sewage and storm water systems. Ash which falls on impervious surfaces, such as roads, roofs and other paved areas, is easily washed into the stormwater system by rain, or during cleaning up operations. Ash may enter the sewage system via illegal connections, manholes, gully traps or the stormwater system if inter-connected. The mean grain-size and density of ash particles decreases with distance from an erupting volcano with finer ash entering the system more easily. The density of ash is usually too high for most water velocities in the sewer or stormwater system to hold a significant amount of it in suspension, therefore ash deposits will tend to collect easily. Finer ash may remain in suspension and be transported to the sewage treatment plant. Where pipes are blocked local flooding may occur. Sewage pumps may also be damaged by ash-laden sewage or fail due to loss of electricity (due to the affects of ash on the electricity supply system). This may result in the banking up of sewage in urban areas. The removal of ash from sewage and stormwater systems will be a time consuming and costly exercise.

Sewage Treatment Plants Ash-laden sewage may enter the treatment plant overloading solid removal equipment at the pretreatment and primary treatment stages. Milliscreens, mechanical grit/sludge removal mechanisms, comminutors and other equipment that comes into contact with ash-laden sewage are likely to be damaged. Ash falling directly into sedimentation tanks will add to the volume of material that will eventually have to be removed. Ash entering secondary treatment facilities, such as oxidation ponds or biofilters will reduce or halt the oxidation process until such time as the ash settles out or is removed. The ash may affect the acidity or toxicity level of the effluent to an extent that bacteria growth is damaged or lost. Release of untreated sewage may result from failure of the plant and/or deliberate shutdown. Problems may also be caused by loss of electricity to treatment facilities, due to the effects of ash falls on electricity supply systems.

Table 2.2: Examples of ash-affected urban stormwater and sewage systems

Volcano, year,	Ash thickness	Impact	Reference

affected town	(mm)		
Mt St Helens - 1980			
Moses Lake	25	Stormwater blocked, sewerage rendered inoperative,damage to plant.	Schuster 1981
Yakima	10	Stormwater blocked, sewerage rendered inoperative,damage to plant.	Schuster 1981
Spokane	5	Stormwater filled with ash, sewage plant received ash but remain operative.	Schuster 1981
Ellensbury	3	Stormwater system overloaded in a number of places but city employees kept the system open using high-pressure water jet sewer cleaners.	Warrick *et al.* 1981
Mt Spurr - 1992			
Anchorage	3	Ash settled in stormwater system and caused some local flooding during the spring thaw.	pers. com. City of Anchorage
Ruapehu - 1996			
Rotorua	1	Small amount of ash removed from stormwater but no major problems reported.	pers. com. Rotorua District Council

Conclusion Ash falls can cause severe damage to sewage and stormwater systems. Ash is easily washed from impervious surfaces, such as roads, carparks and buildings and can enter the systems. The most effective mitigation measure is to reduce the input of ash into the systems. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Bypassing and/or shutting down parts of the plant may need to be considered to reduce the likelihood of damage.

2.6 Impacts of Volcanic Ash Falls on Electrical Distribution Systems

Volcanic ash can cause a number of problems to electrical distribution systems. Investigations on the effect of ash (Nellis & Hendrix 1980; Stember & Batiste 1981; Sarkinen & Wiitala 1981; Heiken *et al.* 1995) showed that:

- Dry volcanic ash is not conductive enough to cause insulator flashover problems.
- The presence of moisture with ash is the critical factor in initiating insulator flashovers if insulating surfaces are completely coated, since ash contains soluble leachates which makes ash conductive when wet.
- Finer ash has a high conductive potential since it has a higher surface area per unit volume therefore can absorb more soluble components and moisture.
- Weather conditions at the time of ash fallout influences how ash adheres to and how it affects insulating surfaces. Dry ash sticks generally to horizontal surfaces and causes no immediate electrical problems. Wet ash sticks to all exposed surfaces and causes electrical insulation problems.

- Insulation that has 30% or more of its creepage distance either clean or dry has a low probability of initiating insulator flashovers.
- Lower voltage insulation has smaller weathersheds and is more prone to becoming completely covered with ash and water.
- Because of the shape and orientation of many bushings and insulators, substation insulation is more susceptible than line insulation to flashovers caused by volcanic ash.
- Heavy rain was found to wash off about 2/3 of ash from insulators, whereas light rain removed little ash. Wind up to 55 km/hr removed 95% of dry ash.
- Ash that falls dry on dry surfaces is easily cleaned by air blast and brushing. Ash that falls wet or is wetted before cleaning is not easily removed without high pressure water or hand cleaning.
- Ash contamination on insulators and conductors increases corona activity which in turn causes increase in audible noise and radio interference.
- Epoxy insulators are especially vulnerable to tracking and flashovers therefore porcelain insulators are now used widely in the region.
- Volcanic ash is a contaminant which abrades and clogs mechanically moving parts. Precautionary measures are needed to service and maintain substation equipment.
- Saturated volcanic ash on switch yard gravel has the potential to be hazardous due to its conductivity.
- Wet ash-laden tree limbs may fall on distribution lines.

During the 1980 eruption of Mt St Helens volcanic ash disrupted the electricity supplies of several communities in Washington State, USA (Nellis & Hendrix 1980). The impacts were largely dependent on the weather prevailing at the time. The main 18 May eruption occurred during dry weather and ash did not cause immediate problems except for a few short-duration outages and ash adhesion to horizontal surfaces. Outages occurred a few days later in areas that received rain. Ash falls from the smaller 25 May eruption occurred accompanying rain fall. Low voltage lines and substations experienced numerous outages from insulator flashovers in areas of >5 mm ash thickness when the ash was wet. A number of wooden electricity poles catching fire were reported. The ash conductivity was found to increase with decreasing grain size and the problem of insulator flashovers increased with distance from the volcano. The 12 June ash fell dry but later rain wetting caused subsequent outages.

Conclusions Falls of volcanic ash can disrupt electricity supply. Weather conditions will influence how falling ash adheres to insulating surfaces, with outages only occurring if the ash is wet (i.e. conductive). The presence of moisture with ash is the critical factor in initiating insulator flashovers if insulating surfaces are completely coated, since ash contains soluble leachates which makes ash conductive when wet. Finer ash has a high conductive potential since it has a higher surface area per unit volume, therefore can absorb more soluble aerosol droplets and/or moisture. Low voltage systems are more vulnerable than higher voltage systems due to smaller weather sheds on insulators. Most outages are usually of short duration. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent wide spread outages. The consequences of loss of electricity are widespread, and a number of public utilities will be inoperative for the duration of the power loss.

2.7 Impacts of Volcanic Ash on Buildings and Building Services

Volcanic ash can cause damage to buildings and building services in several ways; overloading roof strengths causing collapse, soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials. The effects of ashfalls on structures depends on the thickness of ash, soluble components, ash density, water content, the building's roof form, construction, orientation, and the spacing of other buildings nearby.

Loading of ash Building failure or damage may occur due to ash loading on roofs, and against walls or foundations (Bitschene 1995, Blong 1981 & 1984, Blong & McKee 1995, Johnson & Threlfall 1985).

The loading of a building is given by the equation:

$$L = \frac{dpg}{1000}$$

where L is volcanic ash load (kPa)
d is ash depth (m)
p is ash density (kgm^{-3})
g is gravitation (9.8 ms^{-2})

Observed ash falls commonly show a compaction reduction in thickness of around 50%, even without the effects of rain. Such compaction increases the density of the ash cover but not its weight. The loading caused by ash depends on its thickness, density and whether it is dry or wet. Densities range from about 500 kgm^{-3} for dry uncompacted ash to more than 2000 kgm^{-3} for a compacted very wet ash.

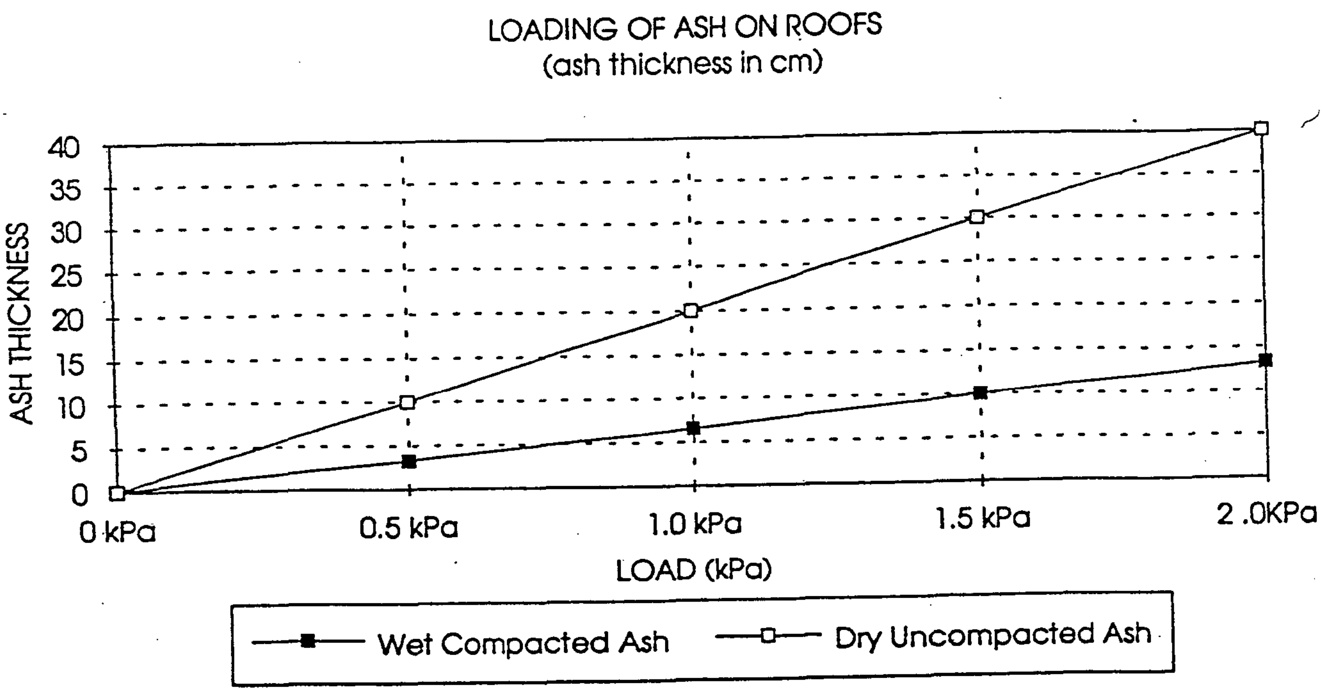

Figure 1: Loading of tephra on a roof for (a) wet compacted ash, and (b) dry uncompacted ash. The uncompacted ash is assumed to have a density of 500 kgm^{-3}. The wet ash is assumed to have a dry (compacted) density of 1000 kgm^{-3} and a saturation of 50% water by volume and therefore a wet density of 1500 kgm^{-3}

Blong (1984) gives several examples of roof collapse under ash falls and concludes that 100 mm appears to be a critical threshold. In most cases where ash fell to a thickness <100 mm only a proportion of building suffered roof collapse and/or damage.

Blong & McKee (1995) describe the damage done to building during the 1994 Rabaul eruption. They conclude that:

> *"The damage sustained by roofs under the load of volcanic ash is undoubtedly a function of many key factors including ash thickness, ash bulk density, the moisture content of the ash, extent to which ash drifts (creating unbalanced dynamic loads), roof span and support systems, construction materials, roof slope and age and maintenance of the building."*

They are unclear as to the relative importance of all of these factors. A summary of their Rabaul observations is shown in Table 2.3

Table 2.3: The effect of various ash loads on buildings in Rabaul (From Blong & Mckee (1995))

Ash thickness*	Observed damage to roofs
< 100 mm	Roofs and guttering generally remaining intact
< 200 mm	80-90% of roofs remained intact with little apparent damage. Sagging or partial collapse occurred in some buildings
< 300 mm	More than 50 % of roofs did not collapse
500 - 600 mm	More than 50% of roofs collapsed.
>600 mm	It is doubtful that buildings survived without significant damage even though the roof remained relatively intact

*** Ash fell wet**

Ash can slide off steeply pitched roofs, but even moderate pitches can be less susceptible to collapse than flat ones. During the heavy ash falls on the town of Vestmamaeyar, Iceland, in 1973, houses with roofs sloping at angles $> 20^\circ$ suffered little damage from ash loading.

Obstructions such as parapets, roof tanks or solar panels may cause the accumulation of ash. Roof guttering was one of the most susceptible parts of the house to damage (Blong 1984). After rain, gutters may fill with ash and pull away from houses. Penetration of fine ash into the ceiling may lead to its collapse.

Damage to exterior materials Acidic ash and associated soluble components can lead to premature ageing and weakening of cladding and other building materials. Most metal roofing used in New Zealand is hot-dipped zinc or zinc/aluminium coated (galvanised) steel, with an additional paint cover. Zinc has a high resistance to atmospheric corrosion due to the development of an insoluble basic carbonate film that protects the surface. However, sulphurous and sulphuric acids are extremely corrosive to almost all metals (Bradford 1992). These acids ionise to H^+ ions and electrode processes occur on the corroding metal surface in contact with the acids. Although rain can release the acidic soluble components from the ash, it will wash off these contaminants and actually reduce corrosion. Unwashed areas such as under eaves, unlined soffits, spouting, overhangs, sheltered walls and the upper part of garage doors may be vulnerable to corrosion if ash infiltration occurs. These areas seldom

receive the benefit of rain-washing and as condensation, dew or humidity moistens the ash, a corrosive reaction may take place.

The 1995-1996 Ruapehu eruptions deposited a few millimetres of ash on several North Island towns. In most cases the ash falls were a nuisance but a few insurance claims (~25) for damage were received by the Earthquake Commission. The majority of claims were for damage to roofs resulting from the reaction between ash and galvanised steel and/or paint. Acrylic paint, if it had been applied within the past 3 - 6 months, was found to be susceptible to the acidic nature of volcanic ash.

Metal corrosion resulting from ash falls has been studied by Matsumoto et al (1988) during eruptions of Sakurajima volcano in Japan. Corrosion strongly correlated with volcanic ash and its concentration of soluble components, and concentrations of SO_2 and fluorine compounds in the atmosphere. The degree and rate of metal deterioration decreased in order from, aluminium, steel, galvanised steel, copper, stainless steel.

Soiling interiors Ash can enter a building by a number of routes ranging from open doors and windows to small gaps between roofing iron or tiles and even closed doors and windows (Deguchi 1988). Even small amounts of ash entering buildings can result in considerable amounts of time spent on its removal (Dillman & Roberts 1982). Fine ash can easily penetrate carpets.

A survey of damage from repeated ash falls from Sakurajima volcano on the cities of Kagoshima and Tarumizu found the finer the ash the easier it is to penetrate buildings (Deguchi 1988). Ash that had built up in gaps promotes surface tension thus drawing in water and causing a tile roof to leak. Leaking also occurred as a result of rusty nails caused by corrosion Ash on outer walls and windows leads to soiling especially when combined with rain.

Damage to Services The highly abrasive and mildly corrosive nature of ash is a threat to mechanical and electrical appliances. Air-conditioning units are vulnerable to ash damage and filter blockage. Penetration of ash into the electrical system can lead to short-circuiting and fires. Computer systems are also vulnerable to ash damage.

Conclusions Volcanic ash loadings can exceed roof strengths causing collapse, soiling of interiors, damaging services (electrical and mechanical) and damaging exterior materials.

2.8 Impacts of Volcanic Ash Falls on Communications

Communications can be severely disrupted around an erupting volcano. Disruptions may result from interference to radio waves due to atmospheric conditions, overloading of telephone systems due to increased demand, direct damage to communications facilities, indirect impacts resulting from disruption to electricity supplies or transportation of communication workers (preventing operations or maintenance).

Large quantities of electrically-charged ash can be generated in an eruption column (Anderson *et al.* 1965, Gilbert *et al.* 1991, Gilbert 1994), causing interference to radio waves. Radio communications were inoperative for four days following the 1912 Katmai eruption on Kodiak Island, 160 km from the vent (Erskine 1962). Clicks of radio static were observed from a passing ship during the 1963 Surtsey eruption (Anderson *et al.* 1965). However, there are numerous examples of radio communications continuing to function around an erupting volcano and in areas receiving ash falls (e.g. Mount St. Helens 1980, Pinatubo 1991 and Ruapehu 1995-1996.).

During most natural disasters, telephone and radio communications are susceptible to overloading by public and emergency services use. Telephone systems were overloaded in communities receiving ashfalls during the 1953 Mt Spurr eruption (Wilcox 1959) and the 1980 Mt. St Helens eruption (Dillman *et al.* 1982).

Ash entering telephone exchanges can cause damage to electrical and mechanic systems and general damage to buildings.

Conclusions Communications are a vital part of everyday life and critical in any emergency. Radio, TV and telephone communications are very vulnerable to disruption during a volcanic eruption, and may fail completely in eruption-affected areas. Loss of communications will make disaster management extremely difficult during and following an eruption.

2.9 Ash Removal and Disposal

Ash removal from roads The removal of ash may be required from urban areas after the fall of only a few millimetres. A number of factors such as the thickness, grain-size and the availability of equipment will influence the removal-method employed, the ease at which ash can be removed and the cost of any clean-up operation. Removal of ash from roads was undertaken by a number of council and works department after the 1980 Mount St. Helens eruption. Few, if any of these organisations had developed plans for ash-removal prior to the eruption and little knowledge of how to undertake this was available (Saarinen & Sell 1984). A range of methods were tried during initial clean-up operations (Hoff 1980, Markesino 1981, Novak & Zais 1981). The best method found was to sprinkle the ash with water, blade it to the side or middle of the road for pick-up using belt or front-end loaders and then use power-broom or more water to remove the remainder (see Appendix 2 for more details). Prior to ash removal, dust retardants have been used to control wind blown ash. "Coherex", an emulsion of petroleum resins, was use as a dust retardant in Oregon (Public Works 1981).

In addition to roads, ash may need to be removed from other paved areas like car parks and airport tarmacs. Similar techniques, described above, have been used. Tyler & Reynerton (1981) describe the clean-up operation at Fairchild Airforce Base, USA after ashfalls from Mount St Helens in 1980. Water was used to wet the ash, graders, snowplows and snow brows worked the ash and loaders picked it up. It was then hauled to a central location, where it was buried using landfill techniques. It was noted that around buildings, the wind blowing ash from roofs tops constantly contaminated previously cleaned areas.

Ash removal from buildings Sweeping dry ash from roofs was found to cause clouds due to the fine particle size of the ash and this slowed the cleanup process (Dillman & Roberts 1982). Wetting down the ash formed a cohesive "glue-like" material, which was not easy to remove and added weight to the deposit. Lightly damping the ash and then sweeping it was found to be the best method for removal ash from roofs. Highest priority should be given to removing ash from roofs for four reasons (F.E.M.A. 1984).

(i) It is a prerequisite to reactivate the ventilating and air-handling system.
(ii) It is fruitless to clear ground level areas for them to be recovered by windblown ash from roofs above.
(iii) The rapid removal may prevent the possibility of catastrophic roof collapse.
(iv) Ash removal from public buildings will enhance morale and confidence of the public if they observe the rapid cleanup and prompt functioning of local buildings.

Disposal of Ash The fall of a few millimetres of ash on an urban community will result in the need for disposal of large quantities. The disposal of ash should be done in a way that minimises ongoing public health problems and is cost-effective. An ash dump, left uncovered, will result in ash being easily blown from the dump.

Methods of stabilizing the dump will need to be employed such as covering with top soil or hydraulic seeding. Ash is generally a good fill, has a good bearing strength, mixes well with soil and will support vegetation if fertilized (F.E.M.A. 1984).

3.0 PYROCLASTIC SURGES

Phreatomagmatic explosions commonly produce rapidly rising, steam-rich vertical eruption columns surrounded by ground-hugging turbulent mixtures of steam and solid ejecta that flow out laterally from the base of the eruption column. People caught in the direct path of pyroclastic surges are most unlikely to survive and any survivors will probably receive severe injuries. Buildings offer some protection on the surge periphery, but will not guarantee survival as the building may be destroyed or severely damaged. The best protection is to evacuate the near-vent area prior to eruption.

Pyroclastic surges travel at high initial velocities and vary from dry mixtures of gas, steam and ash to wet surges with gas, steam, ash and water. Dry surges tend to sandblast objects with a mixture of ash and superheated gas and steam. The ash-laden wind causes varying degrees of damage to structures depending on its temperature, duration and the amount of solid material it is carrying. Buildings near the vent will be totally obliterated, with the possible ignition of combustible material. Structures near the margins of the surge may be less damaged, as the surge velocity decreases, but damage will still be caused by clast impact. The possibility of ignition exists if the surge is still sufficiently hot.

Surges from phreatomagmatic eruptions are often wet containing both steam and water. They are more dense than dry surges and tend to decelerate more rapidly and deposit sticky wet ash. This wet ash will often cause the collapse of structures it buries due to loading as described in the previous section (pyroclastic fall).

A wet surge deposit will have a density between 1300 - 2000 kg/m^{-3}. In the Tarawera eruption of 1886, surges from Rotomahana overwhelmed the Maori village at Te Ariki, burying it under several metres of ejecta. The surges travelled more than 6km from source. In the 1966 eruption of Taal, (Moore *et al.* 1966, Moore 1967) sandblasting occurred as far as 6km from the vent. The was no evidence of charring or burning. The damage from the surge is shown in Table 3.1.

Table 3.1: Surge damage produced by the 1965 eruption of Taal, Philippines

Distance from vent	Impact
0.5 - 1.0 km	All trees and stumps removed
1.0 - 1.25 km	Trees remain but strongly sand blasted. Little or no coating of mud.
1.25 - 6 km	Blast recorded by mud coatings, stripping of bark of trees, breakage of bamboo, deroofing of houses, stripping of palm tree fronds on the blast side and faint scarring of small bushes.

Pyroclastic surges can destroy infrastructural facilities. Any associated structures above ground will mostly likely be destroyed or severely damaged. Pipes which are on the surface may also be vulnerable. Where pyroclastic surges enter reservoirs large amounts of eruptive material can be deposited in the water leading to contamination of the supply. Surges will cut power lines in affected areas. Buried cables and gas pipelines will have a good chance of survival.

4.0 LAVA FLOWS

Lava flows are streams of molten rock that travel down valleys. The distance they travel depends on the viscosity of the lava, output rates, volume erupted, steepness of the slope, topography and obstructions in the flow path. Basalt flows have low viscosity (flow easily) and have been recorded to travel more than 50 km from a volcano but usually only flow 5-10 km. The Auckland Volcanic Field produces both pahoehoe and a'a lava flows. Both flow types will follow topography but only pahoehoe are sensitive to local perturbations, especially in areas with slopes less than 5° (Trusdell 1995). Shallow slopes may slow the progress of lava flows whereas steeper slopes will accelerate them. Lava flows will seldom threaten human life because of their slow rate of movement. The steep fronts of flows may became unstable and can collapse, causing small pyroclastic flows (Blong 1984, Baxter 1990).

Lava flows may cause extreme damage to buildings and other infrastructure, resulting from burial, ignition and/or excessive forces causing structures to collapse. Blong (1984) describes a number of examples of damage from lava flows. Thick slow-moving a'a flows exert larger stresses on structures than more fluid pahoehoe flows. In numerous cases flows have been diverted by resistant structures. When a flow meets an obstruction its orientation to the structure will influence the flows behaviour. Structures perpendicular to flows have a higher risk of collapse. Inflation of pahoehoe flows may cause flows to overtop structures that initially halted their advance (Hon *et al.* 1994).

The ignition of flammable materials is a common consequence of lava flow inundation. Some masonry buildings have survived, but most structures are ignited and gutted by fire.

Diversion of lava flows A number of methods have been used in an attempt to divert lava flows (Blong 1984). In Hawaii, authorities used barriers in an attempt to contain advancing flows in 1955 and 1960 and water jets in 1960 and 1983. It was found that using sprays of water could locally check flows for long enough to remove contents from buildings, but eventually flows continued their advance. The US military resorted to bombing in attempt to break levees in 1935, 1942 and 1975-1976. During the eruption of Heimay (1973) in Iceland sea water was pumped onto flows (Williams & Moore 1973). The effectiveness of these methods is debatable. The first unqualified success was in 1992 on Mount Etna where explosives were used to open a lava-tube cutting the supply to the flow front (Barberi *et al.* 1992).

5.0 VOLCANIC GASES

Volcanic gases consist predominately of steam (H_2O), followed in abundance by carbon dioxide (CO_2) and compounds of chlorine and sulphur. Minor amounts of carbon monoxide, fluorine and other compounds are also released. Concentrations of gases will dilute rapidly away from a volcano and pose little threat to people more than a few kilometres from the active vent. When sulphur dioxide (SO_2) is released it reacts with oxygen, water and sunlight to form aerosols (droplets and tiny particles), sulphuric acid and other sulphur oxide species (Sutton & Elias 1992). This mixture often produces a atmospheric haze known as volcanic smog or "vog". The acid and other compounds in volcanic gases can affect humans and animals eyes and respiration. The same compounds can cause corrosion of metals and other materials (see above). Heavy-than-air gases (i.e carbon dioxide) can collect in depressions and suffocate people and animals. Gases can also be released when lava flows reach the ocean as molten lava boils and vaporises seawater. A series of chemical reactions can produce an aerosol mixture of hydrochloric acid (HCl) and seawater, which is termed lava haze or "laze" (Sutton & Elias 1992). This is potentially harmful to people and is corrosive. Concentrations decrease sharply with distance from the source.

6.0 VOLCANIC EARTHQUAKES AND GROUND DEFORMATION

Earthquakes have preceded and accompanied most volcanic eruptions and are generated by the movement of magma, the formation of cracks through which the magma moves, gas explosions in the conduit and readjustment of the volcanic edifice to magmatic pressures. Volcanic earthquakes rarely exceed magnitude 5, and are usually much less damaging than the associated eruptions. Damage is

usually limited to a relatively small area around the volcano but buildings within this zone may be subject to shaking damage. Many earthquakes occur at or near volcanoes without associated eruptions. Ground deformation may also cause damage to structures near vent, often associated with earthquakes. Commencement of the 1957 eruption of Capelhinos was followed several months later by a seismic crisis and ground deformation that destroyed over 500 houses (Machado *et al.* 1962).

7.0 ATMOSPHERIC EFFECTS

Volcanic eruptions often produce atmospheric effects such as atmospheric shockwaves and lightning discharges. Atmospheric shockwaves have been recorded from many historic volcanic explosions. The largest observed have produced overpressures sufficient to break windows.

Table 7.1: Examples of damage caused by shockwaves (From Blong 1984)

Volcano and year	Damage
Vulcano, 1888-1890	Broken windows 10 km from volcano
Stromboli, 1907	Nearly every window on the island broken
Asama, 1958	Damaged houses within 15 km
Sakurajima, 1977	Broken windows at 3 km from crater

Lightning strikes are commonly generated as a result of electrically charged ash in a convecting eruption column (Anderson *et al.* 1965, Gilbert *et al.* 1991, Gilbert 1994) and can cause injuries to people and damage to facilities. Since telecommunications equipment is commonly situated on high ground it is particularly vulnerable if located near the volcano.

Table 7.2: Historical examples of eruption induced lightning strikes

Volcano and year	Observation	Reference
Tarawera, 1886	Probable forest fires started by lightning.	Keam 1986
Soufrière, 1902	Lightning strikes killed animals and damaged buildings up to 4 km from the vent.	Blong 1984
Kilauea, 1924	Lightning strikes 8 km from the vent destroy 21 consecutive power poles.	Blong 1984
Rabaul, 1937	Lightning strikes hit trees and houses and may have resulted in the loss of several lives.	Johnson & Threlfall 1985
Paricutin, 1943	Three people killed by lightning believed to be caused by the eruption.	Luhr & Simkin 1993
Surtsey, 1963	Spectacular lightning displays within the	Thorarinsson 1965

	ash plume.	
Soufrière, 1979	Strikes 9 km from the volcano.	Shepherd *et al.* 1979
Hudson, 1991	Lightning-strike damage to communication equipment was reported.	Bitschene 1995
Rabaul, 1994	One person killed by lightning.	Blong & McKee 1995

REFERENCES

Refer references section of Report 3.1 (Volcanic Impact Assessment for the Auckland Volcanic Field).

REPORT 3.4

MITIGATION MEASURES FOR VOLCANIC ASH FALLS

Prepared for

AUCKLAND REGIONAL COUNCIL

By

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(Appendix A2 from Volcanic Impact Assessment for the Auckland Volcanic Field, ARC Technical Publication Number 79, April 1997)

CONTENTS

1.0 INTRODUCTION

Volcanic ash is highly abrasive, mildly corrosive and potentially conductive (especially when wet). Ash particles are commonly sub-millimetre in size and are easily entrained in the air by wind or by moving vehicles. Particles are very pervasive and can penetrate all but the most tightly-sealed areas. Mitigation actions have two basic purposes: 1) preventing or limiting ash entry, and 2) effective and efficient removal of ash to prevent or reduce damage.

The most effective method to prevent ash-induced damage is to shut down, close off and/or seal off equipment until the ash is removed from the immediate environment. In many cases this is not practical or acceptable. Some mitigation procedures can cause additional problems or may be counter-productive. No single technique provides a solution to all situations and a range of measures will often provide the best results. Constant monitoring and reassessment of ash effects and mitigation procedures is required to achieve the most effective balance between operational requirements and the level of damage limitation.

Pre-planning can reduce the severity of ash impacts. The mitigation planning should undertake the following:

1. Conduct a vulnerability analysis of equipment and facilities to determine which would be the most affected and which are adequately protected.
2. Identify appropriate methods to protect vulnerable equipment and facilities.
3. Develop a priority list of facilities that must be keep operative versus those that can be shut-down during and after ash falls.
4. Identify effective and efficient ash-removal methods for equipment and facilities.
5. Establish plans to implement ash mitigation measures, containing procedures for; the warning and notifying of potential ash falls, reducing or shutting down operations, accelerated maintenance and ash-clean-up operations.
6. Stockpile spare parts for critical equipment, filters and cleaning/disposal equipment.

The following sections list a series of previously published mitigation measures, issued in response to the 1980 Mount St Helens eruption. Some additional suggestions are provided.

2.0 VEHICLES

Damage to vehicles operating in ash-rich environments can be reduced by using a number of suggested mitigation techniques. Accelerated vehicle maintenance will reduce the potential of damage. From the experience gained from the Mount St Helens eruption, Federal Emergency Management Agency (F.E.M.A. 1984) has produced the following recommendations for ash removal and protection of vehicles.

Table 2.1: Driving in ash fall areas and protection of vehicles (from F.E.M.A. 1984)

1.	*Avoid driving in heavy conditions unless absolutely required. The more dense the dust, more urgent the requirement should be for driving.*
2.	*When required to drive in dense dust, keep speed below 35 mph or lower. Do not follow too close to car ahead. Use headlights on low beam.*
3.	*Change oil often. In very dense dust change at 50 - 100 mile intervals. Light dust conditions change oil at 500 - 1000 mile intervals. Lubricate all chassis components at each oil change.*
4.	*Clean air filters by back-flushing filter paper with compressed air (30 psi). Caution: Blow element from inside (clean side) to outside (dirty side). DO NOT strike filters against anything. Air clean only. If unsure, have a qualified mechanic perform the air filter service. Inspect filters for dents or torn paper. Clean the inside of filters and the filter cover with*

	damp cloth before reinstalling filter. Reinstall filter in housing and tighten on cover very tight, approximately one full turn with pliers after tightening. Do not exceed one full turn with pliers or you may damage the system.
5.	*DO NOT install hose from carburettor air intake (air clean) to inside of car. Outside dust and ash will be drawn into vehicle.*
6.	*Wrapping air cleaner element with a silk stocking or cheese cloth is of questionable value. It will not improve air cleaner filtration and may actually cause serious if not installed correctly. Rags, or any other intended filtering material, should not be placed over the carburettor inlet inside the air cleaner element, serious damage to the engine and/or loss of vehicle control may result.*
7.	*Cover passenger compartment vent inlet (located at base of wind-shield and usually under hood) with thick, loosely woven felt-type material to filters air into vehicles. With vent filter in place, keep heater blower high. Blower will slightly pressurize inside of vehicle and keep dust from entering through body gaps or holes. If a vent filter is NOT installed, keep air conditioner and heater blowers off.*
8.	*Have service garage clean wheel brakes assemblies every 50-100 miles for very severe road conditions, or every 200-500 miles for heavy dust conditions.*
9.	*Have service garage clean alternators winding with compressed air after heavy accumulation or every 500 to 1000 miles or sever dust exposure.*
10.	*Wash engine compartment with garden hose or steam cleaner. Be sure to seal off air intakes and electrical components before cleaning.*
11.	*Commercial truck filters can be installed to increase the filtering capacity of the cleaner. However this is expensive and should only be attempted by trained garage mechanics or experienced personnel. This would be beneficial for vehicles operating continuously in extreme dust conditions.*
12.	*Air filter restriction gauges can be installed by qualified mechanics. The gauge will tell you when your air filter requires servicing in order to avoid over-servicing.*

Table 2.2: Ash removal methods for roads (from F.E.M.A. 1984)

- *Notify bordering property owners to move ash from roofs and the rest of their property to the street, away from the gutters, to prevent the need for more than one ash removal project and to avoid storm sewer blockages.*
- *Encourage and monitor block efforts and volunteer work.*
- *Before beginning cleanup activities, build small dike (using sandbags or other methods) around catch basin inlets to screen ash.*
- *To keep ash out of storm drains, hand sweep the dry ash outwards from the gutters about two feet or so. (Volunteer teams can provide important assistance in this area.)*
- *Moisten the ash using a sprinkling system. Avoid moistening it too much, for it will become unmanageable. Due to its fineness, ash powder when saturated can retain large amounts of water and weigh up to 80 pounds per cubic foot. (Wet sawdust or wood-chips have been used to help reduce the dust, but these methods are not as effective as only wetting ash.).*
- *Use motor patrol graders to blade the ash. Collect, load and transfer the ash to trucks to be hauled to dumps sites.*
- *For a thorough cleaning of paved roads with storm sewers, use power brooms on the dampened residue.*
- *To remove the remaining ash on paved roads without storm sewers, flush the roads with water.*
- *As soon after the street cleanup as possible, remove ash deposits from catch basin inlets with vacuum trucks or machines with jet rodding and vacuum systems. Delaying the*

cleanup allows time for the ash to crust and cake, making it harder to remove. Further, the ash density impairs the self-cleaning function of the sewer's grade, creating the potential for plugging the sewer.

Paved or Oiled Roads That Have No Curbs or Sewers

- *Sprinkle ash with water and blade it onto the shoulders or into the ditches. Then load and remove the ash. Remove the residue by sweeping or flushing it, if necessary. Where gravel shoulders exist, replace lost gravel so as not to lose the integrity of the road way.*

Gravel Roads

- *Blade the ash into ditches, being careful to avoid unnecessary loss of surface materials.*
- *If the existing right - of - way is wide enough, spread the ash along the back slopes outside the ditch. (Note that much of the ash may become integrated into roadside vegetation and that the ash in these areas will blow for some time during windstorms.)*
- *Remove ash blocking the drainage in ditches and culverts, and transport it to a disposal site. A considerable amount of ash will remain on the roadbed surfacing, creating a serious visibility problem for traffic. Nothing can be reasonably done to eliminate it totally, but it will decrease with time.*
- *On the roadbed, place a thin lift of rock consisting of graded material 5/8 inch to 0 in size and crushed to standard specification. This layer can be added and processed into the existing surface to achieve the binding effect that will stabilize the surface under traffic. (While this expensive method will not provide total dust control, it is, nevertheless, the most suitable method available for achieving visibility levels so that traffic operations can be restored.)*

3.0 WATER SUPPLIES

The main problems facing surface water bodies are ash-induced changes in turbidity and acidity. Intake of water should be cut before these levels become excessive and regular monitoring will indicate when the supply can be resumed. High turbidity levels are manageable if water-treatment filters are cleaned or replaced frequently but filters may be blocked if ash loadings become excessive. Where turbidity is high, precautionary warnings to "boil water" should be issued. This is because the suspended ash may have decreased the affectiveness of any disinfection or flocculation processes. As fine ash can remain in suspension for long periods, a coagulation-flocculating agent may need to be added. Alum has been found to be the best agent. To reduce physical damage to the plant, equipment and pumps should be covered when there is an impending eruption, and the ash removed before continuing operations.

4.0 SEWAGE AND STORMWATER SYSTEMS

The blockage of sewer and stormwater pipes is a major problem created by ash falls therefore it is of prime importance to limit the amount of ash in the initial sections of the systems. F.E.M.A. (1984) recommend a number of measures to reduce the amount of ash entering the system.

Table 4.1: Protection of sewage and stormwater systems from volcanic ash (from F.E.M.A. 1984)

1.	*Have local ordinances in effect banning connections of downpipes and roof drains to the sewer.*
2.	*Warn citizens against disposing ash down manholes of both sewer and stormwater systems.*
3.	*When hosing streets, place sand bags around or over manholes covers or avoid covers entirely, since the vent holes and the areas between the cover and the rings allow passage of ash.*
4.	*When washing streets, parking areas, roofs, use a weir (sandbags) in each manhole and stormwater intake to trap the ash.*
5.	*Instruct the public how to protect storm water systems*
6.	*When possible, disconnect downpipes from the stormwater system until roof clearing is complete.*
7.	*Instruct citizens where to deposit ash cleared from property.*
8.	*Closely monitor the cleanup activities of privately owned parking areas.*
9.	*Use dry methods, like hand sweeping, prior to flush cleaning when clearing streets and parking areas served by a free discharging or dry well stormwater system.*
10.	*Sweep the ash outwards from the gutters about two feet or so.*
Note:	*Shallow deposits of ash in the stormwater or sewerage system will not reduce the hydraulic capacity of the pipes by a significant amount, thus expenditure of time and money to clean lines may not be warranted.*

SEWAGE TREATMENT PLANTS

Ash entering sewage treatment plants can cause considerate damage. F.E.M.A. (1984) and White *et al.* (1980) recommend the following precautions to be taken:

TABLE 4.2 Protection of sewage treatment plants from volcanic ash.

1.	*Temporarily cover all equipment (e.g. mechanical, biofilters), including ventilation intakes, that might be directly exposed to the ash fall before or during the onslaught.*
2.	*Shut down all equipment not absolutely necessary.*
3.	*Where possible, place sandbags or other devices at the entrance channel to the plant to trap ash. This procedure will require frequent attention due to normal settleable solids present in sanitary sewage.*
4.	*Consider removing or bypassing the comminutor during the initial heavy flows of ash into the plant.*
5.	*Frequently check the primary clarifiers to prevent (a) damage to the sludge collection mechanism and/or the digesters sludge pumps and (b) the transference of ash to the digester. Depending on the type of mixing employed in the digester, further damage may occur in the sludge transfer pumps.*
6.	*To clear ash from individual sections of the treatment facility, bypass individual units, or extreme instances, make a complete plant bypass to a holding pond or lagoon.*

5.0 ELECTRICITY SUPPLY

The presence of moisture with ash is the critical factor in initiating insulator flashovers if insulating surfaces are completely coated, since ash contains soluble leachates which makes ash conductive when wet. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent wide spread outages. Mitigation recommendations are presented by F.E.M.A. (1984).

Table 5.1: Protection of electricity supply (from F.E.M.A. 1984)

- *Immediately after the ash fall, dispatch personnel to the substations to dust, sweep, and blow ash from electrical equipment. Prompt adequate maintenance of the mechanical and electrical systems is essential.*
- *Shut down all electrical systems before any attempt is made to clean or service them. Throw the main circuit breakers, not just the nearest switches.*
- *Remove dry ash immediately from the most sensitive systems by blowing it off using air pressure of 30 psi or less, so as to avoid a sandblast effect. Avoid rubbing or brushing equipment, as that will damage many surface. Be careful not to blow the dust other places that should be kept clean. Vacuum ash when possible and change filter bags often.*
- *Clean electric components such as small motors and light bulbs, as they will generate excess heat when blanketed with dust. The excess heat can cause fires and short term operating life. The ash should be vacuumed or blown off as described above.*
- *Avoid saturating electrical components when hosing dust off. Many of these systems can handle rain and moisture, but not the effect of water jets from hoses.*
- *Check for trees heavily loaded with ash near power lines because the added weight can cause limbs to fall on power lines.*
- *Check and keep insulators clean. A moderate wind, while the ash is still dry, will clean most insulators on outdoor distribution lines and equipment. Light rain, which does not wash the ash away, is harmful and can cause flashovers and short circuits. Ash that has hardened may require special cleaning methods such as hand cleaning or water jetting.*
- *Protect backup and auxiliary units to avoid starting problems when they are activated.*
- *Maintain protection and cleaning programs continuously until the treat of windblown ash is over.*

6.0 TELECOMMUNICATIONS

From the experience gained from the Mount St Helens eruption Labadie (1983) has produced the following observations and recommendations for mitigating the effects of volcanic ash on communication systems. The most serious problems result from the conductive and abrasive properties of ash.

Table 6.1: Communications systems: observations and mitigation techniques (from Labadie 1983)

Mitigation Techniques

- *Teflon insulators on communications antennas were covered with dust and shorted out. Very difficult to clean as residue would adhere. Replacement with ceramic insulators required.*

- *Plastic switches and push-buttons (especially those with self-cleaning contacts) abrade quickly. Necessary to replace.*
- *Seal up repeater stations and other installations; shut air intakes; internal air circulation and leakage should be sufficient for cooling.*
- *Blow out or vacuum out radio equipment; brush off.*
- *Seal equipment that is not already watertight. Smaller units have low-power consumption and do not generate much heat.*
- *Magnetic particles that stick to relay cores should be blown off.*
- *Keep moisture out of equipment.*
- *Clean equipment daily; increase use of filter paper.*
- *Clean out microwave dishes, feed horns, wave guides. Install covers; plastic tarp will do in an emergency.*

7.0 BUILDINGS AND BUILDING SERVICES

Volcanic ash can cause damage to buildings and building services in several ways; overloading roof strengths causing collapse, soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials. The following table is a list of general guidelines proposed by Labadie (1983) for removing and controlling volcanic ash in buildings, heating/cooling systems and computer services.

Table 7.1: The management of volcanic ash in buildings (from Labadie 1983)

Mitigation Techniques

- *Establish a written procedure; train personnel.*
- *Stockpile disposal containers, mops, brooms, shovels, pails, industrial vacuum cleaners, plastic bags, and sheets.*
- *Stock filters and filter materials.*
- *Remove dust from roofs and entry ways prior to re-activating machinery.*
- *Keep roof drains, storm drains, gutters, etc, clear of dust clogging. It is best to sweep dust from roofs and not flush with water; roof drains clog very easily.*
- *Make a written record of all steps taken to secure the building, so these steps can be retraced for start-up procedures, or if problems arise.*
- *Use a damp mop to clean hard floors.*
- *Use a water-type industrial vacuum cleaner, if possible, for cleaning rugs and cloth furniture.*
- *Use damp, disposable cloths to dust furniture, window sills.*
- *Restrict building access to the most protected entrance. Admit only authorised personnel.*
- *Close and seal all unnecessary outside openings, including air intakes and vents.*
- *Shut down all unnecessary building operations and equipment.*
- *Establish decontamination rooms for personnel entering the building. Require personnel to brush down clothing and shoes prior to entering the building and to vacuum off clothing immediately upon entering the building, or to bring a change of clothing and shoes for use while in the building.*
- *If outside air intake is required, monitor air intake filters at regular intervals, and change as required. Remove dust from area of outside-air intakes.*
- *Maintain a relatively clean environment throughout the entire building. Damp-mop floors, wipe off machinery and furniture at least once a day.*

Table 7.2: Heating/cooling systems: observations and mitigation techniques (from Labadie 1983)

- *Close external air intakes; use internal circulation only; this will create positive pressure inside building.*
- *Control access, seal doors.*
- *Establish decontamination rooms for entering personnel; provide vacuum cleaners, shoe covers, disposable caps.*
- *Stockpile cleaning supplies, duct tape, disposal containers.*
- *use extra (and heavier) filters for external air intakes.*
- *Clean dust away from external intakes; restrict vehicle and foot traffic near intakes.*
- *Install intake hoods that extend farther above ground.*
- *Install pre-filters.*
- *Add sand filters to cooling towers.*
- *Cover cooling towers.*
- *Clean coils, radiators, etc, with compressed air and/or water.*
- *Add cooling coils to un-interruptible power supply to reduce temperature of incoming air by 10° (increases cooling capacity).*
- *Add back-flushed filters to cooler sumps.*
- *Install alarm circuit to warn of excessive pressure differential across filters; filters that get too clogged can break open.*
- *Change from open, drip-proof type motors to totally enclosed, fan-type motors.*
- *Reduce staff to minimum required.*
- *Close and seal unused rooms; turn off unused equipment.*
- *Shutdown air handling system to prevent damage to chillers, fans, pumps, etc.*

Table 7.3: Computer services: observations and mitigation techniques (from Labadie 1983)

- *Best tactic for ash mitigation is prevention. Clean and condition surrounding air to keep ash out of equipment.*
- *Cotton mat filters (used in clean rooms) were found to be best for filtering particles, but they reduce the air flow. A solution is to use larger fans to maintain required air flow. Rack-mounted equipment can be modified to add a larger fan; smaller instruments or components with a built-in fan would require design change to increase fan capacity.*
- *Use fluted filters as a compromise; increases surface area but reduces air flow by only about 20%.*
- *Digital integrated circuits can vary 5-10% in performance (depending on type of circuit) and still be acceptable. It is difficult to generalize about other equipment (e.g. high-voltage power supplies).*
- *Humidifying ambient air (e.g. wet down carpets) will help to control ash re-entrainment.*
- *Ash on equipment can be blown out with compressed air. If the air is too dry, static discharge could damage sensitive components (e.g. MOS integrated circuits). If the air is too damp, the ash will stick. Relative humidity of 25-30% is best for compressed air.*
- *Cleaning with a pressurized water-detergent mix and a hot water rinse is quite effective. However, this process requires at least partial disassembly.*
- *Ash on digital circuits won't cause much of a problem because of the low voltages involved. High voltage or high-impedance circuits are very vulnerable to leakage caused by semi-conductive ash. Ash that is acidic is conductive as well as corrosive.*

- *Ash should be blown or brushed away from power supplies and CRTs (especially high-voltage leads, capacitors).*
- *Ash may have high static charge and be hard to dislodge; requires brushing to dislodge.*
- *Accelerate filter change; use pre-filters.*
- *Change to absolute filters; will keep out particles down to 1 micron.*
- *Keep computer power on to operate filtration, but don't run (especially disk drives).*
- *Maintain "room-within-a-room" configuration; restrict access; re-circulate air; accelerate cleaning of area.*

From the experience gained from the Mount St Helens eruption F.E.M.A. (1984) has produced the following recommendations for ash removal.

Table 7.4: Ash removal methods for buildings (from F.E.M.A. 1984)

- *Promptly notify building owners to remove ash from roofs in a timely manner to prevent streets from being repetitively cleaned.*
- *Inform public of effective methods for (1) removing ash from roofs and property and preparing it for pick-up by emergency crews and (2) organizing neighbourhood cleanup activities.*
- *Caution residents against flushing ash into sewers.*
- *Remove ash dry and before the first rain. Dampen ash with a light spray of water to reduce billowing. (Do not use large amounts of water which will cause the ash to cake).*
- *Make sure that the ash cleanup is supervised by knowledgeable building maintenance personnel to prevent unnecessary damage to roof material and surfaces.*
- *Use protective measures when removing ash from roofs. Walking on roofs and using tools and small equipment can cause breaks and punctures is the roof is dry and brittle. The full force of water from fire hoses will break lap shingles or tear lap roofing.*
- *Do not flush ash into drains and down-spout, for it can clog the small-sized pipes. Ash flushed into dry wells can seal them, rendering them inoperative.*
- *Thoroughly remove all traces of ash near intakes of ventilation systems.*
- *To protect sewer lines, disconnect down drains at ground level until cleanup is complete.*
- *To prevent or reduce the accelerated deterioration of roof coatings by mildly acidic property of ash, clean and/or protect the roof surfaces accordingly. Metallic roofs surfaces, particularly older galvanized roofs which are pitted, and lower gage galvanized roofs are most susceptible to increased deterioration from the properties of ash.*
- *On flat roofs, hand sweep ash into windrows and transport it by wheelbarrow to an edge dump. Use proper protection such as planking, mats, plywood sheets, and pliable footwear to prevent unnecessary damage from impact and abrasion. Hoppers with a funnel pip suspended above a loading truck can be used to collect the ash. To remove final dry residue or thin layer of ash, use air pressures with regulation. Note the small vacuum equipment is not practical because of the abrasiveness of the ash.*
- *On steep shingle roofs, place dams in the troughs to prevent the ash from reaching the down drains. Then hose down the ash and clear it from the eave troughs. This operation must be preformed with care to avoid deforming the gutters and tearing them loose.*
- *On low slope bitumastic mopped roofs, where there is only a thin ash layer or small residue, flush the ash with water. Again too much pressure from high pressure hoses can damage roof materials.*

To avoid clogging the inlets to roof drains, encircle the roof inlet with a fabricated ring

made from heavy sheet metal about four inches wide and two feet in diameter. This serves as a dam allowing water to spill over the top, while the ash settles in the surrounding roof depression. Later, when dry, the ash can be removed manually

Building Exteriors

- *Sills, ledges, parapets, and wall surfaces - usually these building features will not warrant extra cleanup efforts or expenditure if the primary functioning of the building is not impaired.*
- *Air-handling and air conditioning mechanisms.*
- *Shut down systems prior to or during the initial onslaught of the ash fall. Simultaneously, check all public buildings to make sure windows are closed, air conditioners are off, and that all unnecessary outside openings, including air intakes, are closed and sealed. These initial activities will help prevent or reduce the introduction of ash to building interiors and air-handling system's ingestion of ash.*
- *To restart air-handing systems:*
- *Clean the roof-mounted intakes and the roof area adjacent to intakes.*
- *Clean or replace filters.*
- *Inspect, clean or lubricate moving portions of the mechanism, following prescribed routine maintenance.*

Building Interiors

- *Restrict building access to the most protected entrance.*
- *Instruct building managers to educate occupants in preventing ash entrainment into the building.*
- *Have building managers establish an entry room or zone where personnel are required to brush or vacuum clothing and shoes or make clothing changes, if appropriate.*
- *Establish any necessary, extra cleaning procedures to protect the interior environment.*
- *To substantially reduce the need for extensive maintenance of equipment, place coverings over office machines as standard procedures.*
- *Carefully monitor vacuum cleaners to assure that filters and ash bags are changed when necessary.*

F.E.M.A. 1980 (Bulletin 7)

House hold surfaces should be vacuumed to remove ash much ash as possible.

- *After vacuuming carpets and upholstery may wish to be cleaned with a detergent shampoo. Avoid excess rubbing action because the sharp ash particles may cut textile fibres.*
- *Glass, porcelain enamel and acrylic surfaces may be scratched if wiped too vigorously. Use a detergent soaked cloth or sponge and dab rather than wipe.*
- *High-shine wood finishes will be dulled by the fine grit. Vacuum surfaces and then blot with a cloth treated to pick up ash. A tack cloth used by furniture refinishers should work well*
- *Ash-coated fabrics should be rinsed under running water and then washed carefully.*

Remember: Soiled clothing will require extra detergent. Wash small loads of clothing, using plenty of water so the cloths will have room to move freely in the water. Do not mix heavily soiled clothes with garments that are lightly soiled. Be sure clothes are free of ash before putting them in an automatic dryer Ash may scratch the inner surface of the dryer.

During the next few months, filters must be replaced often. Air conditioner and furnace filters need careful attention. Clean refrigerator air intakes. Clean any surface that may blow air and recirculate the ash. Stove fans and vents should be cleaned thoroughly.

REFERENCES

Refer references section of Report 3.1 (Volcanic Impact Assessment for the Auckland Volcanic Field).

SECTION 4

TROPICAL CYCLONE AND TSUNAMI

REPORT 4.1

TROPICAL CYCLONES IN AUCKLAND: A 100-YEAR EXTREME EVENT SCENARIO

Prepared for

AUCKLAND REGIONAL COUNCIL

By

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NIWA Report AK97015

EXECUTIVE SUMMARY

1. This report has been prepared for the Auckland Engineering Lifelines Project to:

   - Provide base parameters of a feasible major cyclone event with a 100-year return period;

   - Model a scenario, cyclone track and rainfall and wind intensities and duration for this storm.

2. Tropical cyclones, which intrude into the New Zealand area, move south and east. Their path is slowed by blocking anticyclones. Once crossing New Zealand they get caught up in the westerly circulation of the mid-latitudes, and move rapidly south east.

3. The Auckland City 100 year return period gust is 140 km/hr. Higher gusts occur in more exposed parts of the region.

4. For rainfall, the 1-hour 100 year event varies between 50 and 90 mm over the Auckland region. The rainfall depth for the 3-day 100 year event ranges between 250 and 500 mm.

5. Three tropical cyclones have passed within 220 km of Auckland City between 1970 and 1994. These produced wind gusts as high as 130 km/hr at Auckland Airport, and rainfall amounts as high as 110 mm.

6. Cyclone *'Grief'* is described as the 100 year cyclone scenario to produce maximum impact on the Auckland region. With central pressures of 970 hPa(mb) from Day 1 to Day 3, it moves south east to lie just north east of Northland on Day 3, before moving across Auckland and then south east of Wairarapa by Day 4.

7. The cyclone initially produces wind gusts as high as 75 km/hr from the north east, then winds veer to the east and strengthen to over 140 km/hr. By Day 3 the winds have veered south east, with gusts to 120 km/hr. However the strongest winds occur on Day 4 from the south west with gusts as high as 170 km/hr.

8. Rainfall rates vary. Maximum hourly amounts occur in the easterlies, with rates as high as 85 mm/hr. The accumulated rainfall totals for the duration of the cyclone varies from 415 mm at Warkworth in the north to 230 mm at Pukekohe in the south.

CONTENTS

1.0 BACKGROUND

1.1 INTRODUCTION

High winds and intense rainfalls can cause havoc in metropolitan areas. Advance planning to minimise the impacts of severe weather conditions in Auckland requires realistic estimates of the magnitude and probability of extreme wind and rainfall events. Such estimates can be obtained by examination of the existing climate record, and using this information to simulate realistic extreme weather scenarios.

The purpose of this report, prepared for the Auckland Engineering Lifelines Project, is to enable the vulnerability of Lifelines services to the various consequences of an extreme cyclone event to be considered by providing base parameters of a possible major cyclone event for the Auckland region. Information is drawn from climate records of cyclones and extreme weather conditions around Auckland to build an extreme cyclone scenario over Auckland. The recurrence interval for the scenario are conditions that would be statistically likely to occur, on average, only once in 100 years during a tropical cyclone.

The scenario for this cyclone, dubbed cyclone 'Grief' in this study, is presented in Section 5 of this report. Earlier sections background the general characteristics of tropical cyclones impacting the New Zealand region (Section 1.2 below). The method used to develop the 100-year cyclone scenario is presented in Section 2, and this is followed by a brief discussion of extreme wind and rainfall extracted from climate records (Section 3) from the Auckland region. These data are drawn from all recorded significant events, including depressions of both tropical and extra-tropical origin, and provide important reference information in the construction of the cyclone *Grief* scenario.

Four significant tropical cyclones have impacted the Auckland region in a serious way since 1970, and these are briefly discussed in a section on 'near miss' cyclones (Section 4). By definition, the 100-year cyclone scenario developed here should be at least as severe as the worst of these *near miss* cyclones, and probably more severe as cyclone *Grief* is tracked to have its highest impact on the Auckland metropolitan area.

1.2 CYCLONES OVER NORTHERN NEW ZEALAND - GENERAL CHARACTERISTICS

The type of storms considered in this report all form over the tropical ocean of the South Pacific. Such storms (tropical cyclones) typically play out their whole life cycle in the tropics. However, a few cyclones migrate out of the tropics each year into mid-latitudes, where New Zealand is situated, undergoing a transformation from a tropical to an extra-tropical cyclone. In the process, they exchange their characteristic tropical core of warm air for one of cold air, which is characteristic of storms found in middle and higher latitudes. Such transformations are very complex physical processes. It remains difficult to predict which storms will take on the full characteristics of a mid-latitude depression, and exactly what path they will take in the process. It is however well known that tropical cyclones which do successfully migrate out of the tropics can produce some of the most damaging weather experienced in mid-latitude countries (Sinclair, 1993a).

The energy source for true tropical cyclones is the heat stored in the warm surface waters of the ocean. Most cyclones form in the area of warmest sea-surface temperature (SST), relatively close to the equator in the Western Pacific. Since the El Niño/Southern Oscillation cycle modulates tropical Pacific SSTs, it also influences the frequency of occurrence of tropical cyclones across the tropics. In El Niño years, tropical storms may occur across the tropical Pacific from the Indonesian region to well east of the dateline, while in La Niña years storms tend to be confined to the far western Pacific. Associated changes occur at higher latitudes, but the effect on the frequency of tropical cyclone incursions into the NZ region is relatively small (Basher and Zheng, 1995).

Tropical cyclones which intrude into mid-latitudes near New Zealand tend to move south and east as they approach the country. Hence, the most likely scenario for a severe event over Auckland involves - a tropical cyclone located in the New Caledonia/Coral Sea region moving towards North Cape. Depressions at low latitudes are often associated with anticyclones at higher latitudes, in what is known as a "blocking" pattern. A blocking anticyclone can retard the movement of a former tropical cyclone, causing continued extreme weather in particular locations, as occurred in 1988 with cyclone Bola (Sinclair, 1993b). While over even a relatively cool ocean, a cyclone can maintain its identity for several days, all the while drawing a virtually limitless supply of warm moist subtropical air southwards. Such conditions could trap a cyclone a few hundred kilometres north of Auckland, resulting in two to three days or more of extreme rainfall and strong easterly quarter winds.

The final chapter in the life cycle of a cyclone is frequently its interaction with a mobile mid-latitude trough moving through in the westerlies. This starts the change to a cold-cored storm and often results in intense redevelopment and rapid movement south east into the southern ocean. In the following 100 year worst-case scenario for Auckland, such an interaction occurs as the cyclone crosses the Auckland region. The re-intensification of the storm to the south of the city sets the scene for a period of very extreme south west winds. While the south westerlies are likely to be even stronger than the easterlies, they are also drier and do not last so long, as the storm centre moves offshore quickly once it becomes entrained into the main westerly wind belt.

2.0 METHOD

The scenario for extreme weather to occur from a cyclone of tropical origin is built up from a number of methodologies. Firstly, possible cyclone paths are derived from examining the paths of those which have passed within 220 km of Auckland City. Next, extreme event intensities for wind and rainfall are derived from the climate record of the Auckland region. Extreme wind gusts are modelled from a combination of extreme wind gust data and statistical procedures. Extreme rainfall isohyets have been calculated from point estimates of storm rainfall up to 1980.

The hypothetical cyclone scenario, with about a 100-year return period is constructed from path analysis of the 'near miss' cyclones and central pressures of the severest, and extreme event intensity analysis. The path the cyclone takes is one that will produce the severest weather likely to be experienced in the Auckland region. This is down the east coast of Northland, with blocking anticyclones to the south east of New Zealand stalling its progress south, and increasing the intensity of the easterly quarter winds over the Auckland region. Rainfall and wind information from the extreme event analysis, and other extreme tropical cyclone case studies are used to derive scenarios of cyclone rainfall and wind gust estimates. These are constructed for a four day period that the cyclone effects the Auckland region.

3.0 EXTREME EVENT INTENSITIES

3.1 WIND GUSTS

The Auckland climate record allows reasonably accurate estimates to be obtained of maximum wind gusts with an average return period of about 40 years. More extreme wind gusts than this, with a less frequent average recurrence interval, must be estimated from statistical procedures.

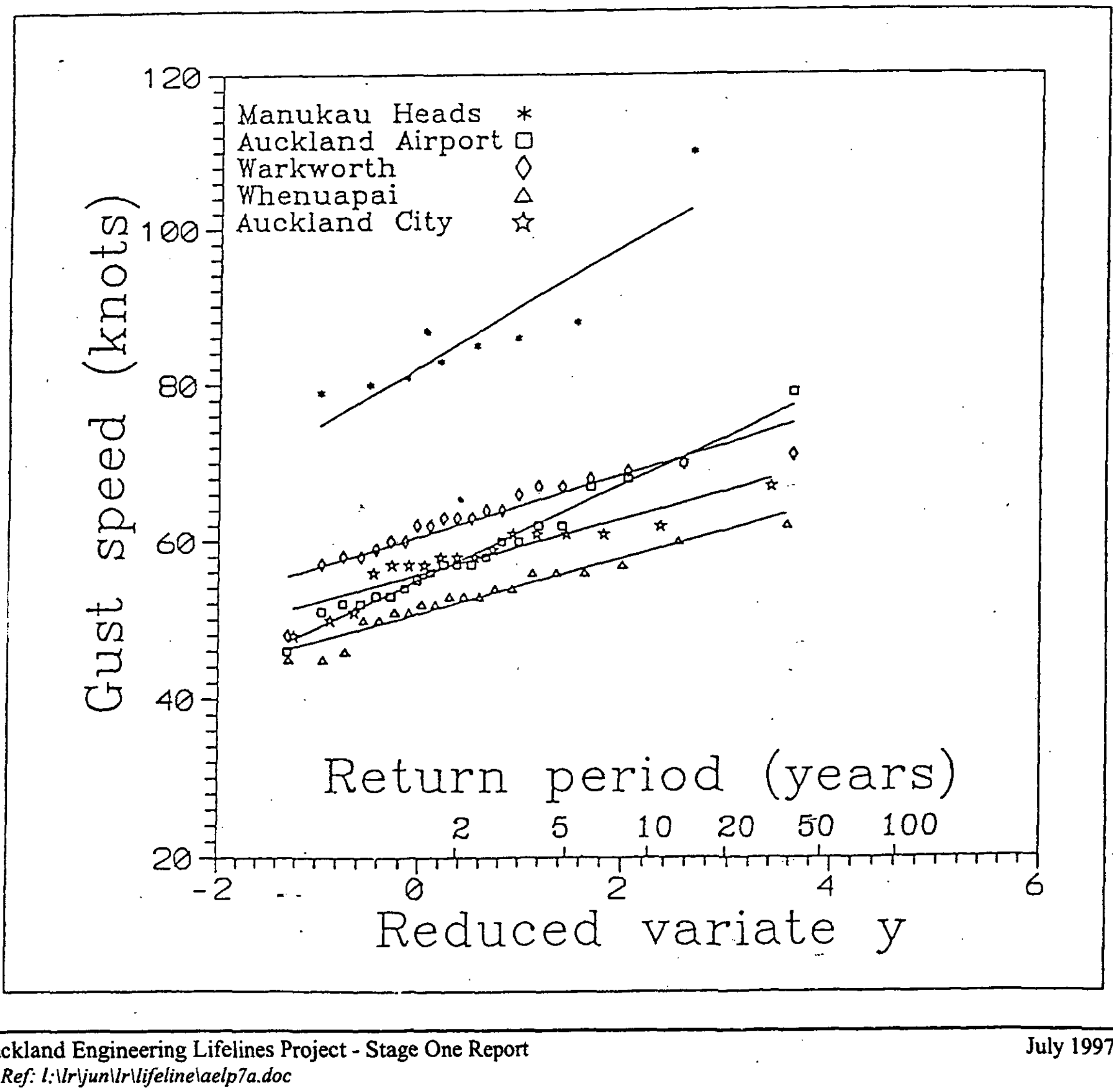
An analysis of the average return period of extreme wind gusts, at five Auckland sites, is shown in Figure 1. The data show, for example, that wind speeds in excess of 60 kts (110 km/hr) are measured on average only about once in 5 years in Auckland City, but more frequently than this at Warkworth, and probably several times a year at Manukau Heads.

It is important to note that the range in maximum gust speeds shown is small in relation to the return period range. Thus a wind speed increment of say 2 knots may give a change in return period of as much as 5 years. While this trend is reasonable for the data collected at a fixed climate site and for the general wind flow patterns of an area, it should be understood that in most places, buildings, hills, and similar obstructions cause significant turbulence and hence localised changes to wind flow characteristics.

The table below shows return period wind gusts at 10m over open, flat land, estimated from the Auckland City climate record.

Return period	m/s	km/hr	kts
20 years	34	122	66
50 years	36	130	70
100 years	39	140	76
350 years	43	155	84
1000 years	46	166	89

Figure 1: Average return period of extreme wind gusts at 5 Auckland sites.



3.2 HIGH RAINFALLS

Extreme rainfall isohyets have been derived for the Auckland isthmus from point estimates of storm - rainfalls up to 1980 (Figures 2-5). Figures 2 and 3 show 1-hour rainfalls that should be expected to occur on average about once in 50 and 100 years respectively. Over Auckland City, rainfalls of 50-60 mm in one hour should be expected on average once in 50 years, while 60-70 mm or more could be expected on average once in 100 years. Higher intensities (+20 mm) should be expected in the Waitakere and Hunua areas, and also around Warkworth.

Estimates of 3-day, 50 and 100-year rainfalls are shown in Figures 4 and 5. Over three days, rainfalls of 200-250 mm or more may be expected on average once in 50 years, and 250-300 mm or more once in 100 years. Again, the Waitakere and Hunua ranges are likely to experience higher rainfall extremes (+50 mm), while the data indicate that extreme rainfalls around Warkworth are likely to be much higher than for the isthmus (+200 mm).

The data presented here are from actual storm rainfall records, and therefore are reasonably good estimates of extreme rainfalls that have occurred over Auckland in the past 30 years or so. These estimates will be compared, in the next sections of this report, with observed rainfall during 'near miss' cyclones, and with rainfall depths expected during the passage of a hypothetical tropical cyclone over Auckland.

FIGURE 2: **Isohyets of storm rainfalls over Auckland for 1 hour falls with a return period of 50 years. The data are estimated from all storm rainfall data for a period in excess of 30 years.**

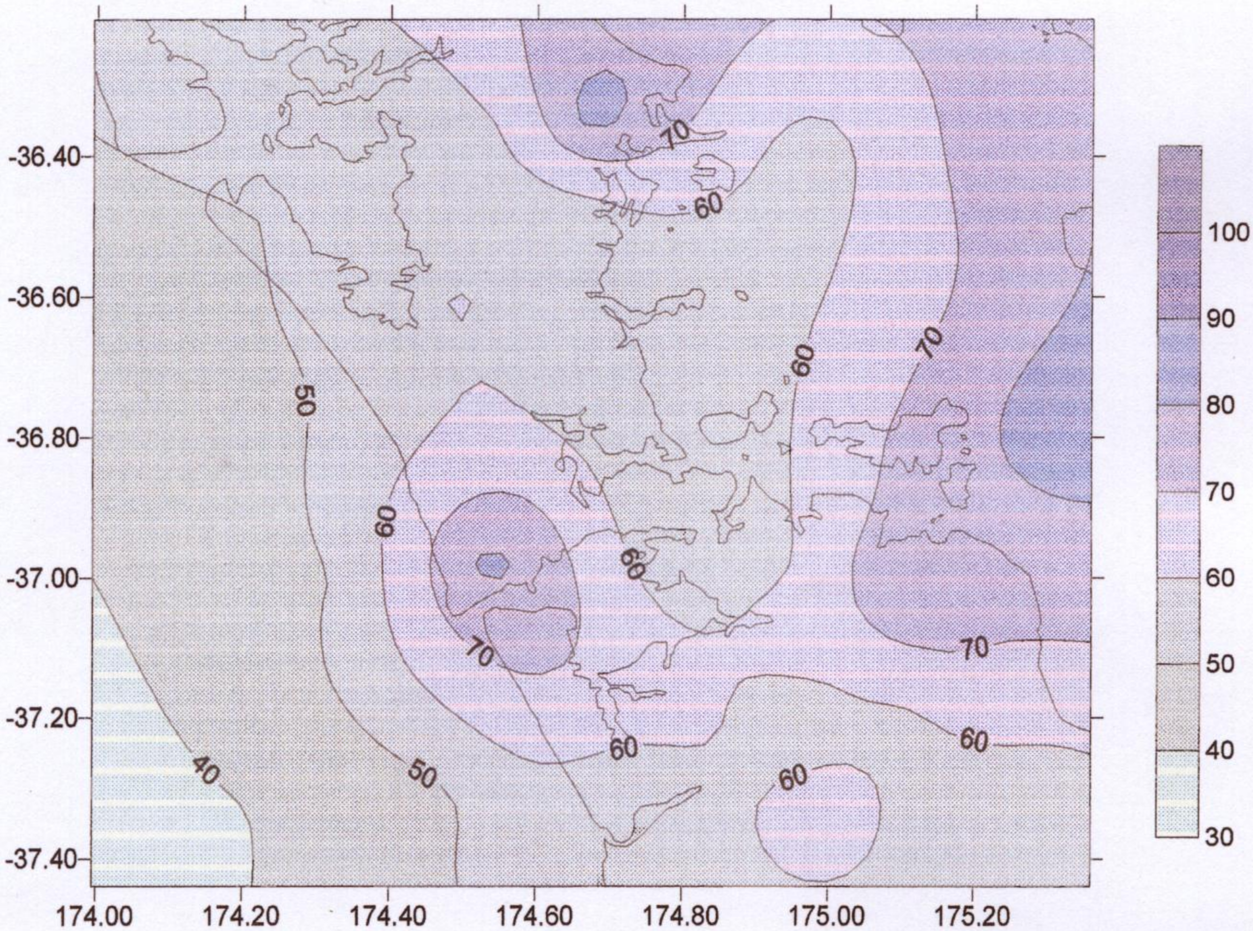


FIGURE 3: **Isohyets of storm rainfalls over Auckland for 1 hour falls with return periods of 100 years. The data re estimated from all storm rainfall data for a period in excess of 30 years.**

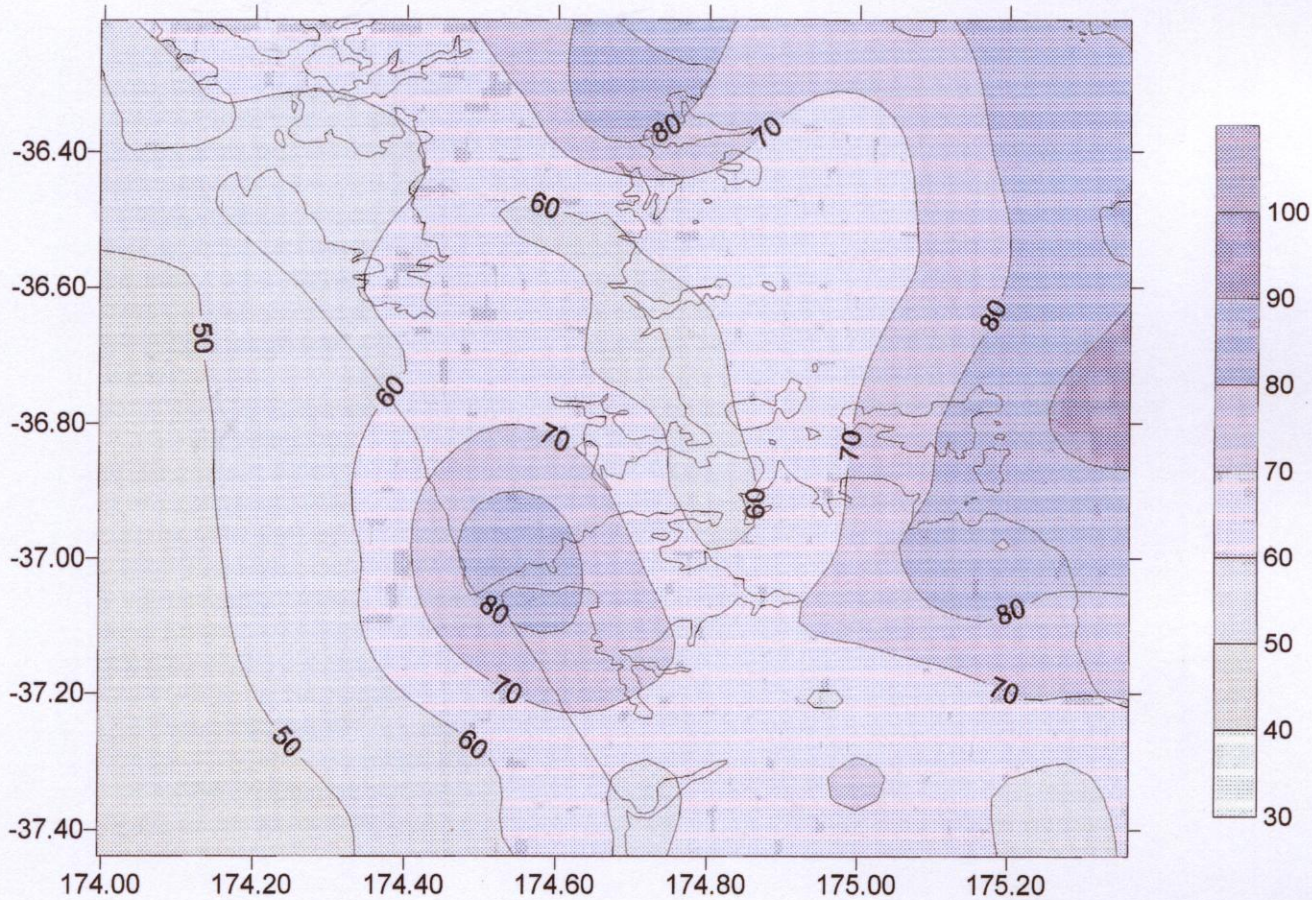


FIGURE 4: **Isohyets of storm rainfalls over Auckland for 3-days falls with return periods of 50 years. The data are estimated from all storm rainfall data for a period in excess of 30 years.**

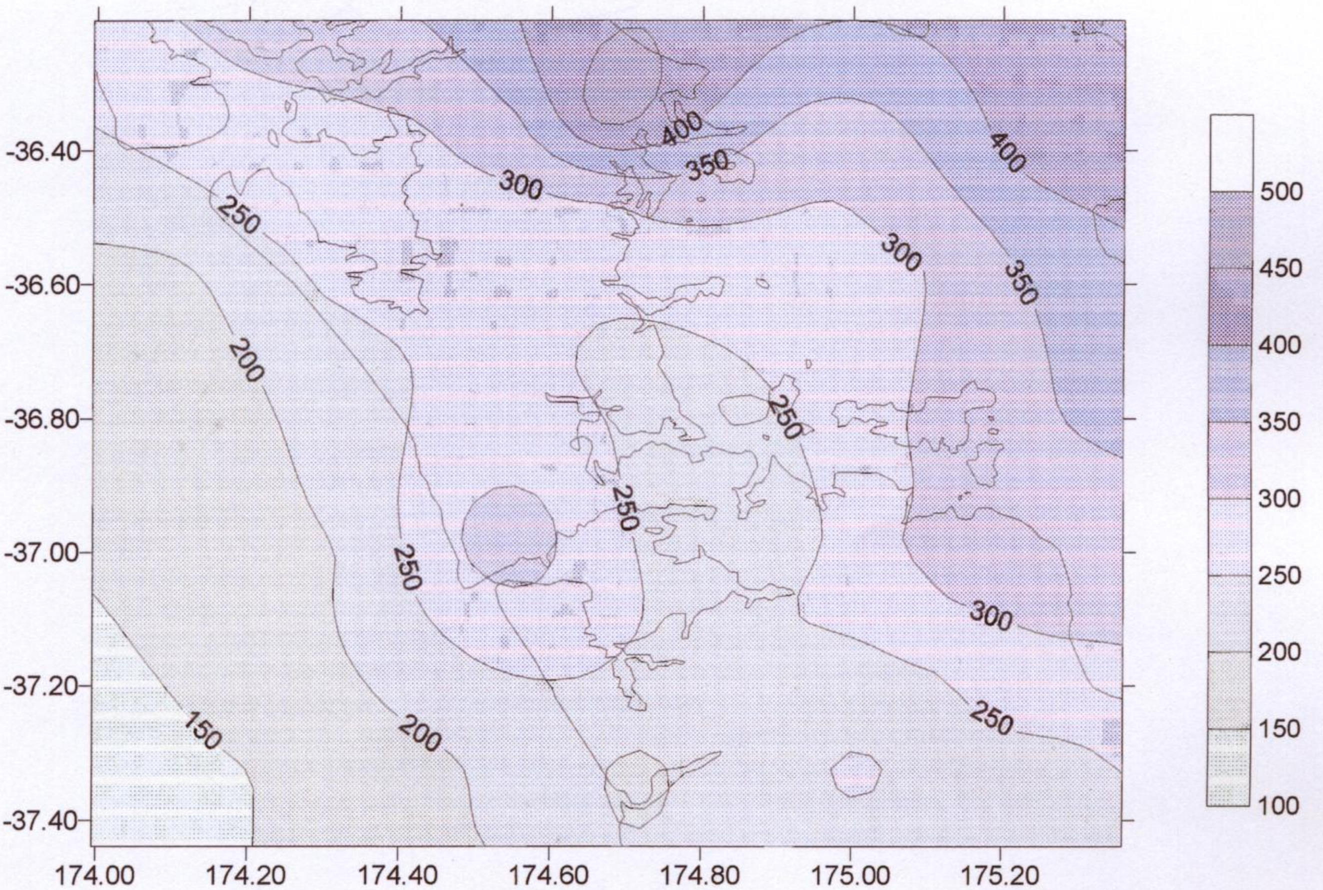
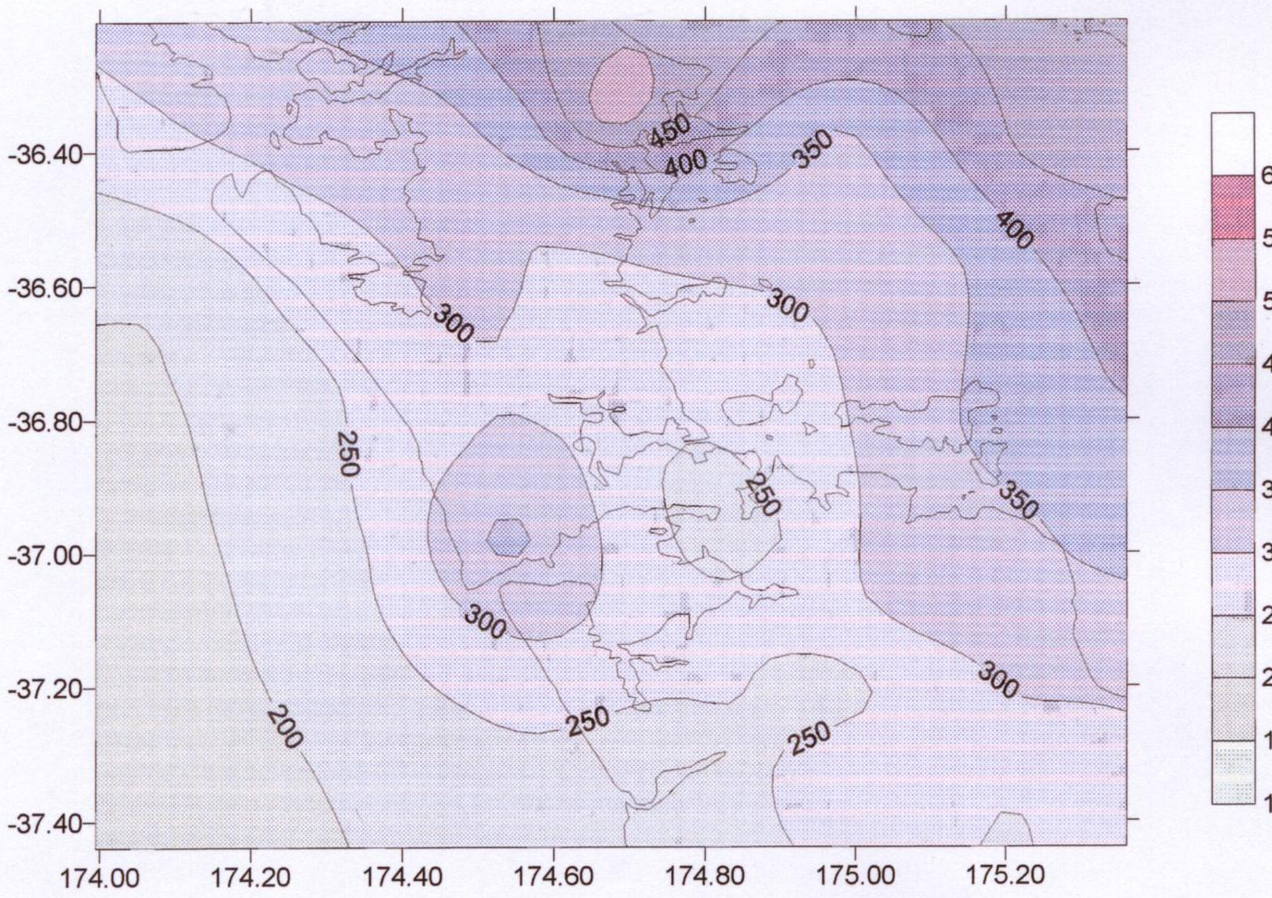


FIGURE 5: **Isohyets of storm rainfalls over Auckland for 3-days falls with return periods of 100 years. The data are estimated from all storm rainfall data for a period in excess of 30 years.**



4.0 TROPICAL CYCLONE 'NEAR MISSES' FOR AUCKLAND

Data gathered during the passage of tropical cyclones near Auckland in the past provides valuable base-line information on the potential wind and rainfall intensities likely to be experienced if a cyclone crosses the city. Three tropical cyclones passed within 220 km of Auckland City between 1970 and 1994 (Figure 6). Two of these, tropical cyclones 'Watorea' and 'Sina' passed to the east of Auckland and brought gale force winds and intense rainfalls to the region. The third cyclone shown, cyclone 'Esau', weakened before crossing the North Island, and was not important. A fourth, well remembered cyclone, 'Bola', (not shown in Figure 6) did not come as close to Auckland as the above 3 cyclones, but also brought extreme weather to the region.

4.1 WATOREA

Tropical cyclone Watorea originated in the Solomon Islands on April 24, 1976 and on April 29 intensified to storm force (48-63 knot winds) as it approached North Cape. The barometric pressure at 9.00 am on April 30 was 991.9 hPa at Whenuapai and 991.5 hPa in Auckland City. Maximum wind gusts of 40 and 44 kts (74 and 82 km/hr) from the west were recorded at the two sites respectively. About 50 mm of rainfall was recorded over the two days.

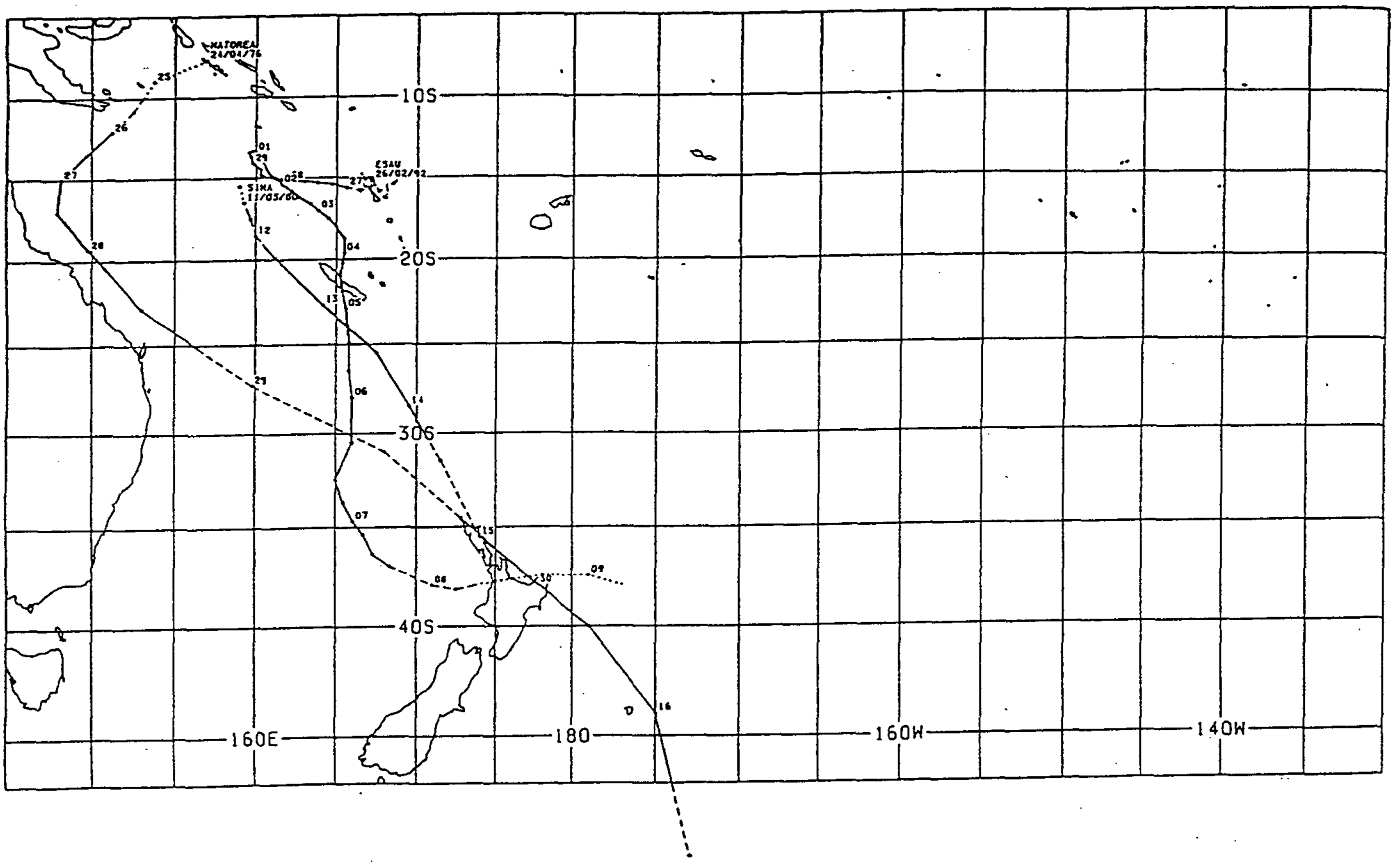
4.2 SINA

A very similar path along Northland's east coastline was followed by cyclone Sina during March 15, 1980. This cyclone carried a lower intensity classification (gale force) with winds speeds in the range of 34-47 kts. However the impacts on Auckland may have been greater, with wind gusts to 57 kts (106 km/hr) from the south, and about 100 mm of rainfall recorded during March 14-15 in the city. About 110 mm of rain was recorded at Whenuapai during the same period. The 9.00 am barometric pressures at Leigh and Auckland were 996.1 and 998.9 hPa respectively.

4.3 BOLA

During March 1988 cyclone Bola passed just to the north of North Cape from the north east, and then proceeded in a southerly direction to the west of the North Island. South easterly wind gusts to 52 kts were recorded in Auckland city on March 8, and to 70 kts at Auckland Airport on the same day. Accumulated rainfall over the wettest three days in Auckland (March 6-8) was 126 mm. The wettest day at Auckland Airport was March 6, with 77 mm of rain.

FIGURE 6: Cyclone Tracks of the Three Tropical Cyclones Since 1970 to Pass Within 220 km of Auckland City. The Progress of Each Cyclone is Shown by the Dates on the Tracks. Intensities are Given as: Heavy Line - Hurricane - (>63 kts); Light Line - Storm (48-63 kts); Dashed Line - Gale (34-47 kts); Dotted Line - Below Gale (< 34 kts).



4.4 COMPARISON WITH 'FERGUS' AND 'DRENA'

Tropical cyclone Fergus impacted Northland and Coromandel, particularly with heavy rainfalls, but its effects were not strongly felt in Auckland. Auckland Airport recorded 41 mm of rainfall during December 30-31, while 52 mm fell in the city. Wind strengths were not particularly high in Auckland, but further south in Hauraki there was damage to buildings and other installations because of wind gusts.

The more recent cyclone, Drena, brought maximum wind gusts of 46 and 50 kts (85 and 93 km/hr) at Auckland Airport on January 10 and 11, although not much rain fell at all. The maximum fall was 21 mm at Coatesville for a 24-hour period. The 9.00 am barometric pressure was 995.3 hPa. Wind gusts of up to 67 kts (124 km/hr) were measured on Mokohinau Island.

4.5 FREQUENCY OF TROPICAL CYCLONES IMPACTING AUCKLAND

Since 1970 four tropical cyclones, Watorea (1976), Sina (1980), Bola (1988) and Drena (1997), have impacted on the Auckland metropolitan area, an average frequency of 1 in 6-7 years.

5.0 A TROPICAL CYCLONE SCENARIO FOR AUCKLAND

This section describes the passage of a hypothetical cyclone, cyclone 'Grief', over the Auckland isthmus. The objective is to describe the weather (wind and rainfall) conditions that might occur in a 100-year cyclone. This task would be straight forward if there were 100 years of cyclone records from which to the worst could simply be drawn. In practice this is not the case. Hence the scenario presented here has to be built from realistic assumptions made from historical weather records, cyclone case studies, and typical cyclone patterns.

In the following text, the daily scenario for each day of a four day cyclone over Auckland is described, with comments for each day included in subsequent paragraphs, following the data tables.

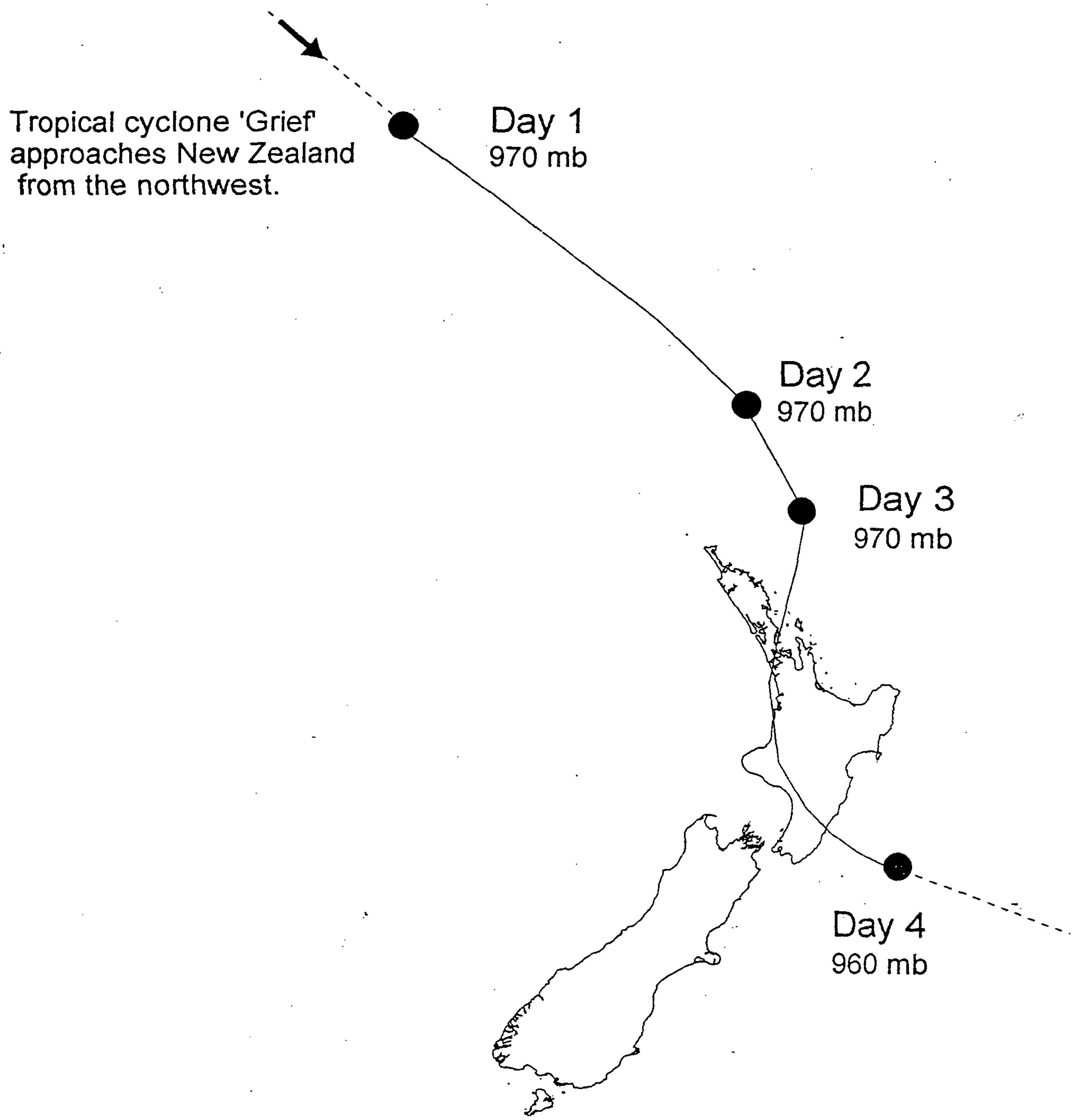
5.1 DAY ONE

Cyclone *Grief*, with a central pressure of about 970 hPa, is centred north west of New Zealand at 30ºS and is moving slowly south-east. A blocking anticyclone lies east of the country centred about 170ºW. Moderate rainfalls have been recorded over much of Northland since the previous day. A front stretches towards the north-east from North Cape, and as it advances down the coast of Northland, heavier rainfall commences over much of northern New Zealand. More than 70 mm of rain is recorded in Auckland overnight, accompanied by moderate to strong north-east winds. Wind gusts up to 30 kts (56 km/hr) are recorded in Auckland City, with gusts to 40 kts recorded at waterfront sites. Barometric pressure at mean sea level starts to drop, reaching about 1005 hPa.

100-year Tropical Cyclone rainfall and wind gust estimates - ***DAY 1***					
	1-hr rainfall (mm)	24-hr rain (mm)	Accum rain* (mm)	Max wind gust (km/hr)	Direction
Warkworth	15	90	110	65	N-NE
Albany	12	80	100	65	N-NE
Auckland City	10	75	90	55	N-NE
Ardmore	10	75	95	58	N-NE
Auckland Airport	3	55	75	50	N-NE
Mokohinau Is	***	***	***	80	N-NE
Waitakere Ranges	15	95	100	70	N-NE
Otara	5	50	65	45	N-NE
Hunua Ranges	15	115	135	75	N-NE
Pukekohe	10	70	75	50	E-NE
Manukau Heads	5	30	30	40	E

* Accumulated rainfall since the storm started, including rainfall the day before Day 1.

FIGURE 7: Track of hypothetical tropical cyclone *Grief*, positioned to provide maximum impact on the Auckland metropolitan region. Estimated mean sea level pressures at the cyclone centre for each day are shown.



Day 1 - Comment

This scenario is similar to the situation on March 6, 1998 when tropical cyclone Bola was centred to the north of the country, although more to the east than the situation suggested here. A moderate pressure gradient of about 5 hPa was present over the north of the North Island. The maximum recorded wind speed in Auckland City was a southerly gust of 28 kts (52 km/hr), and there were 68 mm of rain.

5.2 DAY TWO

Cyclone *Grief* becomes almost stationary to the north of the country due to the intensification of the blocking anticyclone to the south east of New Zealand. The central pressure of the cyclone remains at about 970 hPa, while the mean sea level pressure in Auckland is about 985 hPa, and wind gusts of up to 65 kts (120 km/hr) are recorded several times during the day. Offshore the cyclone is generating sustained (1 minute) wind speeds of up to 75 kts (140 km/hr), gusting to 180 km/hr. Wind gusts of over 70 kts are experienced along the Auckland coastline. Gusts exceed 70 kts (130 km/hr) at Auckland Airport.

Rainfall in Auckland is extremely heavy, with over 125 mm of rainfall during the day and following night.

100-year Tropical Cyclone rainfall and wind gust estimates - ***DAY 2***					
	1-hr rainfall (mm)	24-hr rain (mm)	Accum rain* (mm)	Max wind gust (km/hr)	Direction (deg)
Warkworth	85	170	280	120	E
Albany	75	140	240	125	E
Auckland City	60	125	215	120	E
Ardmore	65	185	280	125	E
Auckland Airport	55	110	185	130	E
Mokohinau Is	***	***	***	180	E
Waitakere Ranges	75	130	230	140	E
Otara	50	120	185	115	E
Hunua Ranges	80	100	235	135	E-NE
Pukekohe	55	90	165	105	E
Manukau Heads	50	65	95	90	E-SE

* Accumulated rainfall since the storm started, including rainfall the day before Day 1.

*** Rainfall estimates for Mokohinau not included.

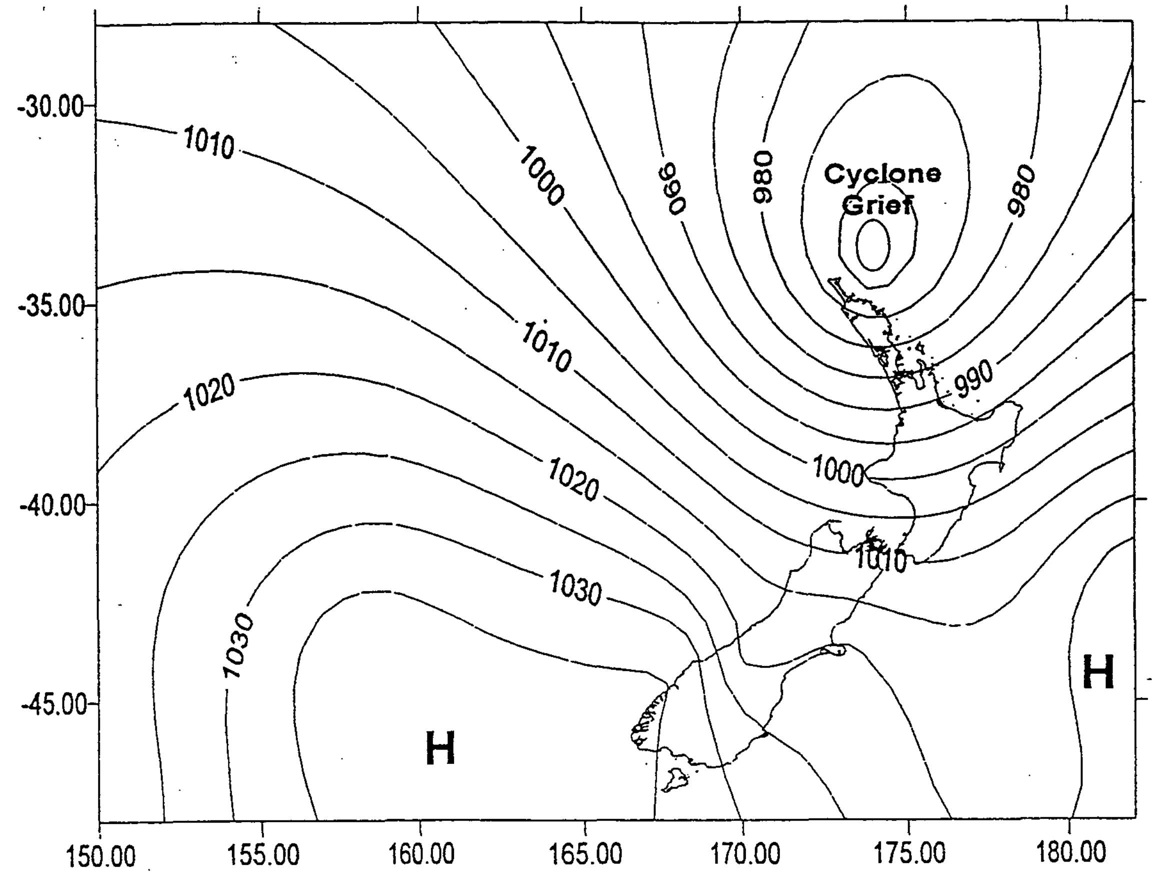


FIGURE 8: Schematic Diagram of the Mean Sea Level Pattern as Cyclone *Grief* Impacts on the Auckland Region

Day 2 - Comment

A mean sea level pressure of 970 hPa is a reasonable pressure to expect at the centre of an intense depression of tropical origin in the New Zealand region (the central pressure of cyclone Bola while off North Cape was lower than 980 hPa), but rare enough to justify its selection as a 100-year event. This pressure has been used to estimate offshore wind speeds for cyclone *Grief*, in the relation $V_m=6.7(1010-p)^{0.644}$, where V_m is the maximum sustained one minute wind speed, and p is the minimum sea level pressure (Atkinson and Holliday 1977[1]). The estimated off-shore gust speed for Mokohinau would be expected to be similar (see table). The highest recorded south easterly gust speed at Auckland Airport is 70 kts (130 km/hr) during cyclone Bola on March 8, 1988, when the cyclone was centred off North Cape. Weather conditions experienced during cyclone Bola have been the most extreme recorded of any tropical cyclone during the last 50 years in the Northland and East Cape regions, but higher winds and more intense rainfalls have been recorded during other types of weather phenomena. Hence it is reasonable to expect a 100 year cyclone to generate stronger wind speeds than cyclone Bola, and for this reason, a maximum gust speed of 135 km/hr has been adopted here.

[1] GD Atkinson and CR Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western north Pacific. *Monthly Weather Review 105*, 421-427.

Maximum wind speeds during tropical storms in the south west Pacific are usually the easterly quarter winds to the south of the centre, and it is this pattern that has been adopted here during day two of the scenario.

5.3 DAY THREE

Cyclone *Grief* moves slowly towards the Northland coast during the day and is north east of Whangarei by late evening. There is a change in the mean wind direction to the south east, and maximum gust speeds ease a little. Rainfall rates are less intense. About 100 mm of rain falls in Auckland during the day, with marginally higher falls in Warkworth and the Waitakeres and Hunuas. Wind gusts exceeding 100 km/hr still batter the city. High winds have been continuing with little respite for 30-35 hours. Mean sea level barometric pressure at Auckland City has been below 980 hPa during the day and down to 970 hPa when the cyclone crosses the Auckland isthmus early next morning.

100-year Tropical Cyclone rainfall and wind gust estimates - ***DAY 3***					
	1-hr rainfall (mm)	24-hr rain (mm)	Accum rain* (mm)	Max wind gust (km/hr)	Direction (deg)
Warkworth	25	120	400	90	SE
Albany	20	65	305	85	SE
Auckland City	45	100	300	100	SE
Ardmore	40	95	375	90	SE
Auckland Airport	35	90	275	105	SE
Mokohinau Is	***	***	***	135	SE
Waitakere Ranges	50	120	350	120	SE
Otara	35	85	270	80	SE
Hunua Ranges	45	110	345	110	E
Pukekohe	25	55	210	85	SE
Manukau Heads	20	85	180	130	S

* Accumulated rainfall since the storm started, including rainfall the day before Day 1.

Day 3 - Comment

The apparent intensity of the cyclone is likely to reduce a little as it moves closer to Auckland City, thus moderating maximum wind speeds to some extent. However heavy rainfall would be likely to continue, particularly in the north of the region. Southern areas of Auckland would receive a little shelter from the Coromandel Ranges. The continuing rainfall would raise 3-day accumulated totals to near or above 300 mm. The scenario 3-day total for Auckland City (300 mm) is higher than the 100 year total estimated in Section 3.2 above because cyclone *Grief* has remained slow moving for two to three days. In the case of Bola, for example, over 300 mm of rainfall was recorded in Whangarei over a three day period at the height of the cyclone, as it slowly approached North Cape from the east, hence similarly high rainfalls would occur in Auckland during cyclone *Grief*. The three day rainfall in Warkworth is likely to be higher due to the orographic effect of the hills behind the town. Similarly rainfall in the Waitakeres would be higher, while the Hunuas would receive some shelter from the Coromandel Ranges.

Mean sea level pressures of below 975 hPa are very rare in Auckland, and the pressure of 970 hPa proposed here would be the lowest recorded by 2-3 hPa. Again, the precedent for this pressure is the central pressure of cyclone Bola, estimated to be less than 980 hPa. A pressure of 973 hPa was recorded at Whenuapai in August 1990.

5.4 DAY FOUR

Cyclone *Grief* crosses the Auckland isthmus during the early morning of day four, and moves away to the south east. The rain eases, and wind speeds drop then build rapidly. From mid-afternoon on day four, the most extreme wind conditions of the four days develop from the south west, with gale force winds lasting for up to12 hours. Wind gusts to 80 kts (150 km/hr) are recorded at Auckland Airport, and wind speeds exceeding 90 kts (168 km/hr) are recorded at Manukau Heads. Rainfall during the day is generally lower than on the previous three days. Mean sea level pressure at Auckland increases from its extreme low to about 990 hPa.

100-year Tropical Cyclone rainfall and wind gust estimates - ***DAY 4***					
	1-hr rainfall (mm)	24-hr rain (mm)	Accum. rain* (mm)	Max wind gust (km/hr)	Direction (deg)
Warkworth	3	15	415	90	W
Albany	3	10	315	70	W
Auckland City	5	20	320	140	SW
Ardmore	5	15	390	145	SW
Auckland Airport	15	25	300	150	SW
Mokohinau Is	***	***	***	110	W
Waitakere Ranges	20	40	390	160	W
Otara	5	25	295	145	SW
Hunua Ranges	5	15	360	85	SW
Pukekohe	5	20	230	145	SW
Manukau Heads	10	50	230	170	SW

* Accumulated rainfall since the storm started, including rainfall the day before Day 1.

Day 4 - Comment

Highest wind gusts over the Auckland region are typically recorded from the south west, and hence - the estimated maximum gust speeds in the scenario for cyclone Grief are predicted to be from this quarter. The highest wind gust recorded at Manukau Heads (see Figure 1) is 110 kts (204 km/hr). This single observation may be correct, but appears to be an outlier compared to the general pattern of wind observations from this and other Auckland sites. In the present scenario, a maximum gust speed of about 170 km/hr (92 kts) is presented as a reasonable expectation during a 100-year cyclone event.

The intensity of the storm on day 4 results from its interaction, as it crosses the isthmus, with a vigorous mid-latitude trough crossing the country from the south west. The resulting cold-cored mid-latitude storm would deepen rapidly as it moves south east, reaching a central pressure of 960 hPa off the Wairarapa coast.

Finally in this scenario *Grief* spends about 2 days just north of Auckland. It should be noted that it is possible, given the right conditions to the south, that such a cyclone could linger for another day before heading south, although we believe that such a situation is unlikely.

6.0 CONCLUDING REMARKS

This study has produced a 100 year return event scenario of a tropical cyclone extreme event. Scenarios provide a plausible description of future events providing certain assumptions hold true. The current cyclone scenario was based on the need to provide impact information as benchmark data for impact studies on the Auckland Engineering Lifelines Project.

Although the study provides scenarios, the assumptions and projections are within the realm of probable climate extremes as they draw on previously archived cyclone data, and from NIWA meteorological data for the Auckland region.

The 100 year cyclone scenario study shows that such an event is likely to produce very high wind gusts, heavy rainfall intensities and low barometric pressure. The maximum wind gusts and rainfall intensities in some areas exceed the 100 year return period value because of the intensity of the cyclone.

FIGURE 9: Accumulated Rainfall at Selected Auckland Sites During the Passage of the Cyclone *Grief*

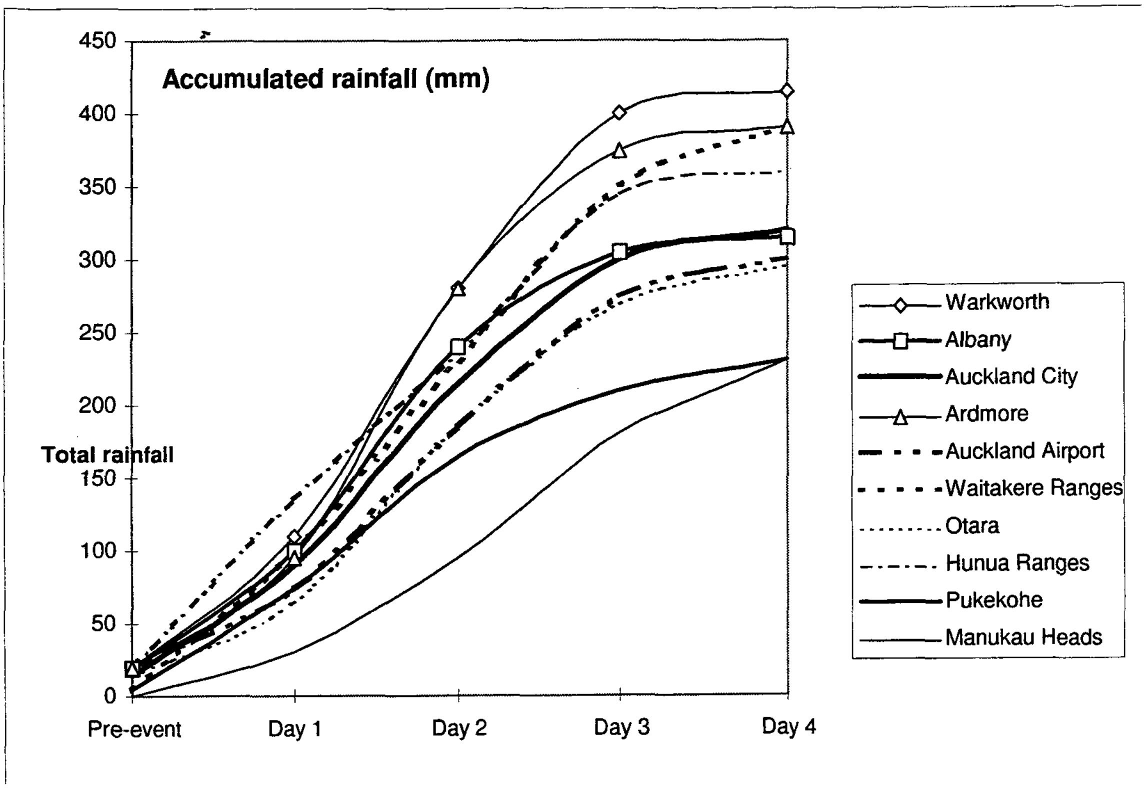
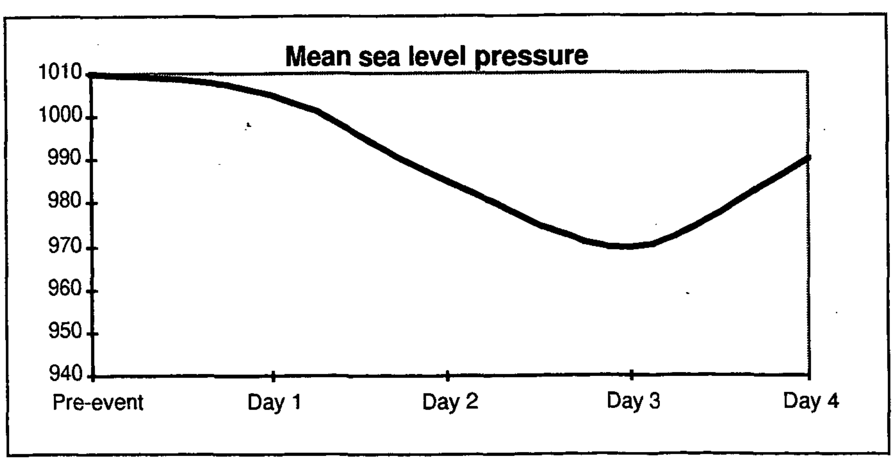


FIGURE 10: Mean Sea Level barometric Pressure at Auckland City During the Passage of the Cyclone *Grief*



REPORT 4.2

RAIN - INDUCED SLOPE INSTABILITY HAZARD MAP (Accompanying Notes)

Prepared for

AUCKLAND REGIONAL COUNCIL

By

BECA CARTER HOLLINGS & FERNER LTD

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CONTENTS

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1.0 INTRODUCTION

The Resource Management Act (1991) designates responsibility for integrated management of the land, natural and physical resources and avoidance or mitigation of natural hazards to Central, Regional and Local Government. As part of the Auckland Regional Council's responsibilities under the Act, a series of studies are being undertaken to assess the potential risks and impacts of cyclone events to the Auckland Region. The current study builds on the slope instability maps presented in ARC Technical Publication No.71 in providing an assessment of the susceptibility of the Auckland Region to heavy rainfall-induced instability.

The objectives of this study are to:

- Identify those areas of the Auckland Region that are potentially susceptible to slope failure in the event of a 100-year cyclone passing through central Auckland. Details of this cyclone scenario are provided by NIWA 1997[1];

- Identify the proportion of slopes likely to be affected by heavy rainfall predicted by this scenario; and

- Assist identification of the vulnerability of services, as part of the next stage of the Auckland Engineering Lifelines Project.

The Rain-Induced Slope Instability Map is prepared at the following scales:

- Region A, areas of medium to high population and services density, 1:100,000;
- Region B, areas of low population and services density, 1:250,000.

For ease of presentation and reproduction, maps accompanying this report are produced at scales of 1:200,000 and 1:500,000 respectively. This report provides background information on rainfall induced slope instability in the Auckland Region, and should be read in conjunction with the maps.

Notice to Reader/User of this Document:

This report is the property of our Client, the Auckland Regional Council, and Beca Carter Hollings & Ferner Ltd. This document discusses ground instability at a regional scale. It is not suitable for a site investigation database and should not be used as such.

Should you be in any doubt as to the applicability of this report or its recommendations and/or encounter materials or conditions that differ from those described herein, it is essential that you discuss these issues with the authors before proceeding with any work based on this document.

[1] *NIWA 1997: Tropical Cyclones in Auckland: A 100-year Extreme Event Scenario. Report prepared for the Auckland Regional Council, February 1997.*

2.0 HISTORICAL RECORDS

2.1 CYCLONE EVENTS THAT HAVE IMPACTED THE AUCKLAND REGION

Tropical cyclones (storms) of the type likely to impact the Auckland Region, form over the South Pacific Ocean. While many remain within this area, a few each year migrate south toward New Zealand. During the migration south, the cyclone changes from a tropical cyclone with a core of warm air to an extra-tropical cyclone with a core of cold air[1]. These extra-tropical cyclones can potentially produce some of the most damaging weather experienced in mid-latitude countries such as New Zealand.

Tropical cyclones which impact New Zealand move generally south and east; once crossing New Zealand, the cyclones tend to be caught up in the westerly circulation of the mid-latitudes, and move rapidly south-east. However, prevailing weather patterns may cause a cyclone to become slow moving to stationary for a period of days (for example, Cyclone Bola became trapped on the East Coast of the North Island).

Three tropical cyclones have passed within 220km of Auckland City between 1970 and 1994. The effects of a further two cyclones were felt in the Auckland Region in late 1996 / early 1997. The characteristics of these storms are summarised in Table 1 together with the 100-year scenario storm event[1]. The limited historical data shown indicate that cyclone events may occur once in 6 or 7 years.

Table 1: RECENT CYCLONES IN THE AUCKLAND REGION

Storm Event	Date	Accumulated Rainfall in 2 days[A] (mm)	Maximum Wind Gust (km/hr)	Direction Day 2
Watorea	30.04.76	50	82	W
Sina	15.03.80	100	106	S
Bola	08.03.88	126 in 3 days (77 in 24hrs)	130	SE
Fergus	30.12.96	52	-	-
Drena	10.01.97	21 in 24hrs	93	-
100 yr Scenario	scenario	185[B] (110 in 24hrs)	180	E

[A] unless otherwise stated
[B] up to 400mm in 3 days and 415mm in 4 days predicted

Articles describing the effects of these cyclones reported in the local and regional newspapers were reviewed. The experience of senior staff was combined with this review to estimate the extent of slope instability caused by these smaller historical events in the Auckland Region. This qualitative estimate provided a check for calibration of the assessment of the amount of rainfall likely to produce erosion or raise groundwater levels sufficiently to initiate slope failure in the scenario event.

2.2 OTHER RECENT HIGH RAINFALL EVENTS

Periods of prolonged rainfall also increase the risk of slope instability in the Auckland Region. Periods of heavy rainfall over a 6 month period (March to June) in 1979 resulted in widespread instability of slopes, with a maximum 24 hour rainfall of 89.5mm recorded on 19.03.79. Rainfall of this magnitude continuing over a 3-day period is comparable to that predicted for parts of Auckland in a 100-year cyclone event.

A higher than usual rainfall over a 5 month period in the winter of 1996 also resulted in a higher than usual frequency of slope failure in the Auckland Region.

2.3 100-YEAR RETURN PERIOD CYCLONE SCENARIO

Rainfalls predicted in the 100-year cyclone scenario developed in the NIWA report[1] are summarised in Table 2.

Table 2: 100-YEAR CYCLONE SCENARIO

Average 24hr Rainfall (mm) [Range of 24hr Rainfall]				Accumulated Rainfall (mm)
Day 1	Day2	Day 3	Day 4	
74 [30-115]	124 [65-185]	93 [55-120]	24 [10-50]	325 [230-415]

3.0 SLOPE INSTABILITY IN THE AUCKLAND REGION

3.1 SOIL AND ROCK TYPES

Much of the Auckland urban area is built on Miocene, Pliocene and Quaternary age sedimentary rocks and soils. Younger basaltic volcanoes have erupted through these rocks, resulting in a wide range of volcanic landforms such as scoria cones, lava fields, explosion craters and tuff rings. The majority of these volcanic deposits rest upon residual and transported soils, rather than rock.

To the west of Auckland City, the hills of the Waitakere Ranges are underlain by volcanic and volcaniclastic rocks (sedimentary rocks derived from eroded Miocene-age volcanoes), and to the east, the hills of the Whitford-Brookby district and the islands of Motutapu, Motuihe, and in part, Waiheke, Kawau, Little Barrier and Great Barrier are underlain by weathered greywacke rocks. To the north, soft sedimentary rocks and hard volcanic rocks support gentle to moderately sloping lowlands and upstanding ranges respectively. Weathering has produced a regolith of soil and slope debris up to 20m to 30m thick.

The Quaternary deposits (Pleistocene and Holocene age, ie <1.6 million years) comprise soils which have been transported into place. Because the Pleistocene deposits (10,000 years to 1.6 million years) are generally considerably older than the Holocene deposits (<10,000 years), and generally occur on higher ground, these materials tend to be stronger, and are often less saturated than the Holocene deposits. However, they are soils (ie much weaker than rock) and do contain some erodible loose sands and sensitive silts.

The Holocene age deposits comprise both sandy coastal deposits and soft clayey estuarine deposits. The soft clayey deposits are generally the weakest materials encountered in the Auckland Region.

3.2 CONDITIONS THAT AFFECT INSTABILITY

Conditions that primarily influence the behaviour of slopes in response to rainfall include:

- geology (interaction of the soil and rock mass, including defects), the degree of weathering of the rock mass, the depth of residual soil, and whether the slope has been subject to past instability or slope modification;
- slope height and angle;
- groundwater level and surface drainage.

3.2.1 Geology

Weathering has produced a thick layer of soil and slope debris up to 20m to 30m thick over most of the older rocks outcropping in the Auckland Region. In rock masses of pre-Pleistocene age, the behaviour of the residual soils and slope debris dominate the response of slopes to rainfall.

(i) **Pre-Pleistocene Age Rock-Masses**. The stability of slopes formed in these materials was analysed using a range of slope heights and slope angles. The sensitivity of the slope to short-term high intensity rainfall events (24 hours) was simulated by modelling a water-filled tension crack, and the sensitivity to longer term high intensity rainfall (more than 3 days) was modelled by adjusting (raising) the groundwater level.

These models also take into account the predisposition of the Pre-Pleistocene rock masses and their residual soil cover to failure along fractures, faults, bedding planes, clay seams, the soil/rock interface, and within the residual soil mantle.

(ii) **Pleistocene Age Sediments**. Pleistocene age sediments are generally of lower permeability and occur in shorter slopes than the older soils and rocks. These materials have typically been subject to slope creep or shallow sliding, where they exist in steeper slopes. Additional wetting of soils exposed in existing slope failure scarps is likely to trigger renewed slope failure.

(iii) **Holocene age Deposits**. These deposits can be broadly divided into sandy coastal deposits and soft clayey estuarine deposits. The high permeability and high friction angle of the sandy materials means that the stability of these soils is unlikely to be influenced by rainfall alone. Because of their location, typically in low lying areas adjacent to swamps and water courses, the soft estuarine sediments tend to be of low permeability and already saturated. This means that these deposits are also unlikely to be affected by a high rainfall event, other than by scour at the base of slopes, caused by raised stream or river flow.

(iv) **Quaternary Volcanics**. The behaviour of young volcanic deposits in slopes is dominated by the underlying materials described above.

Very high rainfall (more than 300mm) over a short period (24 hours) will cause erosion of the surficial residual soils and Quaternary deposits and may cause erosion of the base of slopes adjacent to watercourses with water levels elevated as a result of rainfall and high waves associated with the storm event.

3.2.2 Slope Height and Angle

Lower, flatter slopes will generally be less susceptible to instability than high steep slopes. The weathering products derived from Onerahi Chaos Breccia are typically highly plastic, and although these slopes are generally prone to instability even in gentle slopes (refer ARC Technical Report No.71), storm event rainfall is unlikely to have a significant effect on the stability of these slopes because of the low permeability of these soils.

3.2.3 Groundwater Level

Heavy rain (over a period of several days or weeks) may cause elevation of the groundwater table above the normal range. Raising the water level within a slope reduces the margin of stability[2] of that slope.

2 *Margin of Stability: Refer to Appendix B.*

Cyclonic events typically impact Auckland during the mid to late summer when soils have dried out, tension cracks have opened up, and groundwater levels are at their lowest. Heavy unseasonal rainfall may therefore cause a rapid transition from summer time groundwater levels to winter time levels.

4.0 HAZARD ASSESSMENT

Back-analysis[3] of a series of slopes of different height, slope angle, soil/rock composition and groundwater-level was carried out to provide an assessment of the conditions under which the margin of stability is reduced as a result of rainfall, and the importance of each factor to the margin of stability.

The sensitivity of the slope to short-term high rainfall events (24 hours) was simulated by modelling a water-filled tension crack, and the sensitivity to longer term high rainfall (more than 3 days) was modelled by raising the groundwater level by different amounts for the different slopes analysed.

The rain-induced slope instability hazard assessment for the Auckland Region was then established through preparation of a series of maps of the following conditions:

- slope angle;
- soil/rock mass category; and
- cyclone rainfall scenario.

Categories were developed for each condition, and the categories were then weighted according to their influence on slope stability, as indicated by the back-analyses. The categories established and weighted scores are outlined in the following Sections. These data were superposed to produce Tables 6 and 7 (Section 4) and the hazard maps, Maps 4A (Region A at 1:100,000) and 4B (Region B at 1:250,000) attached.

4.1 SOIL/ROCK MASS CLASSIFICATION

The revised ground shaking hazard map, prepared jointly by BCHF and IGNS, was used as a base plan for the representative soil/rock mass classes for the Auckland Region. This is because both the ground shaking hazard assessment and rain-induced instability hazard are governed by the behaviour of the near-surface soils (top 10-15m).

Residual soils such as those produced by weathering of the Onerahi Chaos Breccia (prone to creep and shallow sliding even on gentle slopes) are generally impervious and plastic, and are therefore likely to behave, in response to short duration heavy rainfall, in a similar way to the clayey soils derived from the Waitemata Group sandstone and mudstone and the Waipapa Group greywacke.

Soil categories developed are described in the Soil Classification Table appended and presented on maps 1A and 1B. Scores were allocated to each class (Table 3) according to the known geotechnical characteristics of that class and their contribution to the margin of stability according to back-analyses. Scores indicate the relative susceptibility of the soils to rain-induced instability, with lower scores indicating higher susceptibility to slope failure. For example, Holocene age Estuarine deposits (Class D) are gauged to be more susceptible than coastal deposits (Class C). Class D soils tend to have the lowest effective strength parameters of the group, whereas Class C deposits are highly permeable and readily take up infiltration water.

3 *Back-analysis starts with a known instability situation (ie gravitational forces just overcoming soil resistance) and works back to assess the relative stability of the same soil or rock slope at different slope angles and groundwater conditions. Refer also to Appendix B..*

Table 3: SOIL CATEGORY CONTRIBUTION		
Soil/Rock Mass	**Class**	**Score**
Residual Soil Overlying Rock	A	0.5
Firm to Stiff Sediment of Pleistocene Age	B	0.4
Coastal Deposits	C	0.8
Estuarine Deposits of Holocene Age	D	0.25

4.2 SLOPE GRADE CLASSIFICATION

Slope angle information was sourced from the New Zealand Land Resource Inventory data licensed to the ARC by Landcare (NZ) Ltd (1:250,000), and was used in conjunction with 20m contour intervals from which slope angles were calculated using the GIS-based ArcInfo system.

Slopes were grouped into the four classes shown in Table 4 and illustrated in Maps 2A and 2B. Relative scores were assigned to each slope category based on the back-analysed behaviour of the soil classes within each slope range. Scores allocated are related to the relative reduction in stability as compared with a slope of 0-7°. For example a very steep slope (Class D) subject to the 100-year cyclone scenario proposed, has a margin of stability four times lower than a gentle slope (Class A).

Table 4: SLOPE GRADE CONTRIBUTION		
Slope Grade	**Class**	**Score**
Gentle (0 - 7°)	A	1.0
Moderately Steep (8 - 15°)	B	0.8
Steep (16-20°)	C	0.5
Very Steep (> 20°)	D	0.25

4.3 CYCLONE SCENARIO

Scores were allocated to rainfall events according to the recorded slope instability generated by historic storms of known rainfall intensity and duration. The scores are relative to a rainfall of <50mm in 24 hours or < 100mm over 3 days. The predicted rainfall for the Auckland Region 100-year cyclone scenario has been grouped into four classes described in Table 5. The distribution of the rainfall classes is shown on Map 3.

Table 5: 100-YEAR CYCLONE 24 HOUR AND 3 DAY RAINFALL CONTRIBUTION			
Rainfall (mm)		**Class**	**Score**
24 hour	**3 day**		
< 50	< 100	A	1.0
50 - 70	100 - 250	B	0.8
70 - 100	250 - 400	C	0.5
> 100	> 400	D	0.4

4.4 HAZARD ASSESSMENT

The combined scores from Tables 3, 4 and 5 are presented as Hazard Scores in Table 6. The allocated scores have been combined digitally for the Auckland Region using the GIS Arcinfo system to produce the Rain Induced Slope Instability Hazard maps (Maps 4A and 4B), which designate zones of low, moderate, moderately high and high hazard, as described in Table 7.

For example, in Table 6, rainfall A (<100mm in 3 days) is likely to have little effect on the pre-existing margin of stability of a slope of soil category A (residual soil overlying rock) and slope category C (16 - 20°), with factor of safety of about 1.5. About 0.5% of all slopes in this category are likely to fail as a result of rainfall of this magnitude. However, if the same soil slope was exposed to a rainfall of 250-400mm in 3 days, the margin of stability is likely to be reduced, causing 5% to 20% of such slopes to fail.

Table 6: HAZARD SCORES

Soil/Slope Category	Rainfall Category			
	A	B	C	D
A/A	0.50	0.40	0.25	0.20
A/B	0.40	0.32	0.20	0.16
A/C	0.25	0.20	0.13	0.10
A/D	0.13	0.10	0.06	0.05
B/A	0.40	0.32	0.20	0.16
B/B	0.32	0.26	0.16	0.13
B/C	0.20	0.16	0.10	0.08
B/D	0.10	0.08	0.05	0.04
C/A	0.80	0.64	0.40	0.32
C/B	0.64	0.51	0.32	0.26
C/C	0.40	0.32	0.20	0.16
C/D	0.20	0.16	0.10	0.08
D/A	0.25	0.20	0.13	0.10
D/B	0.20	0.16	0.10	0.08
D/C	0.13	0.10	0.06	0.05
D/D	0.06	0.05	0.03	0.03

Table 7: INTERPRETATION OF HAZARD SCORE

Hazard Class	Factor of Safety*	Interpretation**	Score
A	≥ 1.5	Low Hazard: 0.5% of slopes fail	≥ 0.2
B	≥ 1.2 - 1.5	Moderate Hazard: 0.5% to 5% of slopes fail	> 0.10 - 0.20
C	≥ 1.1 - 1.2	Moderately High Hazard: 5% to 20% of slopes fail	≥ 0.06 - 0.10
D	1.0 - 1.1	High Hazard: 20% of slopes fail	<0.06

* During or immediately following cyclone. The concept of factor of safety is described in Appendix B.

** Percentages determined from the factor of safety, as described in Appendix B.

4.5 RAIN-INDUCED SLOPE INSTABILITY HAZARD MAPS

The rain-induced slope instability hazard maps designate areas of low, moderate, moderately high and high hazard, corresponding to expected percentages of all slopes within each hazard zone, likely to fail as a result of the proposed 100 year cyclone scenario.

4.5.1 Areas of Medium to High Population and Services Density (Region A)

Map 4A shows that for much of Region A, the 100-year cyclone scenario considered would result in only a low or moderate rain-induced slope instability hazard, that is, the rainfall is considered likely to cause in the order of 0.5% to 5% of slopes in the region to fail. Some moderately high and high hazard zones are indicated, predominantly in higher rainfall areas where steeper slopes occur, such as in valley sides or coastal areas:

- in the southeastern part of the map area (Waitemata Group slopes in the Whitford area and greywacke slopes in the Hunua area);
- in the western part of the map area (volcanic rich rocks in the Waitakere ranges); and
- in coastal slopes.

It is likely that the 100-year cyclone scenario proposed would generate failure of 5% to 20% of these slopes.

4.5.2 Areas of Lower Population and Services Density (Region B)

Map 4B indicates that the likelihood of rain-induced slope failure is higher in Region B than in Region A. In part, this is due to the very high rainfall (in excess of 400mm over 3 days) predicted for areas of steep slopes in the northeast, and relatively steep slopes (for Pleistocene sediments) in the west.

In particular, the 100-year cyclone scenario is likely to cause failure of 5% to 20% of slopes in the following key areas:

- Northeast: Great Barrier and Little Barrier Islands, the Wellsford to Cape Rodney area, and coastal areas of the Tawharanui Peninsula;
- North: Steeper slopes within the Rodney District, including the Kaipara South Peninsula area;
- West: the Waitakere Ranges;
- Southwest: elevated ground south of South Head; and
- Southeast: areas of Waiheke Island, Whitford east to Clevedon and north to Maraetai, and Ararimu east to the Hunua Ranges.

While most of these areas support few critical lifelines, it is noted that Auckland's water supply dams and pipelines occur within the moderately high rain-induced slope instability hazard class.

APPENDIX A: GROUND SHAKING HAZARD ZONES ANDSOIL CLASSIFICATION TABLE

Hazard Zone	Soil Foundation Condition	Soil Category	Engineering Description of Soils/Rock	SPT Blows/300mm (N)	Shear Wave Velocity (m/s)[1]	Typical Ground Failures Resulting From Earthquakes
1	*Residual Soil Overlying Rock*	Residual and colluvial soils, ash and weathered tuff: • up to 30m, overlying greywacke; • up to 20m overlying interbedded sandstone and mudstone; conglomerate and basalt	• CW:[2] sand/silt/clay • HW: gravel in a silty sand/clay matrix • MW: very weak rock • SW-UW: weak to moderately strong rock	5 - 25+ 15 - 50+ 30 - 100+ 50 - 200+	100 - 300 200 - 500 300 - 1000 500 - 2000	• Generally minor to nil damage to gentle slopes; • Movements on critically steep slopes, and on gentle slopes in sandstone and mudstone with clay seams, undercut by streams and coastal erosion.
2	*Firm to Stiff Sediment of Pleistocene age*	• Alluvium; • Basalt, ash and tuff overlying alluvium	• Soft to very stiff alluvium; • Sensitive pumiceous silt; silt, peat and clay; • Loose to dense sand and breccia; • Ash, tuff and basalt overlying these deposits	5 - 25[3]	100 - 300	• Widespread failure of coastal cliffs and river banks; • Movement on moderate to steep slopes; • Localised liquefaction of saturated loose sand lenses in severe[4] shaking
3	*Coastal Deposits*	• Beach and dune sands; • Man-made fills overlying zone 1 or 2 deposits	• Medium dense fine sand and shell, saturated; • Loose fine sand, unsaturated	5 - 40	100 - 500	Localised liquefaction of saturated loose sand pockets
4	*Estuarine Deposits of Holocene age*	• Stream alluvium and swamp deposits; • Man-made fills overlying zone 3 or 4 deposits	Very soft to stiff mud, silt, peat, pumiceous clay; typically saturated	0 - 10	50 - 200	• Widespread sliding failures of moderate slopes; • Widespread liquefaction of saturated sand deposits in moderate shaking

(1) Values of shear wave velocity are assessed

(3) Where basalt rock overlies deep alluvium, the rock stiffness does not significantly influence site behaviour

(4) Shaking levels:
Severe ≥ 0.40g ≥ Strong 0.20g ≥ Moderate 0.15g ≥ Moderate to Low 0.1g ≥ Low 0.05g

(2) Rock Weathering Grades:
CW completely weathered; HW highly weathered (soil)
MW moderately weathered (very weak rock)
SW slightly weathered; UW unweathered (rock)

APPENDIX B: FACTORS OF SAFETY

In slope stability studies, the factor of safety, F is the ratio of resisting forces (shear strength of the soil) to the disturbing forces (gravity). A factor of safety of unity (F = 1.0) indicates that the disturbing forces are equal to the resisting forces an that the soil mass is just on the point of moving, that is, becoming unstable.

Factors of safety of greater than unity (F > 1.0) ae used in engineering design to cover variation and uncertainty in both the properties of materials and the method of calculation. Factors of safety are used in design to provide a **margin of stability** and to limit the risk of failure.

It is important to note that the theoretically calculated factor of safety allows for variations in the soil strength (lower bound of expected values are generally used) and inaccuracies in the method of analysis. In practice, it has been found that on the average, F = 1.0 means that there is a risk of 1:5 that failure will occur in any single year. Table A below shows the average level of risk for different factors of safety used.

Table A: FACTORS OF SAFETY VERSUS RISK LEVEL

Factor of Safety, F	Risk of Failure per Annum
0.8	1:1
1.0	1:5
1.1	1:10
1.2	1:20
1.5	1:200
1.7	1:1,000
2.0	1:10,000

It is noted that in general engineering practise, F = 1.5 is normally used for permanent civil engineering works such as subdivisional slopes, cuts, bridge abutments and road embankments. Other factors of safety are used for more specialised applications. An F = 1.7 has been used in recent years for major earth dams.

A lesser F = 1.2 to 1.3 is normally used for temporary conditions, ie a few weeks to a few months. F = 1.1 is only considered appropriate for earthquake loading.

MAPS

MAP 1A: GROUND SHAKING HAZARD AND SOIL/ROCK MASS DISTRIBUTION: Region A
This is the same as Map 1A, Section 2.1 (Grond Shaking Hazard)

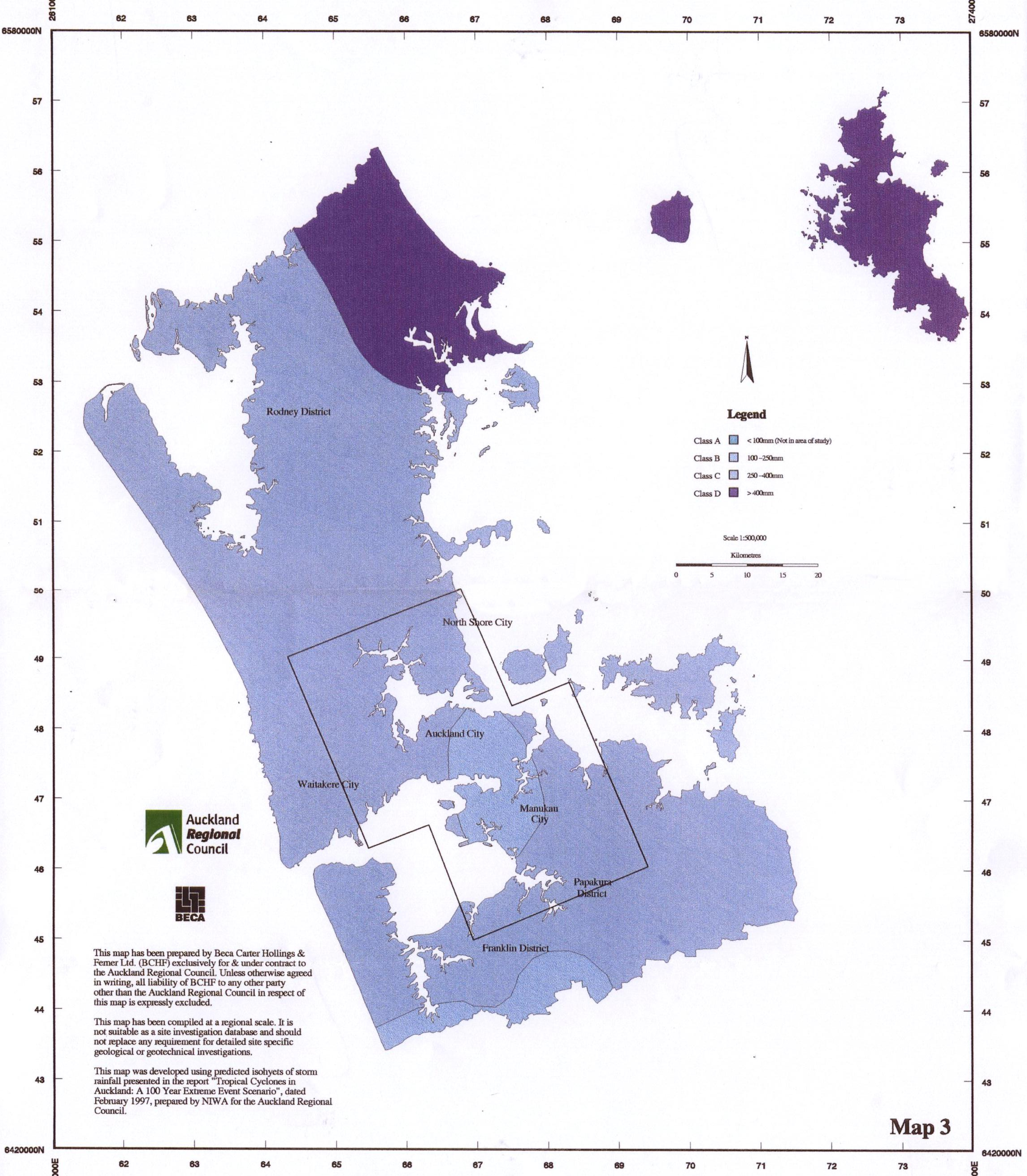
MAP 1B: GROUND SHAKING HAZARD AND SOIL/ROCK MASS DISTRIBUTION: Region B
This is the same as Map1B, Section 2.1 (Ground Shaking Hazard)

MAP 2A: SLOPE GRADE DISTRIBUTION: REGION A
This is the same as Map 2A, Section 2.3 (Earthquake - Induced Slope Instability Hazard)

MAP 2B: SLOPE GRADE DISTRIBUTION: REGION B
This is the same as Map 2B, Section 2.3 (Earthquake - Induced Slope Instability Hazard)

100 Year Cyclone Scenario: Predicted Rainfall Over a Three Day Period

Region A and B

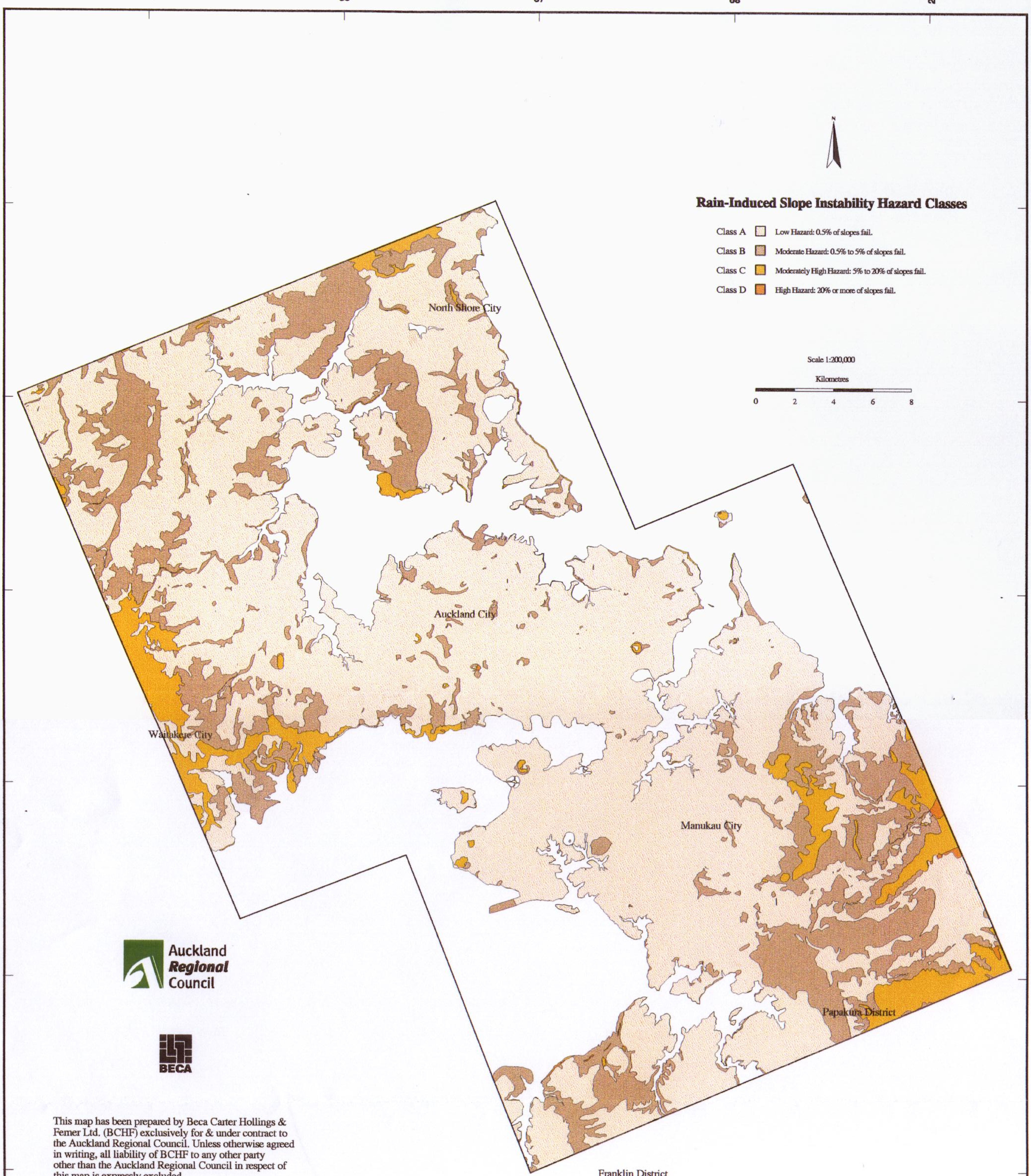


Auckland Engineering Life Lines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Rain Induced Slope Instability Hazard Map

Region A



Auckland Regional Council

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This map has been compiled at a regional scale. It is not suitable as a site investigation database and should not replace any requirement for detailed site specific geological or geotechnical investigations.

This is a compilation of maps 1B, 2B and 3. Source data are referenced on these base maps.

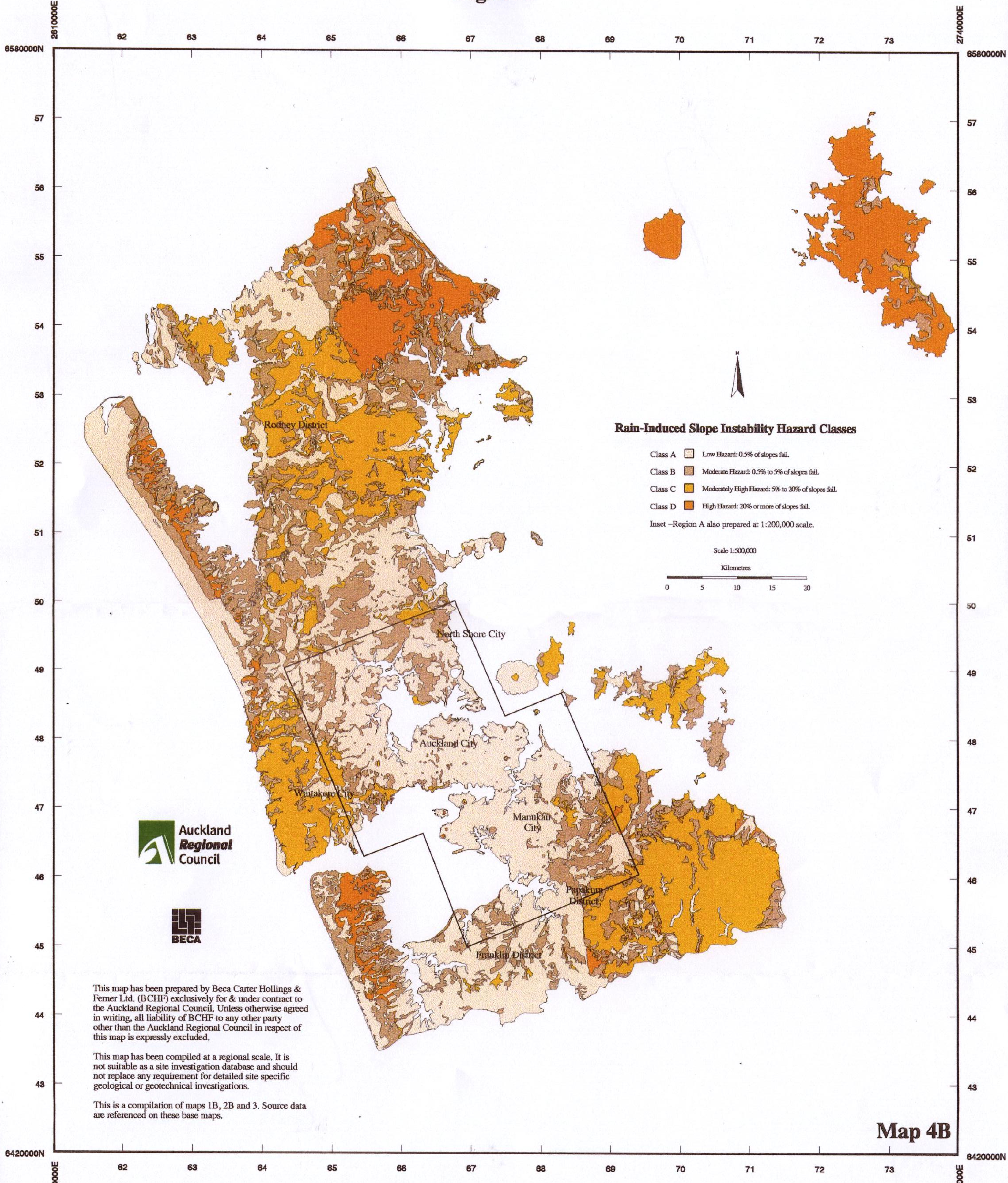
Map 4A

Auckland Engineering Life Lines

This map was prepared as part of the Auckland Engineering Lifelines Project
It accompanies and should be read in conjunction with the
Auckland Engineering Lifelines Project, Stage 1 Report, July 1997.

Rain Induced Slope Instability Hazard Map

Region B



Auckland Engineering Life Lines

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REPORT 4.3

TSUNAMI AND STORM SURGE SCENARIOS FOR THE AUCKLAND REGION

Prepared for

AUCKLAND REGIONAL COUNCIL

By

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March 1997

CONTENTS

1.0 INTRODUCTION

The metropolitan region of Auckland is the largest in New Zealand, with more than one million inhabitants. Auckland occupies the area surrounding the narrow isthmus between the Hauraki Gulf and Manakau Harbour, giving the region a maritime focus. Not surprisingly there is considerable infrastructure located close to the sea, including New Zealand's largest general cargo port, several major marinas (Westpark, Westhaven, Beachhaven, Halfmoon Bay, Gulf Harbour, and Pine Harbour), and recreational beaches and facilities.

This report examines two types of processes that may lead to flooding of coastal regions: tsunamis generated by earthquakes and volcanic eruptions; and storm surges associated with tropical cyclones. The purpose of this report is to present credible scenarios for future events based on historical information and our present understanding of the processes involved.

2.0 TSUNAMI SCENARIOS

Tsunamis are long period gravity waves generated by a sudden displacement of the water surface. The cause of the sudden displacement is normally a submarine earthquake, but may also include volcanic eruptions, submarine landslides, diapiric extrusions[1] and bolide impacts[2] (UNESCO, 1991). All of these source mechanisms produce an impulse that drives the tsunami. Therefore the term tsunami is now confined to long period waves generated by an impulsive source.

This definition excludes meteorological tsunamis generated by coupling with atmospheric disturbances and storm surges generated by low pressure and strong winds: phenomena included in the original Japanese definition of tsunami (Lander et al., 1993).

2.1 TSUNAMI CHARACTERISTICS

Tsunamis are long period shallow water[3] waves with typical periods ranging from 15 to 60 minutes. Due to their long period they behave as shallow water gravity waves. Hence their velocity is solely a function of water depth as given by (Dean and Dalrymple, 1991):

$$C = \sqrt{gh}$$

where C = wave velocity,
g = gravitational acceleration (9.81 $m.s^{-2}$),
and h = water depth.

Clearly the tsunami travels faster in deep water than in shallow water. Consequently a tsunami travelling into shallower water slows down and increases in size. In the deep ocean the maximum height of a tsunami is less than 0.5 m. Tsunamis may be tens of metres in height in shallow water. However, most tsunamis are less than 1 m in height at the shore.

[1] Diapiric intrusion = a body of weak rock, sediment, fluid and gas injected into a fracture or fault. The material may reach the surface to cause mud volcanism.
[2] Bolide = extra-terrestrial object that enters the Earth's atmosphere and survives to strike the surface.
[3] Shallow water wave = wave whose velocity is a function of water depth.

Tsunamis may be assigned a magnitude to define their relative size. Tsunami magnitude is determined from the non-dimensional vertical runup height near (UNESCO, 1991), as given by:

$$m = \log_2\left(\frac{R}{R'}\right)$$

where m = tsunami magnitude,
R = vertical runup height measured near to source (m),
and R' = reference runup height (1 m).

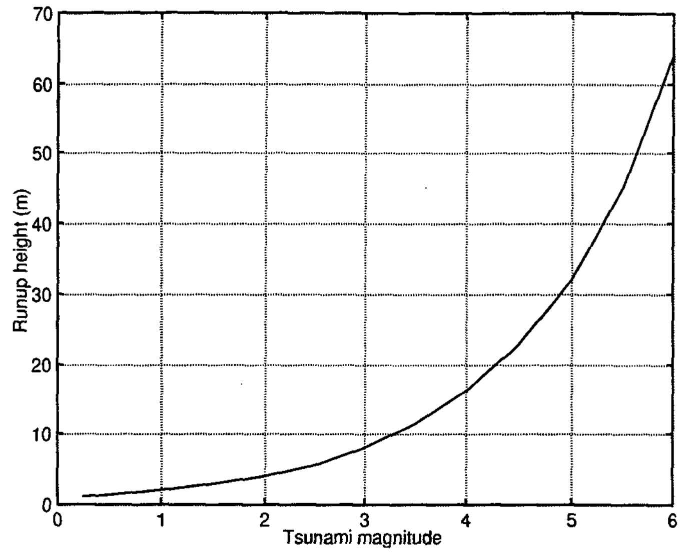

Figure 1: Relationship between tsunami magnitude and the vertical runup at source

Tsunami magnitude is therefore a logarithmic scale (Figure 1) with unequal increases in runup height between steps. Very few historical tsunamis have exceeded magnitude 5 (Lockridge, 1984).

As a tsunami enters shallow water it undergoes shoaling transformations. These can alter its characteristics considerably. For a region such as the inner Hauraki Gulf, the tsunami will tend to develop a narrow peaked crest and a broad shallow trough. This appears at the shore as a short rapid rise in water level followed by a long withdrawal. The tsunami is also refracted and reflected by the bathymetry causing zones of convergence and divergence.

Hence the behaviour of any given tsunami can vary considerably along the coast. The tsunami effects can also differ depending on the tsunami approach direction. This makes it difficult to define tsunami risk for a region. However a number of potential tsunami hazards can be identified for Auckland (de Lange and Hull, 1994):

Tsunami Runup - this may be treated as either the vertical runup height, or the horizontal inland inundation distance (Morgan, 1984). The horizontal inundation distance is a function of the vertical runup and the local topography. Therefore the vertical runup is more useful. Tsunamis crossing a wide continental shelf decompose into a series of solitary waves[4] (Kajiura and Shuto, 1990). On reaching the shore the solitary tsunami waves can behave as either a non-breaking or a breaking wave. Historically all tsunamis affecting the Auckland coast have behaved as a non-breaking wave (de Lange and Healy, 1986). A non-breaking tsunami wave reaches a maximum vertical runup on natural beaches approximately equal to the maximum wave amplitude when the wave first reaches dry land (Shuto, 1967; Synolakis, 1991).

[4] Solitary wave = a non-periodic wave consisting of a single crest.

Tsunami Bores - the most destructive tsunami waves are those that form a bore[5] (Synolakis, 1991; Tsuji et al., 1991; Yeh, 1991) due to the transfer of momentum to the still water trapped in front of the bore. The momentum transfer results in high horizontal and vertical turbulence, and increases the wave height. The vertical turbulence is capable of entraining large objects. Within estuaries and the lower reaches of rivers and streams opposing currents may result in a greater steepness of the wave front and enhance bore formation.

Floating Debris - most fatalities associated with recent tsunamis were due to the impact of floating debris. Studies have demonstrated that debris carried by tsunamis can generate very high impulsive forces (Matsutomi, 1991). Tsunamis may also spread liquid contaminants such as oil (Goto, 1991). The dispersal of contaminants by tsunami waves is of particular concern in port areas, especially regarding the availability of combustible contaminants such as fuel oils, diesel and lighter hydrocarbons and the variety of chemical compounds present, that may cause reactions producing hazardous compounds (Preuss, 1991).

Return Flow and Currents - current velocities generated by receding tsunami waves can be high due to extreme variations in water level. Most drownings associated with tsunamis have been of persons swept into deep water by the return flow. The return flow may also carry floating debris with the same potential for injury and damage as an advancing tsunami bore. The high current velocities make tsunamis very erosive. The velocities are difficult to predict since erosion changes channel characteristics. In confined bays and regions with islands, the interaction of refracted and reflected waves can produce vary complex patterns of currents and waves.

Forced Oscillations - tsunamis may force oscillations within semi-enclosed basins such as estuaries, harbours and the lower reaches of rivers. The forced oscillations may amplify the tsunami and can produce strong reversing currents and eddies within the basins.

2.2 TELETSUNAMI SCENARIO

A teletsunami is a tsunami that travels more than 1000 km from source before reaching the region of interest. The teletsunami scenario is based on historical tsunami impacts around Auckland from the following teletsunamis (de Lange and Healy, 1986):

- Chilean Tsunami 18.5°S 71.0°W 13 August 1868:
- Chilean Tsunami 21.5°S 71.0°W 10 May 1877;
- Chilean Tsunami 41.0°S 73.5°W 22 May 1960; and
- Alaskan Tsunami 61.1°N 147.7°W 28 March 1964.

Some data were also taken from the impacts of the meteorological tsunami generated by the Krakatoa eruption of 27 August 1883. Although not strictly tsunamis, the coastal characteristics and impacts of meteorological tsunamis are the same as true tsunamis.
Additional data were also provided by a simple numerical hydrodynamic model (Black, 1996). The model was not calibrated for tsunami simulation, but the results were consistent with historical data. A short movie of the tsunami response was generated for five consecutive waves with a 1 m height and a 40 minute period. An example of the model output is shown in Figure 2.

[5] Bore = solitary wave in a confined channel or advancing over dry land. It has a steep front face.

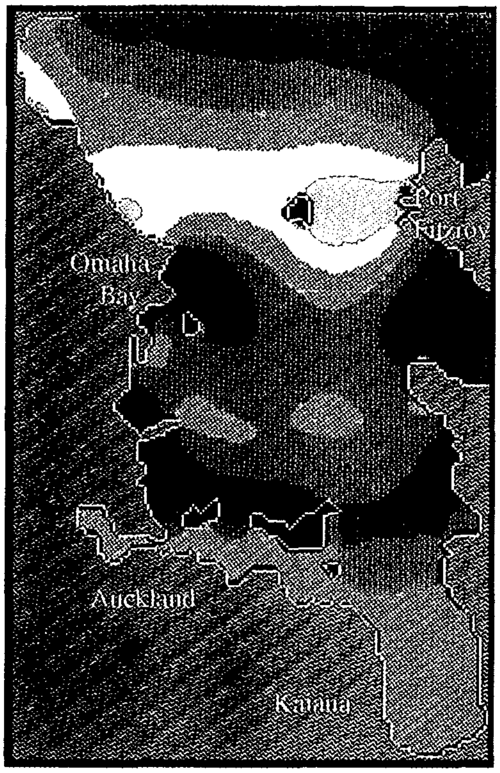

Figure 2: Sea levels during a teletsunami from Chile. Red indicates maximum levels and blue indicates minimum levels. Note that Omaha Bay and Port Fitzroy are 180° out of phase.

The events considered had several features in common, particularly that they generated tsunamis that were easily observed and had periods around 40-45 minutes. There were also major variations in the wave height observed around the Auckland region between these events. The severest impacts were associated with the teletsunami of 13 August 1868, the most northerly of the Chilean tsunamis sourced near Arica close to the Peru-Chile border[1]. The return period for Chilean tsunamis affecting Auckland, similar to those listed above (magnitude 4), is 75 years. Smaller magnitude tsunamis can be expected more frequently (38 years for magnitude 3 tsunamis from Chile).

2.2.1 Scenario 1

Tsunami source region Northern Chile (19°S 71°W)
Earthquake magnitude $M_w = 9$
Tsunami magnitude 4

Chronology

00:00 hours An earthquake occurs near Arica in northern Chile.

00:30 hours Pacific Tsunami Warning Centre issues a Tsunami Alert based on a Mw 9 earthquake located at 19°S 71'W with a focal depth of 15 km.

[1] In 1868 Arica was part of Peru. The border has since moved northwards.

00:45 hours	Pacific Tsunami Warning Centre issues a Tsunami Warning following confirmation of a tsunami from Antafagasta, Chile and La Punta, Peru. National Civil Defence issues a warning with an estimated arrival time for Auckland of 17:30 hours. High-tide is expected at 18:10 hours.
14:30 hours	First tsunami wave reaches the east coast of the Chatham Islands. The estimated wave height is 1.5 m.
15:10 hours	Second tsunami wave reaches the east coast of the Chatham Islands. The estimated wave height is 2.0 m.
15: 50 hours	First tsunami wave reaches East Cape. The height is difficult to assess due to large swells, but thought to be at least 1 m. Third tsunami wave reaches the east coast of the Chatham Islands. The estimated wave height is 1.0 m.
16:00-17:00	Tsunami waves are reported from many eastern coastal regions between North Cape and Stewart Island. Wave heights vary from 0.5 m to 1.5 m.
16:45 hours	Tsunami reported from Port Jackson, Coromandel Peninsula. Wave height is ~1.5 m
17:25 hours	First tsunami wave reported from Auckland. The water level rises rapidly to above high water springs over a 10-15 minute period and remains at that level for several minutes before receding. Wave heights along the open coast of the metropolitan area are very similar (~0.75 m). The maximum wave heights occur in Omaha Bay (>2 m). Port Fitzroy on Great Barrier Island experiences a strong withdrawal of water. A number of tsunami effects are reported over the next 15 minutes:

- Tsunami bores are reported from several locations. The major ones occur on the Mahurangi River (Warkworth) and the Tamaki Estuary. Both are >1 m in height. The Mahurangi River bore reaches the bridge on State Highway 1.
- Strong currents are generated in regions with restricted channels, including the entrances to the estuaries and river mouths (Whangateau Harbour, Puhoi River, Waiwera River, Orewa River, Weiti River), marina entrances, and channels between islands in the Hauraki Gulf.
- Strong eddies and whirlpools form in harbour basins, marinas and several channels between islands. Moorings fail allowing small vessels and boats to drift with the currents.
- The currents associated with the withdrawal of water following the crest cause considerable scour around structures in estuaries and bridge foundations.

17:45 hours	The trough of the tsunami arrives exposing estuary flats and numerous stranded fish. A number of people attempt to collect fish.
18:05 hours	The second and largest tsunami wave arrives.

- Areas exposed by the trough between the waves are rapidly flooded. In the Rangitoto channel the incoming wave is steepened by the receding waters of the first wave. Very strong reversing currents (>5 knots) and eddies form.

- Wave heights along the open coasts of the metropolitan areas are similar (~1.25 m). However due to the interaction between the first and second waves, higher wave heights are experienced in the upper Waitemata Harbour and the Firth of Thames (1.5-2.0 m).

- Tsunami bores are reported on Henderson and Lucas Creeks within the Waitemata Harbour. Further bores occur on the Mahurangi River and Tamaki Estuary (~1.5 m), and on the Waihou, Piako and Kauaeranga Rivers entering the Firth of Thames (1-2 m), and the Wairoa and Weiti Rivers in the inner Hauraki Gulf (~1 m).

- The maximum wave heights are experienced in Omaha Bay (>2.5 m). Large waves are also experienced on Pakiri Beach, the northern shores of Rangitoto, Motutapu and Waiheke Islands (Onetangi Bay), and between Howick and Maraetai (~2.5 m).

- Large waves and very disturbed water occurs between Little Barrier and Great Barrier Islands (>5 m) as the incoming second wave refracts around Great Barrier and collides with the reflected first wave.

18:25 hours Waters recede strongly with levels dropping by 1-2 m below expected tide level over most of the inner Hauraki Gulf. Some areas (Big Omaha Bay, Firth of Thames and Maraetai) experience 2-3 m drops. Strong flows occur in all tidal channels as a result, with some flows exceeding 15 knots in confined areas.

A further 5 waves occur at 40 minute intervals. However the wave heights diminish rapidly and, combined with a falling tide, the shoreline impacts are minor. The waves do generate complex patterns of reversing currents and eddies that cause some problems for navigation. While this occurs on the east coast, the tsunami waves reach the west coast. The waves are considerably smaller. There is some evidence to suggest that the largest waves will be the result of reflection from the Great Barrier Reef. The maximum west coast waves are half the size of those observed in Auckland.

2.3 LOCAL TSUNAMI

Local tsunamis provide less time for a structured response because they are much closer to the areas of concern. Two potential source mechanisms have been identified: seismic tsunamis associated with active faults in the Auckland region; and volcanic tsunamis associated with the Auckland volcanic field.

Another hazard related to seismic activity is the so-called immediate wave[7]. This occurs when there are significant horizontal motions produced by an earthquake. Any area of water partially confined by a barrier can produce an immediate wave. The immediate wave is a surge caused by the barrier pushing against the water. It is most pronounced when the barrier is vertical.

2.3.1 Seismic Tsunami

The local seismic tsunami scenario is based on an earthquake located on the Kerepehi Fault in the Hauraki Gulf. This fault is currently considered to be the submarine fault closest to Auckland likely to be a potential tsunami source (de Lange and Hull, 1994). The southern end of this fault has been active recently. The offshore portion of the fault is considered to have been active during the Holocene.

The maximum credible event is considered to be M_w=6.9 with a return period of 4,500-9,000 years. This corresponds to a surface rupture length of about 25 km, an average fault slip of 2.5 m, a focal depth of 10 km and a fault dip of 60°W. A review of historical tsunamigenic earthquakes suggests that a 10 km focal depth would require a minimum earthquake magnitude of 6.4 (Iida, 1961). Therefore the maximum credible earthquake is sufficiently large and shallow that a tsunami could be generated

Several features of the source area may amplify any tsunami produced:

- The Firth of Thames and Inner Hauraki Gulf has been infilled by a significant thickness of sediment. Unconsolidated sediment may amplify the surface waves of shallow earthquakes leading to the enhanced generation of tsunami waves.

- The source area is confined. The largest tsunami so far this century involved a landslide into a confined water body (a fiord) at Lituya Bay, Alaska (Lander et al., 1993). The confined water body resulted in a larger wave than would have occurred for the same event in open water. The earthquake scenario considered involves the initial displacement of ~5% of the water in the Firth of Thames.

The following scenario assumes an initial disturbance with a wave height of 2.5 m and a period of 20 minutes. The tsunami waves are localised and decay rapidly: most of the impulse energy is transferred to the initial wave; subsequent waves result from readjustments water levels.

2.3.1.1 Seismic Scenario

Tsunami source region	Offshore Kerepehi Fault extension (37° 5'S 175° 26'E)
Earthquake magnitude	M_w = 6.9
Tsunami magnitude	1.3

[7] Immediate wave = surge of water resulting from ground motions due to the inertia of water.

Chronology

00:00 hours	A shallow earthquake occurs on the offshore Kerepehi Fault extension. Shortly afterwards the surface waves are felt at the adjacent coastal centres (Thames, Kaiaua, Te Puru). Immediate waves are generated along the seawalls at Thames, and the coastal road near Kaiaua. A large area of disturbed and discoloured water is seen offshore.
00:15 hours	Tsunami waves 2.5 m high strike the western and eastern shores of the Firth of Thames. A smaller tsunami (1-1.5 m) is seen progressing northwards out of the Firth. Shortly after 1 m high tsunami waves reach the southern shore of the Firth. The waves recede very rapidly (maximum levels are maintained for only a couple of minutes).
00:30 hours	A 1 m high wave travels through the channels between the mainland and the islands north of Ruakura Point (Karamuramu, Pakihi and Ponui Islands). A similar wave enters Manaia and Coromandel Harbours).
00:35 hours	A second set of tsunami waves (~0.75 m) strikes the western and eastern shores of the Firth. The first tsunami wave has reached Pakatoa Island (~0.5 m) and is losing height as it reaches deeper water and speeds up.
00:45 hours	Small tsunamis (~0.5 m) are reported from Maraetai and Omiha. The tsunami is decaying rapidly as it travels through the shallows of Tamaki Strait.
01:00 hours	The tsunami reaches the eastern suburbs of Auckland (~0.25 m). The disturbances have almost ended in the source region.

The impacts of this event are largely confined to the Firth of Thames. Most of the tsunami energy is directed towards the western and eastern shores of the Firth. The waves propagating northwards decay rapidly as they enter deeper water in the Hauraki Gulf, or the shallow waters of Tamaki Strait. The tsunamis generated by small earthquakes are not as stable as the solitons[8] associated with larger earthquakes (teletsunamis).

2.3.2 Volcanic Tsunami

Volcanic activity may generate tsunamis, directly or indirectly, by a number of processes (Latter, 1981). Very few of these are associated with basaltic volcanism as found in the Auckland Volcanic Field. These processes are:

- earthquakes associated with the volcanic activity;
- submarine explosions;
- basal surges; and
- landslides.

The final process is associated with large landslides on the flanks of basaltic shield volcanoes located in deep water. This is not considered a credible process for the Auckland Volcanic Field. The other processes are feasible and have been included in the eruption scenarios developed for the Auckland Volcanic Field (Nairn et al., 1996).

[8] Soliton = very stable wave form that does not dissipate as it travels. Hence it can travel long distances without a significant energy loss.

Shallow seismic activity is a common precursor to volcanic activity and tremors are commonly associated with eruptive events. The magnitudes of both the precursor and co-event earthquakes are normally too low to generate a tsunami. However in confined water bodies shallow earthquakes may generate immediate waves and seiches. These may occur within the Auckland Volcanic Field, but they are likely to be small waves (<0.5 m).

Submarine explosions in shallow water associated with Surtseyan volcanic activity may generate waves. This involves an initial upwards doming of the water surface due to expanding gases and shock-waves resulting from the explosion, followed by the formation of waves as the dome collapses. A sufficient depth of water is required to permit doming (at least the maximum diameter of the dome). This process is very inefficient (Jordaan, 1965). Tsunamis up to 6 m have been attributed to submarine explosions, but these have involved very large volumes of water (~10 km^3) and alternative processes may have been responsible for the tsunamis.
The water depths available in the Auckland Volcanic Field are too shallow to permit the formation of large water domes. It is considered unlikely that tsunamis much larger than 1 m can be generated by this mechanism.

Basal surges are lateral flows often associated with phreatomagmatic eruptions. These flows may entrain the water as they flow over the surface, thereby generating a tsunami. Tsunamis associated with basal surges are highly directional and consist of a single crest. The highest wave is along the direction taken by the basal surge. Except for eruptions at Lake Taal in the Philippines, the tsunamis generated by basal surges have been small (<1 m).

Lake Taal is a confined body of water surrounding Volcano Island which contains the volcanic vent (Moore et al., 1966). Eruptions at Lake Taal have caused large waves up to 5 m in height. It is not clear how these waves formed: possible processes include seiching, submarine explosions, deposition of large volumes of ash within the Lake, and basal surges. These processes are likely to be strongly affected by the configuration of the vent on Volcano Island, Lake Taal and the surrounding highlands (Moore et al., 1966). The volcanic scenarios considered for Auckland do not have similar configurations. Therefore it is not credible to apply the Lake Taal events to the Auckland Volcanic Field.

Volcanoes represent point sources for tsunamis. Therefore the tsunamis are unstable and radially dispersive. Hence they do not travel any great distance (typically <150 km). The tsunamis produced usually only consist of 1 or 2 crests per impulse (volcanic event generating a wave), and they have shorter periods than teletsunamis.

The following scenario is a modification of the volcanic scenario 1 eruption (Nairn et al., 1996). Only the changes are listed here. Note that the volcano scenario report expresses the size of the waves as the amplitude. This report uses wave height, which is roughly twice the amplitude for nearly symmetrical waves. Restrictions on the maximum size of the waves occur due to the shallow water that limits the size of explosion and gas domes, and the small volume of water directly affected by the eruption.

2.3.2.1 Volcanic Scenario

Tsunami source region	Offshore in Rangitoto Channel (36° 48'S 174° 49'E)
Magma type	Basalt
Underlying country rock	Sea floor sediments over Waitemata Group
Erupted volumes	Tephra - 107 m3; lava - 108 m3
Water depth	≤20 m
Tsunami magnitude	<1

Chronology

Day 26 (0) **Eruption Day**

06:00 hours Ground shaking intensifies causing a series of immediate waves to be generated at the Takapuna-Devonport shoreline, particularly near seawalls. Maximum wave heights are ~1 m. Small waves (~0.25 m) are generated close to the vent location by the earthquakes and disturbance of the sea floor sediments.

07:00 hours Small surge waves form as the sea floor domes upward, uplifting estuaries on the western side of the Takapuna-Devonport peninsula and tidal creeks along the east coast bays (Milford). Up-doming of the sea surface by gas emissions create a number of small waves (~0.5 m) that dissipate rapidly as they leave the source area (most are not detectable at the shore).

07:45 hours Initial blasts associated with the subaerial eruption generate small waves (~1 m). These rapidly disperse as they leave the vicinity of the vent. Maximum wave heights along the Takapuna-Devonport shore are ~1 m.

08:30 hours Surtseyan eruptions generate a series of waves varying in height. The largest waves are <1 m in height. Some waves reach the Tamaki estuary and enter the Waitemata Harbour.

09:00 hours Base-surges during the most violent phase of the eruption produce highly directional tsunamis with wave heights up to 2.5 m. There is little dissipation of these waves in the direction of the basal surges. Along the Takapuna-Devonport shore these waves arrive shortly after the generating basal surges. To the south the waves out-distance the basal surge and reach the Mission Bay-St Heliers shore with wave heights of 1.5-2.0 m.

3.0 STORM SURGE SCENARIOS

Storm surges are produced by the combination of two processes: adjustment of mean water level caused by changes in atmospheric pressure; and movement of water over the continental shelf due to stress exerted by winds (Dean and Dalrymple, 1991). The response of mean sea level to pressure changes is relatively slow, taking about 2-12 hours. The response to wind stress is faster. Pressure changes affect large areas fairly uniformly, but wind stress effects vary with water depth.
Atmospheric pressure affects the position of mean sea level through the inverse barometric effect.

Theoretically the inverse barometric effect predicts that sea level will *rise* by about 10 mm in response to a 1 hPa (1 mb) pressure *drop*. In practice the observed inverse barometric effect can vary. The variation of the inverse barometric effect is not well defined for New Zealand due to a shortage of open coast water level measurements. Measurements within harbours are influenced by changes to tidal waves and storm surges as they travel through the confines of the harbour entrance and shallows within the harbour. The barometric pressure factor is 9.5 $mm.hPa^{-1}$ for the Port of Auckland (Hannah, 1990).

The influence of wind stress is harder to predict than that of pressure mainly because secondary forces are involved. The simplest case is of an onshore wind blowing at right angles to the shore. This wind pushes the continental shelf water towards the shore, causing an increase in sea level. The sea level rise continues until sufficient pressure is created to drive a return flow along the sea bed.

Friction between the sea bed and the current reduces the current speed, resulting in a higher water level at the coast. Winds blowing parallel to the coast may also generate a rise in sea level. Due to the rotation of the Earth, objects moving across the surface without friction appear to be deflected from their paths (the Coriolis Effect). For New Zealand the deflection is towards the left of the travel direction.

A rough guide for New Zealand is that the storm surge is approximately twice the inverse barometric response assuming a barometric factor of 10 $mm.hPa^{-1}$.

One of the hazards associated with storm surges is the flooding of low lying coastal land. The other main hazards associated with storm surges are the increased penetration of storm waves, and increased shoreline erosion.

Due to the salinity of sea water, flooding by storm surges can be more damaging than a river flood. Historical storm surges in New Zealand have not produced extensive flooding, except for the Hauraki Plains. A storm surge in 1938 flooded about 35,000 ha, extending inland as far as Ngatea, 7.5 km from the coast (Ray and Palmer, 1993). The total elevation including tide, storm surge and wave set-up was ~3.0 m above mean sea level. Following the 1938 storm surge, stop banks were constructed around the southern Firth of Thames coast.

The storms generating the surges often also produce heavy rainfall. A storm surge can impede the discharge of runoff from natural channels and drainage networks, thereby exacerbating the flood hazard inland. This effect is important where the head in the channels or pipes is insufficient to overcome the head due to the storm surge.

Large wind-generated waves can approach more closely before breaking due to the increased water depth near to shore associated with storm surges. Depending on the nature of the coast, it is possible for the wave to break inland of the mean sea level position.

Apart from the damage caused by the direct impact of the waves and the wetting of objects in the splash zone, the increased wave turbulence will erode loose sediments across a greater width of the beach than normal. Due to the increased water level at the shoreline, a near bed return flow is generated which transports any suspended sediment offshore. The strength of the return current is directly proportional to the increase in water elevation at the shore. Hence large storm surges will transport material offshore faster and further than small surges.

3.1 PREDICTING STORM SURGE

Prediction of the storm surge elevation requires assessment of the two components: the inverse barometric effect; and the wind stress effect. The inverse barometric effect is given by:

$$\eta_p = B_F(1014 - p)$$

where η_p = inverse barometric effect,
B_F = barometric factor (0.01 $m.hPa^{-1}$),
and p = atmospheric pressure.

The Tropical Cyclone scenario developed for the Lifelines Project considers a cyclone with a 1% annual probability of exceedence, Cyclone *Grief* (Salinger et al., 1997). Cyclone *Grief* is closest to Auckland during days 2 and 3 of the scenario. The regional pressure is ~970 hPa, which corresponds to an inverse barometric response of 0.44 m. Therefore the regional storm surge is likely to be ~0.9 m

assuming the regional response is double the inverse barometric effect. This is within the upper limit of storm surge expected for New Zealand based on historical data (de Lange, 1996).

Appendix 1 summarises a more rigorous approach to predicting the storm surge without recourse to numerical modelling. Applying this method to the Cyclone Grief scenario produces a range of heights for the wind stress surge component depending on the chosen shelf width (Figure 3).

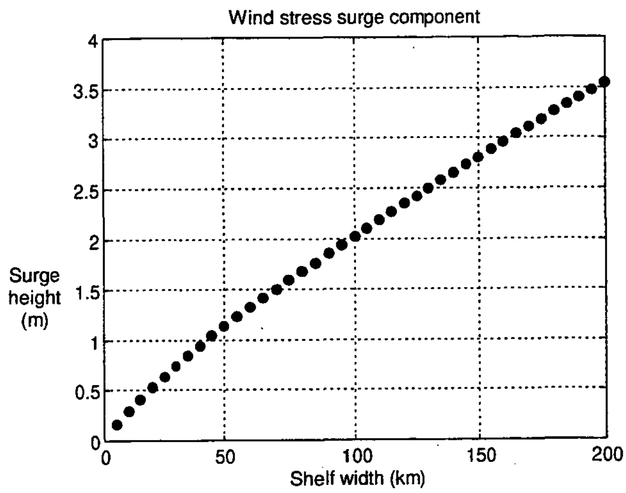

Figure 3: Wind stress surge component predicted for Cyclone *Grief* with a range of continental shelf widths

The difficulty with applying these results to the Hauraki Gulf is deciding which shelf width is appropriate. This arises because the Gulf cannot be treated as an unconfined continental shelf, which is a basic assumption in the method employed. The narrow width of the Gulf will restrict the development of a storm surge, so the actual surge will be less than predicted by Figure 3.

An alternative approach is to undertake numerical modelling of the hydrodynamics of the Hauraki Gulf. Simulations undertaken by NIWA indicate that the wind speed at the Mokohinau Islands is the best predictor of the wind stress component of the storm surge (Black et al., 1996). They also indicate that high wind speeds in the outer Hauraki Gulf are the only precursor necessary for the generation of a large surge in the inner Gulf and the Firth of Thames. A general pattern wind-induced circulation is associated with strong winds from the north-east quarter (Figure 4).

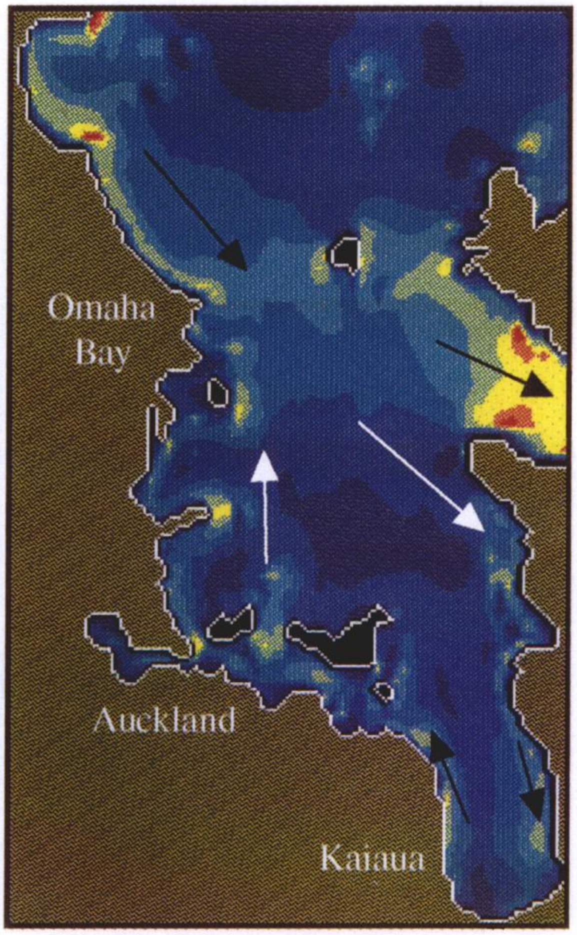

Figure 4: Currents Produced by Strong North-Easterly Winds in the Outer Hauraki Gulf. Brighter colours correspond to stronger currents

This circulation pattern has three main components:

- A strong flow along Pakiri Beach that flows eastwards from Cape Rodney towards the Colville Channel. Initially most of the water then flows southwards along the west coast of the Coromandel Peninsula. However after several hours, when sufficient head exists in the Firth of Thames, most flows through the Colville Channel;
- A gyre in the Firth of Thames where water flows south along the Coromandel Peninsula and north along the Miranda-Kaiaua coast, before entering the Tamaki Strait. The water eventually flows northward, through channels between the islands, to link with the eastward flow near Kawau Island. This circulation weakens as the storm continues and water levels rise in the southern Firth of Thames; and
- Eventually a second gyre develops in the inner Hauraki Gulf, with a westward flow from Colville towards the Whangaparaoa Peninsula. Once this gyre develops the water levels are reasonable stable, although there is an east-west oscillation of the maximum water level in the Firth of Thames.

The numerical model has not been calibrated for storm surge modelling, but it has been shown to predict tidal circulation correctly (Black et al., 1996). Comparison with the storm surge of 14 July 1995 also indicates that the modelling predicts the correct distribution of surge elevations around the Hauraki Gulf (Figure 5).

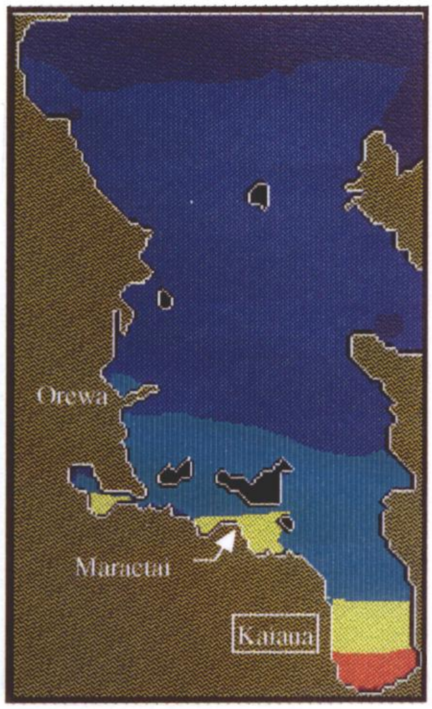

Figure 5: Storm Surge Elevations. Red Indicates the Maximum Rise.

Without a simple method of predicting the wind stress component of the storm surge, a value of 0.90 m will be assumed for the total storm surge.

The maximum elevation reached by the storm surge depends on several other factors (de Lange, 1996). The most important is the tidal elevation, followed by seasonal steric effects[2]. Mean sea level at Auckland varies in response to mean air temperature by 46.3 mm.°C^{-1} (Hannah, 1990).

For the scenario the cyclone is assumed to occur following at least 1 year of La Niña conditions and when sea surface temperatures are reasonably high (late Summer). The storm surge maximum coincides with a perigean spring tide[3] close to perihelion[4] (maximum tidal range for the year). Under these conditions the maximum water level reached will be ~4.8 m above chart datum (1.1 m above the expected tide level). The water level will rise further in the presence of waves due to wave set-up and wave runup. The storm surge peaks early on day four of the scenario.

3.2 STORM SURGE SCENARIO

Atmospheric pressure	970 hPa	(0.44 m)
Sustained wind speed	75 knots	(0.46 m)
High tide elevation	3.7 m	
Mean sea level variation	0.2 m	
Maximum surge elevation	4.8 m above chart datum	

[2] Steric effects = changes in sea level due to changes in the temperature and salinity of sea water. These alter the density of the water, and hence the volume occupied.
[3] Perigean spring tide = occurs when the Earth is closest to the Moon, and therefor lunar tide generating forces are at a maximum.
[4] Perihelion = time of Earth's closest approach to the Sun.

Chronology

Day two	The storm surge develops as the storm approaches Auckland. Swell waves preceding the storm arrive in the Hauraki Gulf.
11:15 am	The high tide coincides with a surge of 0.60 m giving a maximum water level of 4.4 m above chart datum. Large swells (~1 m) cause some spray to cross Tamaki Drive. Occasional waves cross the main road at Maraetai and flood sections of the coastal road between Kaiaua and Miranda. The seawall at Moanataiari, Thames, is reinforced by sand bags. Some water enters the subdivision but the additional pumps installed earlier in the day remove it easily.
11:45 pm	The highest tide of the day and the maximum elevation at high tide is 4.5 m above chart datum. Heavy rain contributes to water levels in natural channels and drains entering the harbour. Some flooding occurs along Tamaki Drive and the Mission Bay to St Heliers coast, as well as at Maraetai, Kawakawa Bay, Kaiaua, Waitakaruru, and Moanataiari due to the heavy rain and sea waves generated by the storm.
Day three	The storm surge continues to develop. The waves generated by the storm increase in size reaching a significant wave height of 8 m in the outer Gulf. North Shore beaches are experiencing 1.5 m swells. The combination of wind and waves breaks moorings at a number of locations. Significant erosion occurs at all open coast beaches. Losses are most pronounced for beaches facing north-east including Omaha, Wenderholm, Waiwera, Orewa, Stanmore Bay, Long Bay, and the beaches of the North Shore.
12.15 pm	High tide is associated with a maximum elevation of 4.6 m. Wave heights decrease as the wind swings to the south-east, but they also become steeper and more erosive due to the opposing wind. Sea conditions are very confused. Spray affects most low coastal roads on exposed coasts. Flooding occurs in the same areas as before. The seawall at Moanataiari fails. The coastal road from Maraetai to Miranda is blocked by flood waters at numerous points. Erosion has undermined the road at some locations.
Day four	The storm surge peaks as the storm crosses the Auckland isthmus and wind directions change.
00:45 am	The maximum water level is 4.8 m above chart datum. With the change in wind direction the waves decrease in size. Different beaches are now facing directly into the storm waves. The northern inner harbour beaches now experience high water levels and large (~1 m) waves. The Coromandel coast between Tararu and Kereta is subjected to large waves (~2 m) which undermine provincial state highway 25. Moanataiari is flooded. Flooding also occurs at Kaiaua, Kawakawa Bay, Maraetai, between Mission Bay and Maraetai and St Mary's Bay. The storm surge on the east coast dissipates. However the strong south-west winds and low pressure develop a 0.60 m storm surge in the Manakau Harbour. The winds also generate large sea waves within the Manakau Harbour and offshore.

4.0 HAZARD MATRIX

The effects of these four scenarios has been summarised in Appendix 2 as a hazard matrix. The matrix divides the coastline of the Auckland Regional Council region into sections. Some of the sections are further divided into subsections (locations in italics) where there may an increased hazard or risk.

The risk has been assessed for each section and subsection for each of the 4 scenarios outlined above. The risk is expressed in a 'code' defined below.

Firstly there are several categories of hazard or potential risk:

- **C = Coastal erosion.** This includes the erosion and deposition of sediment along the coast, near tidal channels, and near coastal structures. The deposition of sediment in a marina entrance is considered as significant as erosion of sand from a beach.
- **E = Economic impacts.** These include damage to property and clean up costs. Due to the nature of the phenomenon considered, these effects are restricted to the coast. There are many different problems in this category. They include:
    - Removal of debris deposited on roads, reserves and coastal property
    - Damage to wharves, outfalls, stormwater drains, and other coastal structures
    - Damage to submarine cables
    - Salt water damage to flooded property
    - Damage caused by fire and impact by floating debris
- **P = Persons at risk of injury and death.** Most of the scenarios have sufficient lead time to allow for evacuation, or for warnings to be issued. However historical data indicate that there is a risk due to sightseers, persons harvesting seafood during water withdrawals, and persons attempting to rescue property. For the local tsunami scenario there may not be sufficient time for warnings to be issued and there is a risk of death and injury due to impact by floating debris, heart attacks and drowning.
- **S = Threat to shipping.** This considers vessels in transit, at moorings, or tied up at wharves, and includes small craft. Tsunamis produce strong currents that can make small craft unmanageable. The same currents can break mooring ropes. Similarly the large waves associated with many storm surges can affect small craft and break moorings. Most damage results from collisions and vessels being swept onshore.
- **T = Threat to land transport.** This considers problems affecting coastal land transport. It includes flooding of coastal roads and rail-lines, and damage to bridges, causeways and roads and rail-lines. Tsunamis in New Zealand have caused considerable damage to coastal bridges in particular. Tsunami bores can remove the bridge decking, and the strong currents can scour away bridge approaches. Coastal erosion may damage coastal roads, making them unusable or unsafe.

Each of these categories of hazard or potential risk are ranked as follows:

- 1 = high probability and/or severe impact potential.
- 2 = moderate and/or moderate impact potential.
- 3 = low and/or low impact potential

Note that this ranking considers both the probability of occurrence and potential impact if an event occurs. Hence a low probability problem that has a severe impact has a high ranking.

5.0 CONCLUDING COMMENTS

The scenarios presented above are fairly similar in that all involve a similar increase in mean sea level and consequential flooding. However the scenarios do differ due to the varying time scales of the events: local tsunamis and immediate waves or surges have short time scales; teletsunamis have periods of 40-60 minutes; and storm surges have durations of 6 hours to several days. This variation in time scale is largely responsible for the variation of impacts.

Although wind-generated waves have only been mentioned accompanying the storm surge scenario, these are also present during tsunami events. The presence of large swell or sea waves during a tsunami will increase the probability of flooding. A worst case scenario would involve a tsunami event during a tropical cyclone. This has occurred once in New Zealand since 1840.
Considering the scenarios in isolation the following points can be made:

- The most hazardous event is a magnitude 4+ teletsunami from Chile. These have a return period of ~75 years. There is no reason to expect annual variations in probability so this equates to an annual probability of exceedence of 1.33%.

- The most likely event is a storm surge associated with a tropical cyclone. Although the scenario presented is for a 1 in 100 year event, the scenarios for similar storms whose centres do not cross Auckland are not too different. These storms have return periods of 6-7 years. Their annual probabilities vary due to the ENSO phenomenon so it is difficult to define an appropriate annual probability of exceedence.

- Currently sea level is rising at the Port of Auckland by 1.3 ± 0.1 mm.y^{-1}. This will affect the tsunami and storm surge risk over time.

APPENDIX 1: PREDICTING STORM SURGE

There are various relationships available to predict the wind stress component. As the winds in the Tropical Cyclone scenario approach the shoreline obliquely, it is necessary to account for the Coriolis Effect. The wind set up associated with a bathystrophic storm surge may be defined by (Dean and Dalrymple, 1991):

$$\frac{x}{S'} = \left(1 - \frac{h+\eta}{h_o}\right) - A\ln\left(\frac{\frac{h+\eta}{h_o} - A}{1-A}\right)$$

where x = distance across shelf,
η = storm surge elevation at x due to wind stress,
h_o = water depth at the shelf break,
S' = effective shelf width,
and A = ratio of shear to hydrostatic forces.

The effective shelf width corrects for the Coriolis Effect, longshore bed friction, longshore wind stress and elapsed time, and is given by:

$$S' = \frac{S}{1 - f_c\sqrt{\frac{8k\sin\theta}{f}\frac{WS}{gh_o}}\tanh t'}$$

where S = shelf width,
f_c = Coriolis parameter,
k = wind friction factor,
θ = angle between wind direction and shore normal,
f = Darcy-Weisbach friction factor,
W = wind speed 10 m above sea surface,
and t' = effective elapsed time.

The Coriolis parameter is defined by:

$$f_c = 2\Omega\sin\phi$$

where Ω = angular velocity of the Earth ($7.29\text{x}10^{-5}$ rad.s^{-1}),
and ϕ = latitude.

The wind friction factor is best defined by:

$$k = \begin{cases} 1.2\times10^{-6}, & |W| \le W_c \\ 1.2\times10^{-6} + 2.25\times10^{-6}\left(1 - \frac{W_c}{|W|}\right)^2, & |W| > W_c \end{cases}$$

where W_c = critical wind speed (5.6 m.s^{-1}).

The Darcy-Weisbach friction factor is a dimensionless friction factor used to characterise bed roughness. For coastal waters it is in the range 0.019-0.087. The effective elapsed time is given by:

$$t' = \sqrt{\frac{kf\sin\theta}{8}}\frac{W}{h}t$$

This can be rearranged to define the time required to achieve equilibrium (t'=π) as:

$$t_e = \frac{\pi h}{W\sqrt{\frac{kf\sin\theta}{8}}}$$

The ratio of the shear to hydrostatic forces for a storm surge is given by:

$$A = \frac{n\tau_{w_x}S'}{\rho g h_o^2}$$

where n = wind stress and bottom friction factor,
τ_{w_x} = onshore wind stress,
and ρ = fluid density.

The factor n combines the effect of wind shear stress and bottom friction. It has values for coastal waters that typically range between 1.15 and 1.30. The onshore wind stress is given by:

$$\tau_{w_x} = |\tau_w|\cos\theta$$

where τ_W = wind stress.

The wind stress on the water is defined by:

$$\tau_w = \rho k W|W|$$

A number of simplifications can be made to solve for the storm surge height at the shore:

- The distance x equals the effective shelf width S' so $x/S'=1$
- The water depth at the shore is zero, so $h'=\eta/h_o$
- Sufficient time has elapsed to reach equilibrium, so $\tanh t'=1$

The sustained wind speed at the Mokohinau Islands Gulf on day 2 is ~75 knots (39 m.s^{-1}). The wind direction is at an angle of ~ 25° to the shore normal at this location. Taking n = 1.2, f = 0.05 and h_o = 100 m the wind stress component of storm surge for a range of shelf widths can be calculated. The predicted values (Figure 3) are consistent with observed storm surges in the Bay of Plenty for shelf widths <30 km, but are larger than observed in New Zealand for wider shelves.

APPENDIX 2 - HAZARD MATRIX

	Tele-Tsunami	Local Tsunami	Volcanic Tsunami	Storm Surge
EAST COAST				
Pakiri Beach to Cape Rodney	C3	-	-	C1
Cape Rodney to Tokatu Point (Omaha Bay)	E2,C2,P3	-	-	C1,E2
Whangateau Harbour	E2,C2,P3	-	-	C3,E3
Tokatu Point to Mullet Point (Kawau Bay)	-	-	-	C3,E3
Matakana River	E3,P3,T3	-	-	-
Kawau Island & associated islands	E2,P3	-	-	C3,E3
Mullet Point to Hatfields Beach	-	-	-	C3
Mahurangi Harbour	E2,P3,T2	-	-	-
Puhoi River	C3,E2,P3,T3	-	-	C3,T3
Waiwera River	C3,E2,P2,T2	-	-	C2,T3
Hatfields Beach to Huaroa Point (Whangaparaoa Bay)	C2,E3	-	-	C2,E3
Orewa River	P3,T2	-	-	-
Huaroa Point to Piripiri Point	C3,E3,P3	-	E3	E3
Gulf Harbour	E1,P2	-	E3	E3
Weiti & Okura Rivers	E2,P3,T3	-	E3	E3
Piripiri Point to Toroa Point (Long Bay)	C3,P3	-	-	C2
Torbay to Milford	C2,E2,P2	E3	E3	C2,E2,P3
Milford to North Head	C2,E2,P2,S3	E3	C1,E1,P2	C2,E2,P3
North Head to Bastion Point	S3	S3	S3	-
Shoal Bay and Bayswater Marina	E3,P3,T2	T3	E3	C3,E3,T3
Inner Waitemata Harbour and Westpark Marina	E2,P3,S3,T3	-	-	E3,T3
Ports of Auckland & Westhaven	E1,P2,S2,T2	E3,S3,T3	E3,S3	E3
Hobson Bay	E2,P3,T2	E3,T3	E3	E3,T2
Bastion Point to Musick Point	C3,E3,P3,T3	E3	E3	C3,E3,T3
Tamaki Estuary and Half Moon Bay Marina	E2,P3,S3	E3	E3	C3,E3
Musick Point to Whakakaiwhara Point (Tamaki Strait)	S3	S3	S3	S3
Pine Harbour Marina	E2,P3	E3	-	-
Maraetai	C2,E2,P3	C2,E2,P3	-	C2,E2,P3,T2
Waiheke and other Inner Gulf Islands	E2,P3,S2	E2,P2,S2	-	E3
Whakakaiwhara Point to Raukura Point	-	P3	-	-
Wairoa River	E2,P3	E2,P2	-	E3
Kawakawa Bay	E3	E2,P2	-	C2,E3,P3,T3
Raukura Point to Waimangu Point	-	E2,P2,T3	-	T3
Waimangu Point to Kaiaua	E3	E1,P1,T2	-	E2,T3
WEST COAST				
Kaipara Harbour	-	-	-	C3,E3,P3
South Head to Muriwai Beach	-	-	-	C2
Muriwai Beach to Manukau Entrance	-	-	-	-
Manukau Harbour	-	-	-	E3,P3
Manukau Entrance to Waikato River	-	-	-	C3,E3

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REPORT 4.4

CYCLONE EFFECTS ASSESSMENT

Prepared for

AUCKLAND REGIONAL COUNCIL

By

BECA CARTER HOLLINGS & FERNER LTD

Final
June 1997
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CONTENTS

Report prepared by
D A Papps

Report reviewed by
S J Priestley

1.0 INTRODUCTION

Beca Carter Hollings & Ferner Ltd (BCHF) have been commissioned by Auckland Regional Council (ARC) to assess the engineering effects of a cyclonic event on a range of infrastructure in the Auckland region. A tropical cyclone scenario has been prepared by NIWA. This report represents part of the information gathering phase of the Auckland Engineering Lifelines Project (AELP). The objective of the AELP study is to reduce the impact of all known hazards on the lifelines services of Auckland Metropolitan Region.

Death rates from natural hazards have declined dramatically in the western world. However, at the same time the costs of damage to structures and lifelines has climbed (NHRC, 1996). In response, this decade - the United Nations 'International Decade for Natural Disaster Reduction' - has seen extensive research directed at the vulnerability of lifelines.

In New Zealand and worldwide, emphasis has been placed on earthquake research rather than flooding and cyclone hazards. Research on U.S. East and Gulf Coast hurricane damage (e.g.: Ayscue, 1996; Chiu, 1997) provides some guidance, but these events are much more severe than that considered in this study. The effects on Auckland Lifelines from the tropical cyclone scenario considered will be unique and are best extrapolated from experience of local historical events. As such, information has been drawn from published reports on storms in the Auckland and Northland regions (ARWB, 1979, 1985a, 1985b, 1981; MWD, 1981).

This report presents an assessment of damage to engineering lifelines based on the findings of a 4 hour workshop on May 8, 1997. Workshop participants included staff from ARC, senior engineers from BCHF and Dr. Bruce Melville from the University of Auckland. Those present were:

Michelle Daly	ARC
Tim Rix Trott	ARC
David Wilkie	Carson Group
Dr Bruce Melville	University of Auckland
Gary Hadfield	BCHF
Stephen Priestley	BCHF
Ian Billings	BCHF
Graeme Levy	BCHF
Dr David Papps	BCHF

In this report, a matrix of effects is presented and the rationale behind the effects assessment is described.

2.0 CYCLONE SCENARIO

A tropical cyclone event with 1% annual exceedence probability has been characterised by NIWA (Salinger et al., 1997). The hypothetical cyclone would have similar strength to Cyclone Bola but would pass directly through the Auckland region with a due south direction of travel. The cyclone event would have a duration of four days.

2.1 WIND SCENARIO

Wind and rainfall will vary throughout the Auckland Region. As the majority of the critical infrastructure is within metropolitan Auckland, data for Auckland City will be considered. It is emphasised, however, that when critical infrastructure is investigated in more detail at each location, site specific values should be adopted.

The wind speeds predicted for the cyclone scenario are listed in Table 1. The sustained wind speed has been estimated as 67% of the gust speed predicted by NIWA.

Table 1: Cyclone Wind Speeds

Direction	Gust Wind Speed (km/hour)		Sustained Wind Speed (>1 hour; km/hour)
	Auckland City	Regional Range	
North/north-east	50	45 to 80	35
East	120	115 to 140	80
South-east	100	80 to 120	65
South-west	140	85 to 170	95
Note - Sustained wind speed taken as 0.67 of gust speed.			

2.2 RAINFALL SCENARIO

The rainfall predicted for the cyclone event is shown in Table 2.

Table 2: Cyclone Rainfall

Duration	Rainfall (millimetres)	
	Auckland City	Regional Range
20 minutes*	40	–
1 hour	60	~ 50 to 85
2 hours*	80	–
6 hours*	110	–
24 hours	125	~ 80 to 170
4 days	320	230 to 415
* Derived from regional values.		

2.3 FLOOD ESTIMATES

Based on the 100 year return period rainfall data in the previous section, the following specific flood flow estimates are provided for Auckland City.

Table 3: Flood flow estimates for Auckland City

Catchment Size	Response Time (Hour)		Peak Flood Flow (m^3/second/hectare)	
	Urban	Rural	Urban	Rural
10 hectares	0.2	0.4	0.30	0.20
100 hectares	1.0	2.0	0.16	0.11
1,000 hectares	2.0	4.0	0.10	0.07

Note:

- For urban catchments the effective runoff coefficient is 0.8.
- For rural catchments the effective runoff coefficient is 0.6.
- Assume clay type soils.

2.4 STORM SURGE SCENARIO

Dr W. P. de Lange has investigated tsunami and storm surge scenarios for the ARC (de Lange, 1997). During the tropical cyclone, the combination of low atmospheric pressure and wind stress on the ocean surface will produce a storm surge.

During the two days when the cyclone is closest to Auckland, the regional atmospheric pressure will be 970 mb. The inverse barometer effect associated with this low pressure would be 440 millimetres. Wind set-up was estimated to have a similar effect and the resulting surge would be 0.9 m on the east coast. This surge, in combination with tide, seasonal variations, and wave set-up effects in exposed locations, was estimated by Dr. de Lange to produce a maximum still water level of 4.8 m above Chart Datum (ie. 3.0 m above Mean Sea Level). The rationale used by Dr. de Lange is presented in Table 4:

Table 4: Storm Surge for Auckland East Coast

High Tide (HAT)	3.7 m
Seasonal Sea Level Variation	0.2 m
Barometric Surge	0.44 m
Wind Set-up	0.46 m
Total (above Chart Datum)	**4.8 m**

The scenario of the 100 year storm surge coinciding with the highest astronomical tide (HAT) is acknowledged by de Lange (1997) as an extreme case with a return period in excess of 100 years. This conservative scenario was adopted by Dr. de Lange to allow for additional wave set-up effects on exposed coasts, uncertainty in tide-surge interactions, and the insensitivity of the surge level to return period.

3.0 DISCUSSION OF EFFECTS

3.1 WIND EFFECTS

Wind gust speeds of up to 140 km/hr are predicted for Auckland City with gusts of up to 170 km/hr elsewhere in the region.

While many studies have examined wind-induced damage experienced in various storm and hurricane events (Chiu et al., 1997; Ayscue, 1996), the damage to lifeline structures expected for the Auckland tropical cyclone event will be unique and generally more subdued. The effects are considered mostly dependent on the engineering of Auckland lifelines and the severity of the particular cyclone. For this study, a comparison of the expected scenario with design wind speeds of the NZ Loadings Code (NZS4203) is most relevant.

The 140 km/hr gust speed corresponds approximately to the design wind speed of the Loadings Code. This indicates that wind damage to engineered structures is not likely, however buildings not complying with design codes will be vulnerable to a low degree. Widespread damage to structures, such as experienced in hurricane events on the U.S. East and Gulf Coasts, is not expected. Damage will be largely non-structural and will include damage to roofs and cladding in non-complying residential buildings and window loss and impact from wind-borne debris in non-residential buildings.

Lifelines will also be temporarily affected in other ways by the wind. Transport links may be temporarily inoperable and falling trees will damage power lines and buildings. It is likely that flights would be diverted from Auckland Airport at times during the storm. Typically large aircraft will prefer not to land if wind speed (sustained) across the runway is greater than 30 knots (55 km/hr) or 60 knots along the run-way (110 km/hr).

The Auckland Harbour Bridge will likely be closed by wind, if not by inundation of the northern approaches. Transit N.Z. have no trigger wind speed at which the bridge would be closed. Bridge closure was considered but not implemented for the 90-110 km/hr winds forecast for cyclone Drena. Gusts of 140 km/hr are predicted in the 100 year cyclone, and it is likely that the bridge would be closed to traffic.

The Port of Auckland will not be shut down as such, but container cranes will not operate in winds greater than 40 knots (75 km/hr). It is unlikely that any ships would leave port. The decision for a ship to leave port is up to the master and there has only been one recollected incidence of this. Extra storm lines would be used to secure ships. Empty containers are a hazard, but would be stacked in a pyramid shape to reduce windage effects.

Falling trees will threaten lifelines indirectly by falling on power lines and buildings, uprooting pipelines, and blocking bridges and culverts (possibly leading to washing away).

3.2 RAINFALL EFFECTS

The direct effects of rain (not including flooding) will be limited to water damage to buildings with flat or wind-damaged roofs and visibility effects. Heavy rain squalls will make roads un-driveable due to a loss of visibility and collisions on the motorways are likely. Significant traffic blockage would occur in this situation depending on the time of day and location of collisions.

A lack of visibility due to heavy rain is unlikely to close the airport, although a squall may mean that a pilot aborts landing and goes around for another attempt. Generally larger aircraft have efficient windscreen wiping systems, and visibility has only to be good enough for them to see the runway lights. Aircraft will be less affected than road vehicles.

3.3 FLOODING

The effects of flooding from the cyclone scenario will be site specific and will depend on such factors as:

- the size of catchment;
- the areal variability of rainfall intensity;
- design capacity of drainage system;
- provision of overland flow paths;
- uprooting or breaking of vegetation which could block drainage system;
- land slips;

- the presence of slab on grade structures which allow for no freeboard of houses in lower lying areas;
- planning controls and provision of engineering works within the catchment to alleviate flooding.

Within the last 30 years the worst storm to affect metropolitan Auckland was the July 1979 storm. The measured depths of rainfall over the Auckland area are listed in Table 5.

Compared to the rainfall depths associated with the cyclone scenario which have a return period of 100 years, the 1979 storm corresponded to between a 10 and 50 year event and its affects were worse on urbanised areas. It is also noted that the 1979 storm occurred during the middle of winter with wet antecedent conditions with a high potential for runoff. With a cyclonic event the antecedent conditions would be dry or normal and for storms occurring early in the cyclone, high infiltration could be expected. A feature of the cyclonic event is its persistence and after four days many of the catchment areas will be saturated and reporting direct run off. Another feature of the cyclonic event is the high wind conditions which will uproot and break off vegetation which will enter the drainage system and cause blockages. Similarly, slope failures and slumping of stream banks will entrain sediment into the drainage system to limit capacity over lower lying reaches.

Table 5 - Rainfall (mm) Comparison with July 1979 Storm

Duration	Cyclone Scenario	1979 Storm
30 minutes	45	24
60 minutes	60	40
2 hours	80	58
6 hours	110	100
12 hours	115	127
24 hours	125	148

Since the 1979 storm almost all the territorial local authorities (TLAs) have carried out engineering improvement works and have implemented planning controls to limit the degree of flooding. The flood standard for the Auckland region is the 100 year event and this is the level to which most TLAs are trying to avoid flood damage. A factor which would have increased the potential runoff, however, is the intensity of land development over metropolitan Auckland. Infilling of sections and office park type developments would have increased areas of imperviousness considerably above the 1979 levels. Overall it is considered that the effects of a cyclone scenario will be slightly worse than the effects reported for the 1979 storm. Damage could be amplified by a factor of 2.

Using the 1979 storm as a basis, the effects/damage of the cyclone scenario could be:

- Flooding could be expected in lower lying areas where the major drainage system has a relatively low capacity, or where development has limited the opportunity for overland flow. Examples of this would be in Blockhouse Bay, Avondale, St Heliers, several parts of East Coast Bays and the Wairau Valley in Takapuna.
- Open drains would potentially be blocked by upstream influx of vegetation or landslips. Examples of this could be the Takanini area in Manukau City, and Opanuku and Oratia streams in Waitakere City.
- Flooding of low lying areas relying solely on soakage or with poor drainage systems, and areas with low lying houses and no overland flowpaths. Examples include areas of Epsom, Mt Albert, Meola Creek and Newmarket.
- No major loss of vital services is envisaged although minor disruption to, for example, small pipelines and access to services could occur in some areas.

- Flooding of habitable houses will occur although the total number affected is likely to be less than 500. In addition flooding of commercial and industrial buildings in low lying areas would occur, as would flooding of house basements and garages.
- Wide spread flooding of roads could be expected and could extend well over a day given the persistence of the cyclone scenario. In some areas this would severely restrict traffic, although there will generally be alternative routes available.

3.4 SLOPE FAILURE

Lifeline effects caused by slope failures have been included in this report in recognition of the fact that precipitation is one of the most common causes of slope instability. The effects are not discussed in detail as this has been addressed in another study for the ARC (BCHF, 1997).

3.5 STORM SURGE AND WAVE EFFECTS

Wind waves generated by the sustained wind speeds in Table 1, are approximately estimated in Table 6 below:

Table 6: Cyclone Wave Conditions

Location	Wind Direction	Sustained Wind Speed (kilometres/hour)	Significant Wave Height (metres)
Hauraki Gulf	East	80	4 to 5
Waitemata Harbour	East	80	1.5 to 2
Manukau Harbour	South-west	95	2 to 2.5

Damage will be experienced due to inundation by elevated sea levels and wave run-up. The peak of the storm surge will last for several hours and the maximum still water level will include storm surge and wave set-up effects at high tide. Wave set-up will only be significant on exposed shorelines, such as East Coast Bays and the Firth of Thames, and the maximum still water level in these regions would be 4.8 m above Chart Datum (3 m above mean sea level) on the east coast. Where wave set-up effects are less important, such as the Waitemata Harbour and Tamaki Estuary, the still water level is more likely to be about 4.3 m above Chart Datum (2.5 m above mean sea level). Waves will run-up beyond the still water level. As a rough guide for run-up on coastal structures, the run-up elevation is approximately estimated as the still water level plus the wave height.

On coastlines where the storm surge level does not inundate roads or berms, the wave run-up can be estimated from the above guide. In this case, 'green water' overtopping can be expected where the run-up level extends beyond the crest of the seawall or berm. Levels above the run-up elevation will experience 'white water' overtopping or heavy spray. For instance, green water over-topping is expected at the Port of Auckland and on the oxidation pond bunds at the Mangere Wastewater Treatment Plant, while heavy spray will affect Tamaki Drive.

In low-lying coastal regions, inundation will occur where the storm surge level is above the level of berms and roadways. Wave run-up levels on inundated berms will be limited by wave breaking in shallow waters. In shallow water, and inundated areas in particular, unbroken wave heights will generally be limited to 80% of the water depth. Broken waves will travel over inundated areas as bores. Such bores are destructive in their own right and can also throw floating debris against structures.

Storm surge and wave action effects experienced on low-elevation (inundated) shore areas have been described by Rogers (1991). Four zones are categorised:

1. Wave erosion zone.
2. Zone of wave flooding.
3. Still water flooding zone.
4. High-ground zone with no flooding.

The effects experienced in each zone are described as follows:

The wave erosion zone, the most hazardous location, is the closest to the ocean and is the area that experiences erosion due to storm surge and waves.

The next zone, typically extending across the beach road and one or two blocks inland, is at risk from flooding with waves but not erosion. Conditions are dissipated from the wave erosion zone, but water levels and wave heights are still significant threats. Rather than eroding, this region is often buried by overwash deposits transported landward from the erosion zone. If the wave heights are high enough to deposit significant amounts of sand, the waves are usually large enough to cause significant damage to buildings.

Farther inland, most wave activity usually dissipates before the still water flooding zone is reached. Flooding by storm surge can extend inland over low topography and is similar to still water flooding typical of slow velocity riverine floods.

It should be noted that these effects were based on observations of Hurricane Hugo, which caused a storm surge of 1.5 to 6 m. The effects described would be applicable to exposed coastlines but the landward extent of the damage zones will be limited by elevation.

The wave erosion zone is likely to be limited to exposed shorelines and will affect shoreline roadways and properties with shore frontages. Lifeline services located on the coastline, such as pipelines, roads and rail will potentially be affected by erosion.

The still water flooding zone will be limited and it is likely that it will not extend beyond the wave flooding zone. This zone can be estimated as extending to a level equal to the still water level (tide plus storm surge and wave set-up) plus a wave height of 80% of the inundation depth. Damage in the flooding zone is likely to be limited to effects similar to river flooding, but accentuated by the saline water. Depending on the inundation depth, wave heights will generally not be large enough to cause structural damage to buildings.

Inundation is likely to cause the closure of low-lying sections of motorways. Sections of the North-western motorway are at a level of 1m above high water (4 m above Chart Datum) and low points on the Northern Motorway just north of the harbour bridge are at 4.2 m above Chart Datum. The storm surge scenario predicted for the Waitemata Harbour, with reduced wave set-up effects, is a level of 4.3 m above Chart Datum. During this event, these motorways would be inundated and are likely to be impassable.

Storm surge and storm waves on the Manukau Harbour would result in some perimeter flooding at Auckland International Airport and over-topping of oxidation pond bunds at the Mangere Wastewater Treatment Plant.

5.0 CONCLUSIONS

An assessment has been made of likely damage to Auckland Lifelines for the tropical cyclone and - storm surge scenario produced by NIWA and Dr. W.P. de Lange (Salinger et al., 1997; de Lange, 1997). For Auckland City, the cyclone scenario includes wind gust speeds of 140 km/hr, rainfall of 320 mm over the four day event, and storm surge of 2.5 m to 3.0 m above mean sea level. The resulting damage has been assessed largely from engineering experience with local historical storms.

The predicted wind speeds are approximately equivalent to current New Zealand design standards, and wind effects are expected to be largely non-structural.

Flooding effects are expected to be slightly worse than that experienced in the 1979 storm. Flooding of roads will affect traffic and up to 500 houses are expected to be flooded.

Inundation by the storm surge and associated wave erosion will cause damage to properties on exposed eastern coastlines. Effects to engineering lifelines will include closure of low-lying sections of motorway, possible damage to pipelines, and over-topping of seawalls at the Port of Auckland and oxidation pond bunds at the Mangere Wastewater Treatment Plant.

Overall, the effect on Auckland's Lifelines is expected to be limited and most effects will last only for the duration of the storm. Potential damage would include:

- Airport flights being excessively delayed due to high winds.
- Auckland harbour bridge being inoperable due to high winds.
- Port of Auckland not being operational due to high winds and wave and spray wash over the terminal.
- Sewage treatment plants may have their treatment processes affected by an influx of saline water.
- Sections of the north-western and northern motorways being inundated or subject to wave overtopping due to storm surge and wave action. Tamaki Drive would experience heavy spray and occasional wave overtopping. Alternative inland road routes will need to be used.
- Any critical service in a low lying area near a catchment outlet could be potentially flooded.
- Personnel involved in emergency services could be affected by:
  - their residential property being subject to wind damage and/or flooding
  - taking alternative road routes to their place of work, and at times being unable to drive because of high winds and intense rainfall

4. EFFECTS MATRIX

		Wind	Rain	Flooding	Slope Failure	Surge & Waves
Pipes	**pressure**	Negligible effect (4)	Negligible effect (4)	Scour of backfill (3.5)	Small (non-engineered) lines will be vulnerable (3.5)	Pipelines in wave erosion zone and outfalls (3)
	non-pressure	Negligible effect (4)	Negligible effect (4)	Scour of backfill (3.5)	Small (non-engineered) lines will be vulnerable (3.5)	Pipelines in wave erosion zone and outfalls (3)
Building Structures	**residential**	Roof and cladding damage to non-complying houses (3.5)	Flooding of damaged and flat roofs (3.5)	Evacuation of limited low-lying areas (2.5)	Slight vulnerability in recently established hilly areas (3)	Inundation and wave erosion in low-lying coastal areas (3)
	non-residential	Non-structural damage only (4)	Flooding of damaged and flat roofs (3.5)	Evacuation of limited low-lying areas (2.5)	Low vulnerability (4)	Generally lower risk (4)
	bridges	No structural damage, but may become unserviceable (4)	Negligible effect (4)	Low risk due to small catchments or estuarine location (4)	Similar risk to adjacent bank erosion (3.5)	Inundation at some motorway locations (3.5)
Services	**lampposts**	Decayed hardwood poles will be vulnerable (3.5)	Negligible effect (4)	Negligible effect (4)	Low risk (4)	Negligible effect (4)
	cranes	Will be shut-down (4)	Negligible effect (4)	Negligible effect (4)	Negligible effect (4)	Negligible effect (4)
	power lines	Shorting, falling debris (2.5)	Negligible effect (4)	Negligible effect (4)	Low risk (4)	Negligible effect (4)
	pipe bridges	Negligible effect (4)	Negligible effect (4)	Generally comprise steel pipe (4)	Low risk (4)	Pipes strapped to wharves (3.5)
Civil Structures	**roads**	No structural damage, but may become unserviceable (4)	un-driveable in downpours, potential for collisions (3.5)	Flooding, scour where culverts overtop, slips (3)	Motorways engineered for this risk, other roads susceptible (3)	Low-lying motorways closed, scour on exposed coasts (3)
	rail	No structural damage, but may become unserviceable (4)	Negligible effect (4)	Risk to rail bridges from debris in flooded rivers (3)	Cuttings susceptible (3)	Some potential for embankment scour and inundation (3.5)
	rivers/floodways	Negligible effect (4)	Negligible effect (4)	Scour, bank slumping and reduced capacity (3)	Slumping of banks - not a lifeline hazard (4)	Backwater effects will accentuate flooding (3)
	embankments	Small (farm) dams only affected by wave chop (4)	Negligible effect (4)	Older stormwater detention dams may overtop (3.5)	Dams are usually engineered for this risk (4)	Foreshore erosion (3)
Specific Infrastructure	**masts**	Engineered masts (eg: Telecom) will not be damaged, but may be unserviceable (3.5)	Negligible effect (4)	Negligible effect (4)	Low risk (4)	Negligible effect (4)
	airports	Some flights re-directed (3.5)	Visibility effects will not disrupt (4)	AIAL runway will not be flooded, some loss of friction (4)	Negligible effect (4)	Low risk (4)
	ports	Container cranes shut down (3.5)	Negligible effect (4)	Negligible effect (4)	Negligible effect (4)	Flooding by wave overtopping, containers moved around (3.5)
	wastewater treatment plants	Negligible effect (4)	Negligible effect (4)	High inflows would be bypassed (3.5)	Negligible effect (4)	Inundation of Mangere ponds, overflows (3.5)
	water treatment plants	Negligible effect (4)	Negligible effect (4)	Negligible effect (4)	Negligible effect (4)	Negligible effect (4)
	electrical	Negligible effect (4)	Negligible effect (4)	Low-lying infrastructure flooded (3.5)	Low risk (4)	Low risk (4)
Other	**large trees**	Moderate impact (2)	Negligible effect (4)	Negligible effect (4)	Not a lifeline hazard (4)	Loss of trees which protect coastline (3.5)

Key to effect ratings system:
(1) high probability and/or severe impact potential
(2) moderate probability and/or moderate impact potential
(3) low probability and/or low impact potential
(4) negligible impact potential

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SECTION 5

DROUGHT

REPORT 5.1

DROUGHT

Discussion Paper Prepared for the

AUCKLAND ENGINEERING LIFELINES PROJECT

By

Royd Cumming (Auckland Regional Council)
Michele Daly (Auckland Regional Council)

July 1997

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1.0 INTRODUCTION

Drought and dry periods are a result of monthly and seasonal climate patterns. Drought can be defined in various ways, depending on the sensitivity of various requirements to dry periods of different time scales and severity. For example, an "agricultural drought" is a period when the soil is estimated to be "moisture deficit" as determined by a balance of daily pasture evapotranspiration and rainfall. For water supply purposes, a "hydrological drought" is usefully defined as a recurrence value of "one-in-x-years" for a fixed period such as a season. This is determined by considering the value of a fixed percentile of rainfall at a certain place.

The two regionally significant hazards produced by drought and dry periods are agricultural drought and water supply shortage.

In terms of the region's engineering Lifelines, droughts can directly affect the ability of the water supply network to meet consumers' water supply requirements. A lack of water has economic and public health implications for the whole region. However the physical integrity of the network is unlikely to be unaffected.

2.0 DROUGHT IN THE AUCKLAND REGION

A severe seasonal drought in the Auckland region is most likely to occur in Summer. For the Albert Park rainfall record analysis of 3-month consecutive rainfall totals (1910 to 1985 inclusive) has shown that out of the ten lowest, nine were in the Summer months. Similarly, of the nine driest 6-month periods, 8 included the three summer months (December-February) and the 9th, included two of them (Hessell, 1996). Droughts can become prolonged if anticipated autumn rainfall doesn't eventuate.

Auckland has experienced a number of significant droughts since rainfall records began in 1853 (Albert Park). Using the Albert Park record as an example, and comparing twelve month cumulative rainfall totals with that of the July 1993 to June 1994 (most recent drought) rainfall total of 796mm, four other events are significant. These are the twelve month periods starting:

14 May 1885	792mm
20 May 1891	782mm
6 Oct 1912	762mm
12 Dec 1913	705mm

From this, the July 1993 to June 1994 total of 796 mm shows a return period of 1:25 years (Cumming, 1995).

However, the assessment of a return period of a drought (and hence its severity) can vary depending on the number of rainfall stations used, the length of record at each station, the quality of the records and the duration over which the rainfall data is analysed (i.e. start and finish of drought period). Stream flow records can also be used to assess the return period of a drought.

The accurate determination of the return period of a drought is particularly important with respect to water resource and water supply management (see section 3.0 below). With shorter period droughts (e.g. 1:50 years), the selection of stations, record length and data quality considerations can become critical, and often subjective, due to the uncertainties involved. This was no more evident than during the 1994 drought which caused a water supply shortage for Auckland. The drought was reported as being anything from a 1:20 year return period to a 1:120 year return period event. These variations were due to differences in the number and locations of stations selected, different record lengths and

different drought durations. Some of the uncertainty and subjectivity in determining drought severity can be removed using independently assessed data.

Much has been said about the effects of longer term climatic changes on drought. These are superimposed on the short term (< 30 years) climatic fluctuations. However, they are able to be only coarsely estimated and are considered of little relevance in trying to predict drought. The shorter term fluctuations are those that must be managed from a water supply (and agricultural) perspective (Cumming, 1995).

3.0 WATER SUPPLY SHORTAGES

Simplistically, a water supply shortage occurs when the severity of a drought is greater than the water supply system has been designed for. Water supply shortages can also occur when demand exceeds the supply capabilities of the water supply system.

Water supply shortages are not uncommon for Auckland. Since the 1840s and up until the construction of the Hunua dams in the 1950s to 1970s, water supply has barely kept abreast of Auckland's water requirements. At one time in 1943, the city faced a water crisis so serious that the reservoirs at the time held only one day's supply. The situation was saved by rigid water restrictions and emergency pumping from back-up sources (Turner, 1995).

Estimating the vulnerability of an area to water supply shortage is often referred to as Reliable Yield estimation. Reliable Yield estimation is complex as it needs to take into account the stochastic variability in inflows to a water supply storage system, the demand on the water supply system and the storage availability of the system. Demand estimates may need to incorporate temporal increases or decreases due to changes in development or behaviour, seasonal variability and often involve a "random" component which reflects variation in demand that cannot be explained. Adequate regional growth projections need to be available for demand projections. Reliable Yield analyses for large complex water supply systems are therefore often undertaken using computer modeling.

Water supply systems cannot be 100% reliable. Generally a level of acceptable risk that the system will fail to meet demand is derived by considering the cost of that eventuality versus the cost of additional infrastructure to lessen that risk.

4.0 WATERCARE WATER SUPPLY SYSTEM

Watercare has ten water supply lakes behind dams in the Hunua and Waitakere Ranges. The primary function of the dams is to capture and store water from catchment runoff during periods of higher rainfall to ensure a supply during periods of lower rainfall.

The 1994 drought necessitated a rethink of Watercare's previous future source investment programme and other resource management issues (Turner, 1995).

At the request of its customer territorial authorities, Watercare has adopted a 1 in 200 year drought standard to determine yield and supply requirements. This means that Watercare will construct and operate its water supply sources to ensure that normal water demand (without restrictions) would not empty the supply lakes more often than with a 0.5% probability (1 in 200 years). A 1:200 year drought is an extreme event and Watercare is essentially guaranteeing the ability of the water supply to meet water requirements even under extreme drought conditions. There is less uncertainty in terms of defining a drought of this magnitude (compared to the difficulties in defining more frequent

droughts as discussed under section 2.0 above). A 1:200 year standard takes away the necessity of an independent means of assessing the severity of a drought.

A water supply shortage resulting from drought generally occurs over time periods of months to a year or more depending on the storage capacity of the water supply system. The severity of a drought is not known until it has ended and water restrictions may be applied to reduce demand. This is done in accordance with a Drought Management Plan (agreed to between Watercare and the local authorities).

The 1 in 200 year yield of the water supply system is currently 335,000 m^3/day. The current twelve month average demand is 305,000 m^3/day.

5.0 SUMMARY

Drought is a factor in causing a regional water supply shortage. However, a water shortage is also dependent on design characteristics of the water supply system such as storage capacity and demand.

The assessed severity (return period) of a drought can vary depending on the rainfall record used and the duration of the interval selected.

In terms of the region's engineering Lifelines, droughts can directly affect the ability of the water supply network to meet consumers' water supply requirements. However the physical integrity of the network is unlikely to be unaffected. A lack of water has economic and public health implications for the whole region. There may be indirect effects on other Lifelines, particularly those that depend on for example cooling water. Industries requiring large amounts of water (e.g. food processing and washing industries) may also be affected. These effects will be largely economic as plants may be required to shut down for certain periods to conserve water. Generally water savings are encouraged from the domestic user first along with voluntary savings from industry. As a result of the 1994 drought, many industries became more efficient in terms of their water use (e.g. recycling water). Others investigated alternative sources of water (e.g. groundwater) which in many cases was also more economic, particularly for industries not requiring a drinking water standard (e.g. some washing industries). Many of these water conservation measures remain in place today.

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SECTION 6

BIOLOGICAL HAZARDS

REPORT 6.1

BIOLOGICAL HAZARDS

DISCUSSION PAPER PREPARED FOR THE AUCKLAND ENGINEERING LIFELINES PROJECT

by

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With Assistance From

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June 1997

CONTENTS

1.0 INTRODUCTION

This paper looks at the *direct* effects of biological agents (mainly disease and algal blooms) on the region's engineering Lifelines. The most directly affected engineering Lifelines are the water supply and treatment networks. Damage to filtration and treatment plant may occur (see section 3.0 below), and the system may be required to shut down.

Other engineering Lifelines *indirectly* affected include transportation networks (for example, if access in and out of an area with a disease outbreak needs to be restricted), and communication (for example, telephone exchange overloading). These indirect effects are similar to those experienced for most other emergency situations (earthquakes, hazardous substances spill etc.).

There are many *health risks* associated with other hazard events (such as sewage overflows due to ruptured pipes in an earthquake, flooded stormwater/sewer systems etc.), or effects on health services such as hospital overloading. While not the focus of this paper, or the Engineering Lifelines Project, they are mentioned in the text where appropriate for completeness.

2.0 DISEASES

Diseases may or may not severely impact a community (and Lifelines) depending on whether the spread of the disease can be easily controlled. For a disease to become a major problem, it needs to be beyond the resources of the Health Authorities to quickly contain it.

Diseases can be spread in four ways: consuming contaminated food or water, airborne transmission, vector transmission (e.g. by mosquitoes), or blood borne diseases. Some diseases may be spread by more than one of these ways.

Each category poses its own special problems with respect to control and effect on Lifelines.

A large outbreak of any disease could complicate a civil defence emergency and overload health services.

2.1 FOOD/WATER BORNE

Diseases spread by consuming contaminated food or water supplies include *Cholera, Typhoid, Campylobacteriosis, Salmonellosis, Giardiasis, Cryptosporidiosis,* and *Hepatitis A*.

Contaminated food sources can not always be quickly identified and controlled.

Civil defence emergencies and other natural disasters can disrupt appropriate treatment of water supplies with resultant outbreaks of diseases such as *Giardiasis* and *Cryptosporidiosis*. Protozoan parasites such as these can only be eliminated reliably from the drinking water supply by meticulous attention to chlorination and filtration. The potential cost of deficiencies in such water treatment are illustrated by the huge outbreak of *Cryptosporidiosis* experienced in Milwaukee (see Appendix 1).

Public Health control of outbreaks of food- and waterborne disease consist of:

- investigation of the outbreak
- identification of the source of the outbreak
- control of the source of the outbreak

Containment is achieved by restricting activities on an individual basis rather than restricting activities or movement on a population basis.

Lifelines indirectly affected include transportation (particularly around hospitals), and communications (overloading). Some Lifeline operations (and other industries) would be affected due to loss of part of their work force due to illness. Industries dependent on a clean supply of water may have to shut down until alternative water supplies are found (e.g. some food processing industries).

The disruption of transportation or water supply due to other hazard events (e.g. earthquake) can seriously impair the capacity of the food industry to maintain food safety standards and distribute safe food in a timely fashion to the Auckland population.

2.2 AIRBORNE

Diseases such as *Influenza, Meningitis* and *Measles* are transmitted by airborne particles.

Vaccinations can help reduce the risk. Many airborne diseases are vaccine-preventable. However immunisation uptake in New Zealand is not sufficiently high to prevent epidemics and for some diseases there is no vaccine (e.g. *Group B meningococcal meningitis*).

Isolation of patients can have a role in the public health control of these diseases.

The indirect effects on Lifelines would be similar to those for food/water borne diseases (see above).

Any civil defence emergency necessitating the rapid and prolonged placement of people in temporary and overcrowded accommodation increases the likelihood of epidemics of airborne infectious disease.

2.3 VECTOR BORNE

The most serious vector borne diseases affecting humans such as *Malaria,* and *Dengue fever* are presently unknown in New Zealand. However, mosquito species capable of being vectors have been found in New Zealand and it's considered just a matter of time before more competent vectors of these diseases reach our shores.

With climate change scientists predicting an increase in temperature, disease vectors may move further south closer to New Zealand and the range of vectors may increase.

One of the main problems for New Zealand is that we have a very vulnerable population to vector borne diseases because of a lack of exposure and hence lack of widespread population immunity. Many of the diseases are not vaccine-preventable.

An outbreak of one of these diseases could reach epidemic proportions given favourable conditions. The workforce could be seriously affected, and movement may have to be restricted in and out of the region, including air travel. Areas where the vector was established (e.g. water reservoirs, lakes) would need to be treated (e.g. aerial spraying). Currently New Zealand does not have the chemicals available to undertake vector control or source treatment. This is currently being investigated by the Ministry of Health. Use of these chemicals could pose other health and environmental risks which would need to be taken into consideration.

Water supply and treatment facilities may be directly affected by the outbreak of vector borne diseases if they are the source, or if they are in an area needing to be sprayed to control the vector. The indirect effects on Lifelines would be similar to those for food/water borne diseases (see above).

2.4 BLOOD BORNE

Blood borne diseases include exotic diseases such as *Ebola, Lassa fever,* and *Marburg fever.* They are low probability/high risk diseases. They are only transmitted to those who have close contact with the secretions of patients (for example nurses). New Zealand outbreaks are highly unlikely.

Other blood borne diseases such as *HIV* and *Hepatitus B and C* would be unlikely to become epidemic if Auckland's engineering Lifelines were disrupted (e.g. by an earthquake) unless the interruption of energy supplies was such that hospitals were unable to maintain infection control and surgical hygiene.

3.0 ALGAL BLOOMS

Algal blooms have the potential to seriously affect the utility of fresh water lakes and rivers especially for recreational use.

As a first principle lake water should not be used as a drinking water source. Communities that still rely on lake water for their supply of potable water are particularly inconvenienced by algal blooms.

Unicellular and filamentous blue-green bacteria (e.g. *cyanobacteria*) are almost invariably present in freshwater lakes. In nutrient-rich (i.e. eutrophic) lakes the bacteria sometimes bloom to levels as high as 10 cells per ml. Problems arise from:

- the presence of such a biomass in the water. Biological oxygen demand rises, light penetration diminishes.
- the die-off once the bloom subsides. The smell is offensive and the decaying bacteria leads to deoxygenation of the water, along with flow-on effects on other species.
- the toxins that are produced by some *cyanobacteria.* The toxins are lipid-soluble phenolic compounds which are both neuro and hepato toxic. Symptoms of toxin poisoning include redness of the skin, itching round the eyes, sore red throat headache, diarrhoea, vomiting and nausea. Poisoning has caused the death of animals but there are no human fatalities recorded - mainly because humans tend to be a little more discerning about what they drink. Approximately 25% of blooms ca be toxic while another part within the same lake can be non-toxic.

There is no easy and safe way to control a bloom. Pesticides (e.g. copper sulphate) have been used but their cost and social acceptability present a major problem. Boiling the water will only kill the bacteria releasing more toxins. The toxins themselves are relatively stable and unaffected by boiling.

Conditions that favour *cyanobacter* blooms include alkaline soils, light, water temperatures, lack of wind, nutrient concentrations (particularly Nitrogen and Phosphorous) and the present of organic solutes.

The world's largest recorded river algal bloom occurred in Darling River, New South Wales in November 1991. 1000 km of the river was severely affected by toxic algae resulting in a State of Emergency being declared in New South Wales for 21 days.

Generally, algal blooms are regarded as a symptom of environmental degradation which has been accelerated by human settlement, land clearance, river and lake height regulation and waste discharges. They do not tend to be a problem for a well-controlled reservoir catchments.

Blue-green algae affect water treatment operation by blocking filters and requiring increased use of flocculants and disinfectants.

Additional monitoring is also required to allow constant adjustment to compensate for the changes in the source water quality.

4.0 OTHERS

Other biological hazards include insect plagues (locusts, wasps, flies), which are unlikely to occur on a scale in New Zealand which would seriously disrupt the region's infrastructure. Isolated problems may occur, such as airports having to close and disruption to telecommunications.

Some diseases such as *mad cow disease* have a much longer lead in time and occur over a longer time frame. There is no rapid onset affecting hundreds or thousands of people as in an epidemic, making the disease easier to control and contain.

The chemical contamination of some foods (e.g. milk) could cause major problems for a large number of people, causing indirect effects on Lifelines.

5.0 SUMMARY

A range of different biological hazards have the potential to seriously disrupt our communities and Lifelines. Most of the effects on Lifelines are indirect, such as telecommunication overloading caused by people wanting information, traffic congestion around hospitals and caused by people wanting to leave the area, and staff shortages. If the area needs to be isolated, airports and other access routes in and out of the region may be closed or severely restricted.

The most directly affected Lifelines due to disease outbreaks and algal blooms are water supply and treatment systems.

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APPENDIX 1: CRYPTOSPORIDIUM INFECTION FROM MILWAUKEE'S PUBLIC WATER SUPPLY

A MASSIVE OUTBREAK IN MILWAUKEE OF CRYPTOSPORIDIUM INFECTION TRANSMITTED THROUGH THE PUBLIC WATER SUPPLY

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Abstract *Background.* Early in the spring of 1993 there was a widespread outbreak of acute watery diarrhea among the residents of Milwaukee.

Methods. We investigated the two Milwaukee water-treatment plants, gathered data from clinical laboratories on the results of tests for enteric pathogens, and examined ice made during the time of the outbreak for cryptosporidium oocysts. We surveyed residents with confirmed cryptosporidium infection and a sample of those with acute watery diarrhea consistent with cryptosporidium infection. To estimate the magnitude of the outbreak, we also conducted a survey using randomly selected telephone numbers in Milwaukee and four surrounding counties.

Results. There were marked increases in the turbidity of treated water at the city's southern water-treatment plant from March 23 until April 9, when the plant was shut down. Cryptosporidium oocysts were identified in water from ice made in southern Milwaukee during these weeks. The rates of isolation of other enteric pathogens remained stable, but there was more than a 100-fold increase in the rate of isolation of cryptosporidium. The median duration of illness was 9 days (range, 1 to 55). The median maximal number of stools per day was 12 (range, 1 to 90). Among 285 people surveyed who had laboratory-confirmed cryptosporidiosis, the clinical manifestations included watery diarrhea (in 93 percent), abdominal cramps (in 84 percent), fever (in 57 percent), and vomiting (in 48 percent). We estimate that 403,000 people had watery diarrhea attributable to this outbreak.

Conclusions. This massive outbreak of watery diarrhea was caused by cryptosporidium oocysts that passed through the filtration system of one of the city's water-treatment plants. Water-quality standards and the testing of patients for cryptosporidium were not adequate to detect this outbreak. (N Engl J Med 1994;331:161-7.)

HUMAN infection with cryptosporidium was first documented in 1976.[1,2] Since that time, cryptosporidium has been recognized as a cause of gastrointestinal illness in both immunocompetent[3-6] and immunodeficient people.[6,7] Infection with cryptosporidium results in watery diarrhea associated with varying frequencies of abdominal cramping, nausea, vomiting, and fever. In immunocompetent people, cryptosporidiosis is a self-limited illness, but in those who are immunocompromised, infection can be unrelenting and fatal.[5,8] Infection occurs in a variety of settings[8-11]; waterborne outbreaks of cryptosporidium infection have been documented in association with drinking water from a contaminated artesian well,[12] untreated surface water,[13] and filtered public water supplies.[14-16] We report our investigation of the largest documented outbreak of waterborne disease in the United States.

On April 5, 1993, the Wisconsin Division of Health was contacted by the Milwaukee Department of Health after reports of numerous cases of gastrointestinal illness that had resulted in widespread absenteeism among hospital employees, students, and schoolteachers. Little information was available about the nature of the illness or the results of laboratory tests of stool specimens from those who were ill. On April 7, two laboratories identified cryptosporidium oocysts in stool samples from seven adult residents of the Milwaukee area; none of the laboratories surveyed had found evidence of increased or unusual patterns of isolation of any other enteric pathogen.

The Milwaukee Water Works (MWW), which obtains water from Lake Michigan, supplies treated water to residences and businesses in the City of Milwaukee and nine surrounding municipalities in Milwaukee County. Either of two water-treatment plants, one located in the northern part of the city, and the other in the southern part, can supply water to the entire district; however, when both plants are in operation, the southern plant predominantly serves the southern portion of the district.

Examination of the two plants' records on the quality of untreated water (intake) and treated water (that supplied to customers) revealed an increase in the turbidity of treated water from the southern plant, beginning approximately on March 21, with increases to unprecedented levels of turbidity from March 23 through April 5. These findings pointed to the water supply as the likely source of infection and led to the institution, on the evening of April 7, of an advisory to MWW customers to boil their water. The southern plant was temporarily closed on April 9.

From the Bureau of Public Health, Wisconsin Division of Health, Madison (W.R.M., N.J.H., M.E.P., J.J.K., J.P.D.); the Epidemiology Program Office, Division of Field Epidemiology (W.R.M., D.E.P.), Epidemic Intelligence Service (W.R.M.), Division of Parasitic Diseases, National Center for Infectious Diseases (D.G.A.), Centers for Disease Control and Prevention, Atlanta; the City of Milwaukee Department of Health (K.A.B.) and Bureau of Laboratories (M.S.G.), Milwaukee; the U.S. Environmental Protection Agency, Cincinnati (K.R.F.); and the University of South Florida, Tampa (J.B.R.). Address reprint requests to Dr. Davis at the Wisconsin Division of Health, Bureau of Public Health, 1400 E. Washington Ave., Rm. 241, Madison, WI 53703.

Methods

Investigation of Water-Treatment Plants

The policies, procedures, and physical plant of the southern MWW facility were reviewed and inspected in April 1993. Data on the monthly maximal turbidity of untreated and treated water from both plants were reviewed and analyzed for the period from January 1983 through April 1993. Data on the daily maximal turbidity and

SECTION 7

FIRE

REPORT 7.1

FIRE

DISCUSSION PAPER PREPARED FOR THE AUCKLAND ENGINEERING LIFELINES PROJECT

By

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Michele Daly (Auckland Regional Council)

June 1997

CONTENTS

1.0 INTRODUCTION

Fire is one the most common hazards encountered by a community. The Auckland Fire Service responded to 5 858 fires in 1995 and 5 134 in 1996. There has been 65 fire-related fatalities between 1991 and 1996 in Auckland.

Generally, fires are localised, and are unlikely to severely impact on the ability of the region's engineering Lifelines to cope.

Fires at key installations (for example, power substations, major pump and treatment facilities, junctions etc.) may cause local disruption to services until the fire is extinguished and repairs made. Power transmission lines are extremely vulnerable and in many instances pass over industrial as well as residential property where in a serious fire they could be damaged by heat, or in dense carbonaceous smoke could arc to earth (see also section 4.0). An attendent risk to fires at some facilities is that of hazardous substances being released due to damage of storage containers (see also discussion paper on hazardous substances). However, there are unlikely to be any longer term effects on wider areas or on other services.

For these reasons the following discussion is very general, and no attempt will be made to assess the vulnerability of individual sites to fire hazard as part of the Lifelines project.

2.0 GENERAL PROTECTION MEASURES

Individual Lifeline operators need to assess their particular facility or network's vulnerability to fire, and consider implementing mitigation measures where appropriate. Operators should not rely on compliance with the fire regulations (Fire Service Act 1975, Building Act 1991, Fire Safety and Evacuation of Buildings Regulation Act 1992) to ensure that their facility is as protected as it could be.

The legislation ensures the safety of people rather than property. The Fire Safety and Evacuation of Buildings Regulations Act (1992) determines the need for an evacuation scheme in a building and how it should operate. The Building Act (1991) requires buildings to be able to be evacuated safely. Consequently, sprinkler systems may not be required in all circumstances (depending on the ratio of floor area to height for example), such that facilities critical to the operation of a network may not always have adequate fire protection.

Specialist equipment (plant rooms etc.) may benefit from a fire audit to assess how equipment may be best protected. Fire auditing is done by IQPs (independent Qualified Persons) and does not include the Fire Service. Their philosophy is that as they give advice and respond to put fires out, they should not audit facilities as well.

Fire protection is based on fire resistant divides creating compartments which will contain a fire and conversely prevent the spread of smoke through the building allowing safe egress of occupants. Divides comprise fire rated walls, doors and windows. The size of the compartments may be increased if sprinkler systems are fitted.

The use of smoke and heat detectors serves to give early warning of fire to the occupants allowing more time to exit the building. Manual alarms allow a general warning to be announced and evacuation to be commenced once a fire is discovered. Detectors and alarms do not protect a facility but do allow early attendance by the Emergency Services.

3.0 EARTHQUAKE AND VOLCANIC ERUPTION INDUCED FIRE

Earthquake and volcanic eruption induced fire have the potential to affect a wider area and consequently the potential to affect a number of Lifeline services.

Severe ground shaking has the potential to rupture gas and fuel pipes, with fire spreading to nearby structures. Fire could be minimised by careful choice of piping material (ductile HDPE versus steel for example) to reduce pipe breakage (covered under earthquake hazard).

Flammable substances (e.g. LPG) are generally sufficiently isolated under present legislation not to cause complications for nearby structures and services.

Hot ballistics and projectiles from volcanic eruptions will ignite flammable materials on impact, as will lava flows. Hot surges will also incinerate above ground structures near the vent. Ash is not hot enough by the time it hits the ground to ignite objects (due to it's very small particle size and consequent rapid loss of heat). High surface temperatures may also affect some buried services, depending on their depth (covered under volcanic hazard).

Generally the best protection measures for individual facilities are the same as those discussed above for smaller more localised fires.

While lava flows may be able to be diverted around critical facilities (overseas success rate of this is low), the only option may be to relocate the facility or have some redundancy built into the network (similarly for hot surges).

A complicating factor with earthquake and volcanic hazard induced fire will be the inaccessibility of many fires to the Fire Service and of course the slower response to callouts due to the volume of fires requiring attention. It is probable that in a severe earthquake or volcanic eruption that the Fire Service will be rendered inoperative. Fire stations are likely to suffer damage which will make it difficult to respond. Roads may be so badly damaged as to be impassable. Water main ruptures will make water unavailable for not only firefighting but for other services such as cooling in industrial plants. Volcanic ash, depending on its thickness, may also make it difficult to locate fire hydrants. In the longer term, fire appliances from outside the effected area could be used to pump water from remaining supplies.

4.0 WILDFIRE

There is a risk of wildfire in the forested areas to the west (Waitakere Ranges), south (Hunua Ranges) northwest (Woodhill Forest) and north (Mahurangi Forest). Elsewhere the risk is low. Fires in these area can result from agricultural burn-offs getting out of control, arson, careless actions (e.g. camp fires in restricted areas), or natural causes such as lightning strikes.

If there are any critical facilities in these areas, additional mitigation measures to those discussed might include keeping vegetation down around facilities (i.e. a fire break). Severe herbage fires can generate enough smoke to promote arcing of power transmission lines. Gorse is known to be particularly bad in this respect. The potential arcing of power transmission lines would be avoided if services were buried underground.

5.0 EXPLOSIONS

The risk of explosions in the Auckland region is small and extremely unlikely to affect Lifeline services on a regional scale.

Explosion sources include gas, petroleum products, explosives, oxidisers (chemicals such as ammonia, chlorine, oxygen, and hydrogen peroxide), steam (boilers) and dust (i.e. ignition of fine combustible dust in suspension, at for example fertiliser works and grain mills).

These substances occur in both clearly defined, fixed sources (e.g. gas pipelines) and as movable (transportable) sources. The risk area around a fixed source is able to be more clearly defined. Explosions resulting from movable sources are random (e.g. fuel tanker collisions), and consequently their risk to specific Lifelines is difficult to define. The proximity of critical Lifeline facilities to sites where significant quantities of potentially explosive substances are regularly in use or stored should be a matter for consideration at the planning stage of the facility (see also discussion paper on hazardous substances).

The blast pressure effects of explosions can be considerable and cause significant damage in the vicinity of the blast.

Most explosions are localised and are able to be contained (for example, gas build-ups (BOC store), turbine explosions, and gas pipeline ruptures). Fire and explosions at the Western Reclamation are unlikely to cause major disruption as the quantities stored in the area are relatively small. Wiri Oil Terminal and the Liquigas depot are quite isolated but may cause some disruption at Auckland Airport if an explosion occurs.

The tanker fire at Manukau in 1990 is an example of a fire and explosion involving a transportable combustible product. The incident caused an interruption to air traffic. A tanker and trailer unit overturned after colliding with a parked car. Spilled fuel ignited immediately and approximately 20,000 litres entered the stormwater system. The burning fuel discharged into a creek which drained into the Manukau Harbour and scrub on the banks of the creek was set on fire. At some stage the fuel in the stormwater system must have stopped burning as there was an underground explosion outside of the main entrance to the Manukau Shopping Mall which lifted a manhole cover and a 2 metre radius of ground around it. The fire at the Tanker was allowed to burn under control for some time as this was seen to be the best way to protect the young girl trapped under the trailer. Had the fire been extinguished there was a probability of reignition with the flame being uncontrolled.

Chemicals are not manufactured in Auckland, and product is either brought in already processed or partially processed. The spontaneous combustion for example, of some chemicals, presents a small risk, as there is limited processing and handling. Again, explosions are likely to be small and able to be contained.

Mitigation measures for explosions are similar to those dealing with fire (see above).

6.0 SUMMARY

Although fires are one of the most common hazards affecting our communities and facilities, it is unlikely that the region's infrastructure would be severely impacted (except for earthquake and volcanic eruption induced fire - these hazards are dealt with elsewhere).

Good 'housekeeping measures' at critical facilities will reduce the impact of fire at individual locations, and Lifeline operators should consider undertaking regular fire audits to see whether specialist plant is adequately protected.

7.0 REFERENCES

Brown, N (1996) *Technological Hazards.* Paper No.7, Hazards Presentation Seminar, Dunedin City Lifelines Project, 1996.

SECTION 8

HAZARDOUS SUBSTANCE SPILL

REPORT 8.1

HAZARDOUS SUBSTANCE SPILL

DISCUSSION PAPER PREPARED FOR THE AUCKLAND ENGINEERING LIFELINES PROJECT

By

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Michele Daly (Auckland Regional Council)

June 1997

1.0 INTRODUCTION

Hazardous substances occur in both clearly defined, fixed sources and as movable (transportable) sources. The risk area around a fixed source is able to be more clearly defined. Spills from movable sources are random, and consequently their risk to specific Lifelines is difficult to define. The proximity of critical Lifeline facilities to sites where significant quantities of hazardous substances are regularly in use or stored should be a matter for consideration at the planning stage of the facility.

Hazardous substance spills are too localised to cause any long term effects on the region's infrastructure. However, they have the potential to have a high impact on people, and stretch services such as welfare agencies, hospitals, and emergency services. When occurring as the result of another hazard (e.g. earthquake), the combined cumulative effects will be significant.

The main impact on Lifeline facilities in the vicinity of a hazardous substance spill is the loss of operating personnel due to injury or their evacuation. While this would cause considerable inconvenience, the spill would not cause the facility to 'fail'. However, isolation of key components of a particular lifeline facility for a period of time may occur, to prevent damage or avoid exacerbating the hazard. Other effects include potential corrosion of vital equipment. Infiltration of under-ground pipe or duct systems by spilled hazardous substances could allow toxic vapours or liquid to spread for considerable distances, possibly reaching critical Lifeline facilities (e.g. pumping stations) some distance away.

Other Lifelines impacted indirectly (same as for any emergency) are roads, which would quickly become congested around the incident in question, and communications, which would quickly become overloaded.

Hazardous substances spills can occur in combination with fire (see also discussion paper on Fire). The Nufarm chemical fire in Otahuhu in 1995 is a recent example of such an event. The fire itself was a relatively small incident, well controlled by the automatic sprinklers fitted in the building. The major problem was that the chemical involved, a thioorgano-phosphate known as Azinphos Methly has an extremely low odour threshold (i.e. it is detectable at very low concentrations) and is also very toxic. The actual quantities which escaped from the premises were quite low but very detectable by smell. Central Otahuhu was closed and evacuated as a precaution for 3 hours. Civil Defence, although on stand-by and taking some steps, was never activated.

This incident was similar to the Civil Defence emergency in Parnell in 1973, but was much better controlled. The Nufarm incident was resolved in under 5 hours, whereas Parnell took 5 days.

2.0 SCENARIO

Hazardous substance spills are random events, and if a transportable source is involved, could occur anywhere. For this reason it is useful to illustrate the effects of a hazardous substance spill using a scenario.

Appendix 1 contains a scenario involving a hazardous substances spill from a transportable source in Newmarket. It has been developed by Auckland Regional Council Civil Defence and the NZ Fire Service for use in a Civil Defence exercise. The scenario highlights problems mainly concerning people management (evacuation, casualties) though with respect to Lifelines also illustrates problems concerning traffic congestion (making access to the site difficult for the emergency services and evacuation) and communications (overloading).

Individual utilities might find it useful to consider how their operations would be affected if a similar emergency occurred in the vicinity of their facility(ies), particularly if a complete evacuation was required.

3.0 SUMMARY

Hazardous substance spills are unlikely to severely impact on the region's infrastructure. Short term inconvenience to operations may be experienced due mainly to lack of personnel rather than equipment or plant failure.

4.0 REFERENCES

Auckland Regional Council, Civil Defence, Emergency Management Seminar, October 1996, Seminar Workbook.

Brown, N (1996) *Technological Hazards.* Paper No.7, Hazards Presentation Seminar, Dunedin City Lifelines Project, 1996.

APPENDIX 1: HAZARDOUS SUBSTANCE SPILL SCENARIO

Location: The Southern Motorway, Auckland on the Newmarket Viaduct and Broadway, Newmarket.

Weather: Overcast with light rain. The wind is North Easterly 5-10 knots and variable.

Scenario: At approximately 1400 hrs, a truck traveling North in the centre lane of the Motorway at about 100 kph, suffers a front tyre blow-out which causes the truck to career across the inside lane striking several other cars before hitting the barriers at the side of the motorway. On impact with the barrier the container breaks free and falls over the viaduct into Broadway, Newmarket at the Southern end of the shopping area.
Traffic in Broadway is moderate to heavy. The lights at Alpers Avenue have just changed and there is a gap in the traffic. The load lands in the road without directly impacting on any vehicle or person but flying debris hits passers by and causes injuries. The container of chemical breaks partially open dispersing some of its contents.

The chemicals: The chemical is Sodium Hydrosulphite also known as Sodium Dithionite.
In contact with water it will heat and can catch fire giving off Sulphur Dioxide an irritant and toxic gas. It is raining.
Sulphur Dioxide is detectable at extremely low levels and will cause concern over a considerable area.
Sulphur Dioxide dissolves in water to form acidic solutions of Sulphurous Acid which will irritate.

Effects: The noise of the impact of the container on the road will cause consternation. It is likely that flying debris will break windows. It will certainly damage cars parked at the side of the road and cause injuries amongst passers by. The site is a busy major intersection and there will be a large number of people in cars and buses pointing towards the incident and unable to escape. The roads likely to be held up are Manukau Road and Great South Road which are also down wind. The people will need to be controlled.
There are several major institutions immediately down wind. Epsom Girls Grammar School, Auckland College of Education allied with Epsom Normal Intermediate School, Brightside Hospital and Southern Cross Hospital. They will need to be protected and parents and relatives will need to be informed.
Gillies Avenue is a main arterial route from the Airport feeding the Southern Motorway, Northbound and lies directly down wind. Roads may need to be closed.

Summary: There is a major motor accident on the Southern Motorway. Several cars have been struck by the truck. There are casualties and persons trapped. The scene will be almost inaccessible North bound due to traffic build up.

There is an incident in Newmarket where persons are injured and in need of treatment. Access to the site is difficult due to traffic congestion.

The chemical in the container is getting damp and emitting fumes. It will start to show signs of heating and will need urgent attention.

There are large numbers of people in the down wind area who because of the fumes need to be moved or kept in place under control. These include school children and hospital patients who will have special needs.

POTENTIAL EFFECTS OF THE SCENARIO

Hazards of Chemical

Flammable/combustible material; may ignite itself if exposed to air; may reignite after fire extinguished; may burn rapidly with flare burning effect; runoff to sewer may create fire or explosion hazard; will form sulphuric acid if diluted with water.

Health Affects of Exposure to Chemical

The chemical is oxidized in the presence of air and moisture to sodium bisulphite and presumably can produce sulfite toxicity. Acute (short term exposure to high concentrations) exposure to sodium bisulphite may result in nausea, vomiting, diarrhoea, abdominal pain and gastric haemorrhage. Extremely large amounts may produce central nervous system stimulation, seizures, hypertension and cardiovascular collapse. Hypersensitive reactions may occur in asthmatics resulting in bronchoconstriction, tachycardia, hypertension and anaphylaxis.

Smaller amounts if inhaled may be harmful; contact may cause burns to skin and eyes; fire may produce irritating or poisonous gases; runoff from fire control or dilution in water may present further hazards; possibility of MCS (Multiple Chemical Sensitivity Syndrome) after prolonged exposure to low levels.

Casualties

Casualties would result from four distinct incidents involved in the scenario. These include:

1. Casualties suffering crushing impact injuries due to the effect of the shipping container falling into a populated area. The number of casualties will generally be small and may include a number of fatalities due to the severe trauma suffered as a result of the impact (6 significant, 20 minor).

2. Casualties resulting from acute exposure to the chemical (12 people including 3 emergency services staff).

3. Longer duration exposure to low concentrations of fumes over a wide area (500 people, including people caught in traffic jams).

4. Traffic accidents as a result of rubber necking or risk taking due to traffic congestion. This group needs to be considered as they will tie up resources and further congest access routes for emergency personnel (5 significant, 14 minor).

Traffic Flow

Within 15 minutes of the incident, traffic flow within 5 km of Alpers Ave will be at a standstill. The ensuing gridlock will hamper any movement by road. It will take hours to return the roads and motorways to the usual capacity. This is likely to impede the evening return of workers to their families.

Communications

Most people will be concern about the welfare of family and friends in or near the incident. The resultant use of telephones (mobile and fixed) may cause significant disruption to the service. Priority number handling may alleviate some of this problem.

Media Reporting

The media will wish to report as much as possible about the emergency, and will take calls from anyone who has some information. It is very important that the correct information is passed to the media. Media reports also need to be monitored to allow inaccuracies to be corrected.

DEMOGRAPHICS OF IMPACT AREA

Area Analysis: 0.5 km spread

Streets Affected:

Silver Road	Parts of:
Alpers Avenue	
Edgerley Avenue	Broadway
Clovernook Road	Gillies Avenue
Mortimer Pass	Motorway
Morrow Street	Crowhurst Street
Nuffield Street	Remuera Road
Belmont Street	Balm Street
St Marks Road	
Albury Avenue	
Withiel Drive	
Almorah Road	
Laviston Avenue	

Schools:	Newmarket School, Gillies Avenue	220
	Epsom Girls Grammar	1,650
	Epsom Normal	630
		2,500
Tertiary Institutions:	Auckland College of Education	2,800

Hospitals:	Mercy Hospital, Mountain Road	160	beds
	Omana Hospital, Omana Ave	28	
	Brightside Hospital, Brightside Road	36	
	Southern Cross Hospital, Gillies Avenue	60	
	Auckland Birth Centre, Gillies Avenue	8	
	Auckland Surgical, St Marks Road	10	
		302	
Emergency Services:	Police Station, Remuera Road		
Rest Homes:	Chadderton, Alpers Avenue	21	beds
	Rossaiore, Kipling Avenue	18	
	Kipling Lodge, Kipling Avenue	18	
		57	
Daytime Population:	Epsom North	3,5000	appr
	Epsom Central	1,950	
	Epsom South	1,350	
	Newmarket	8,100	
		14,900	

DEMOGRAPHICS OF DRIFT AREA

Possible effects to:

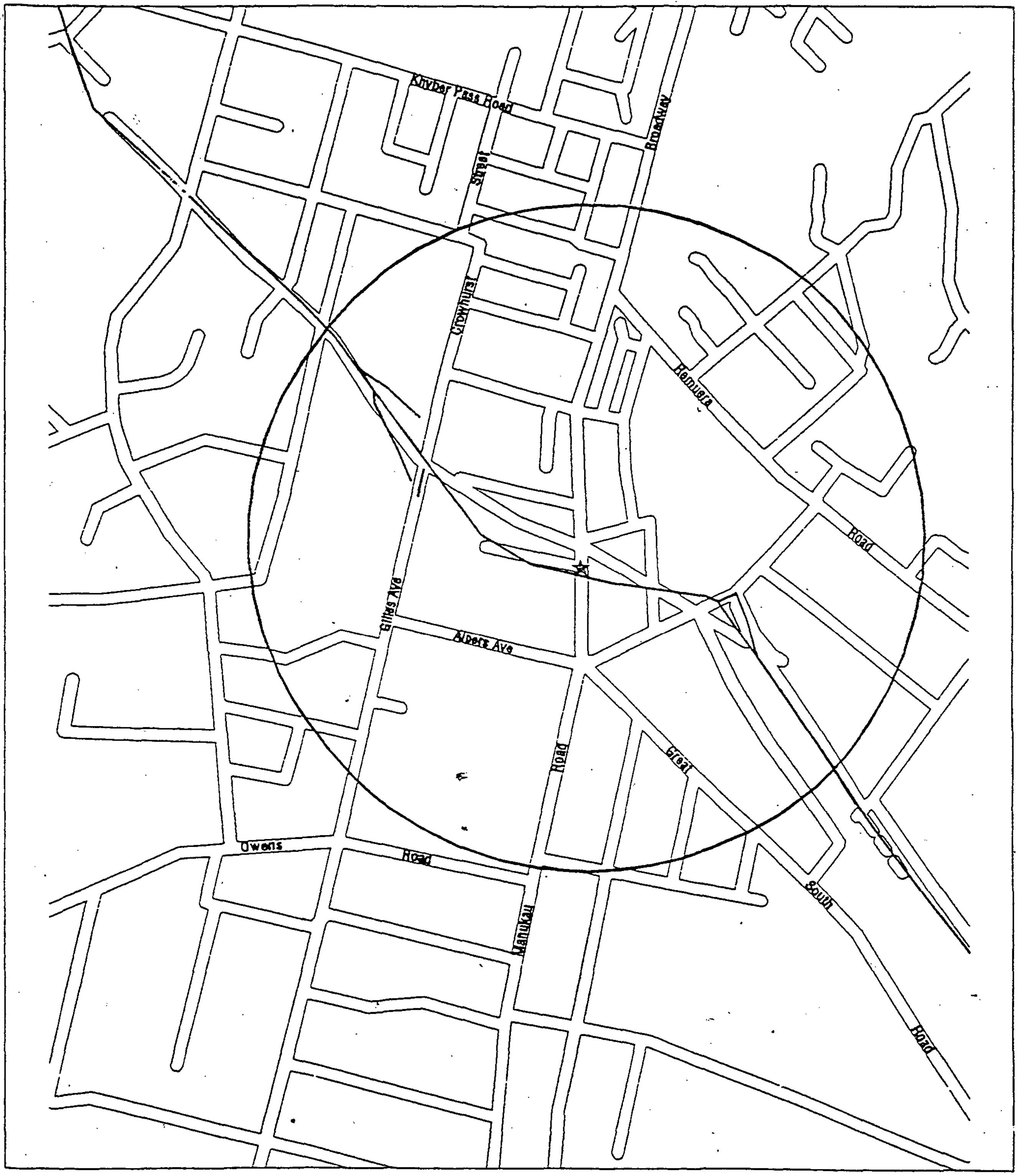
Schools:	St Peter College, Mountain Road	790	
	Auckland Grammar, Mountain Road	2,050	
	Diocesan School, Margot Street	1,200	
	Dilworth School, Erin Street	275	
	Dilworth Junior School, Market Road	180	
	St Cuthberts, Market Road	1,200	
	Balmoral Intermediate, Brixton Road	260	
	Maungawhau School, Ellerton Road	600	
	Seventh Day Adventist, Balmoral	80	
		6,635	
Hospitals:	Wesley Village, Mt Eden Road	101	beds
	Rawhiti Hospital, Mt Eden Road	32	
	Bellune Hospital, Mt Eden Road	24	
		157	
Emergency Services:	Balmoral Fire Station, Balmoral Road		
	Balmoral Police Station, Halsdon Road		
Rest Homes:	The Avenue, Epsom Avenue	10	beds
	Kendred, Epsom Avenue	18	
	Elizabeth Knox, Ranfurly Road	127	
	Cromwell House, Warborough Avenue	30	
	Ash-Lynn, Market Road	16	
	Oak Park, Manukau Road	20	
	St Patricks, Wilding Avenue	12	
	Shamrock, Walters Road	14	
	Albans House, Invermay Avenue	25	
	Walnut Court, Cambrai Avenue	14	

Clovernook, Mt Albert Road	28
Resthaven, View Road	50
Claire, Prospect Terrace	14
Edenvale, Edenvale Crescent	49
Taumata, View Road	10
Mabel Smith, Mt Eden Road	8
Bethesda, Esplanade Road	48
Chadwick, Lovelock Avenue	13
Steele House, Bourne Street	6
Resteden, Ashton Road	16
Hollyhurst, Fairview Road	14
Bruns Cottage, Kingsview Road	35
Villa Florence, Kingsview Road	19
	596

Daytime Populations:

Kingsland	3,400
Mt Eden North	3,500
Sherbourne	1,800
Balmoral	2,900
Mt Eden East	1,500
Owairaka East	1,750
Mt Albert Central	2,600
Sandringham West	2,100
Sandringham East	1,100
Maungawhau	1,760
Mt Eden South	1,600
	24,010

FIGURE 1: LOCALITY DIAGRAM



Disaster site — Site Area — Streets — Motorways

Map Produced By GIS Unit
Regional Development Section
ARC Environment

"Cadastral information derived from the Department of Survey and Land Information's Digital Cadastral Database (DCDB)
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FIGURE 2: PLUME DRIFT

★ Disaster site | Drift Area | Motorways | Plume drift area
Site Area | Streets | Meshblock Areas | Affected areas

Map Produced By GIS Unit
Regional Development Section
ARC Environment

Digital Meshblock Database
Statistics New Zealand
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Auckland Regional Council
ENVIRONMENT

SECTION 9

TERRORISM / VANDALISM

REPORT 9.1

VANDALISM / TERRORISM HAZARD

DISCUSSION PAPER PREPARED FOR THE AUCKLAND ENGINEERING LIFELINES PROJECT

By

Michele Daly (Auckland Regional Council)

With Assistance From

Superintendent D McConnell, NZ Police
Inspector B England, NZ Police

June 1997

1.0 INTRODUCTION

Vandalism at an individual property level is fairly common in New Zealand. However, vandalism at a scale which would seriously affect Lifelines (or other major facilities) has a relatively low probability.

Acts of terrorism/extremism in New Zealand are low probability, but have the potential to be high risk events. While recent acts (see below) have been small scale, the possibility of larger scale acts on major Lifeline facilities cannot be ruled out.

In both cases, the best preventative measures are good security, well trained and prepared personnel, and having up-to-date, well understood operational plans in place.

2.0 VANDALISM

Vandalism involves the wilful damage of property generally without reason (compare other definitions below). There have been no known reported cases of vandalism which have seriously compromised the ability of a Lifeline to maintain its service.

The best preventative measure is ensuring that there is good security in place. Security consultants can advise on appropriate security measures (see also section 4.0 below).

3.0 TERRORISM

Terrorism, extortion and sabotage actions in New Zealand are comparatively rare. Most incidents to date have been the result of internal agencies or individuals with particular agendas, and/or who wish to attract media attention to their cause. Some recent examples of these include an attempt to cut down the tree on One Tree Hill (political activism), damage to the Americas Cup (political activism) and the hijacking of a helicopter and hostage taking (environmental activism). These are normally one off situations which are a cause for embarrassment and publicity rather than a threat of national importance.

There is no known information in relation to terrorism against any facilities that would constitute a hazard to Engineering Lifelines.

International terrorist acts are rarer still, with only one known incident in New Zealand (Rainbow Warrior). New Zealand is probably at a higher risk from internal activists than those based overseas with an international political (or other) agenda against New Zealand.

The New Zealand Police has a Threat Assessment Unit at Police National Headquarters which deals with intelligence that could relate to terrorism. The Auckland Services District have Threat Assessment officers who analyse intelligence in relation to all terrorism and activist activities.

The SIS also analyse intelligence information in relation to terrorism and activist activities.

Contingency plans for dealing with specific terrorist situations can be developed, but these will generally depend on the particular situation and on the particular demands. The police are available to give advice on dealing with the situation once it has occurred, and will also give organisations general advice on a one-to-one basis. While the police would respond to an incident involving for example sabotage, and conduct an investigation as to who was responsible, the consequences of the act would need to be managed by someone else (in the case of a Lifeline, presumably the Lifeline operator).

4.0 THREAT ASSESSMENTS

Organisations which consider themselves a possible target for terrorism or vandalism should consider undertaking a threat assessment. Managers need to understand the extent of the security problems that they face and to identify those areas of their responsibility which are most likely to be threatened.

Key elements of a facility need to be identified and their security tested. In most organisations some controls and safeguards will already be in place, however they should be regularly reviewed and updated if necessary.

The security of key elements of a facility should be regularly reviewed and security measures maintained. Security consultants can advise on appropriate security measures. Good operating procedures should be in place and organisations should be aware of safety requirements under OSH (Occupational Health and Safety). There should be a contingency plan in place, or policy, which outlines the organisation's position with respect to incidents of this type. Staff training should also be considered.

5.0 SUMMARY

Antisocial behaviour has the potential to cause disruption to Lifeline services. Key installations and critical facilities should have adequate security measures in place to guard against incidents of this type.

6.0 DEFINITIONS

Extortion: Obtaining money or information from another party by coercion, intimidation or the wrong use of an official position.

Sabotage: The deliberate damaging of property or disruption of procedure with the intention of obstructing productivity or normal functioning.

Terrorism: The use of terror, violence, and intimidation to achieve a political end or other agenda.

Vandalism: The wilful or malicious destruction of public or private property.