Meteorological Hazards and the Potential Impacts of Climate Change in Wellington Region

A Scoping Study

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This report has been specially prepared for the Wellington Regional Council.

Andrew Tait, Rob Bell, Stuart Burgess, Richard Gorman, Warren Gray, Howard Larsen, Brett Mullan, Steve Reid, John Sansom, Craig Thompson and David Wratt

National Institute of Water and Atmospheric Research Ltd
PO Box 14-901, Kilbirnie, Wellington.

and

Mike Harkness

Wellington Regional Council
Regional Council Centre, 142-146 Wakefield Street, Wellington.

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Executive Summary

THE AIM OF THIS STUDY: In this study, the impacts of meteorological hazards and the potential impacts of climate change on the Wellington region are identified. The hazards investigated are intense rainfall and floods, droughts, landslides and erosion, coastal flooding, severe winds, snowfall and frost, excessively high temperature, lightning and hail, ex-tropical cyclones and wildfire. The likely impacts of climate change on these hazards over the next 50 to 100 years have been identified and the potential climate change impact on Wellington Region activities has also been reported.

USE OF SCENARIOS: Climate change predictions given in this report are derived through the use of scenarios, in which a number of greenhouse gas emission pathways are constructed for the future, based on a range of plausible social, economic and technological developments. For each of these scenarios, predictions are then made for greenhouse gas concentrations and the resulting climate changes, based on scientific understanding and incorporating science-based uncertainty ranges. The result is a set of several different climate "projections", spanning likely future emissions pathways.

FLOODS: These present a significant hazard to the Wellington Region. 1-in-100 year flood inundation maps based on historical climate and river data are provided in Figures 2.4 to 2.7 for the Hutt, Otaki and Waikanae Rivers and a 1-in-50 year flood map for the Wairarapa Plains is shown as Figure 2.8. Climate change is expected to increase flooding risk, but science-based quantitative information on this is currently weak, with projected possible changes spanning a wide range. Interim projections are that the intensity of heavy rainfall could increase by up to about 7% by 2050. By 2030 the return period of heavy rainfall events and associated floods could be reduced by up to a factor of 2, and by 2070 by up to a factor of 4, but also the possibility cannot be ruled out that there will be no discernible reduction in return periods.

DROUGHTS: The part of the Wellington region most affected by droughts is the Wairarapa, where there are on average 15 days per year when soil moisture deficits exceed 130 mm. There is substantial year-to-year variability however, with up to 74 days of deficit exceeding this amount in some years. In the Kapiti, Wellington and Hutt Valley areas there are on average 10 days annually with a deficit exceeding 130 mm. Dry growing seasons (October – May) in the Wairarapa are frequently but not always associated with El Niño climate patterns. Projected temperature and rainfall changes suggest there will be a trend of increasing drought occurrence in the Wairarapa through the coming century, but no quantitative predictions are yet available.

LANDSLIDES: The Wellington Regional Council has made a number of attempts to define the landslide hazards in the region, focussing on both rainfall and earthquake induced landslides. Maps of landslides resulting from specific storms are shown as Figures 4.2 and 4.3. However, the current landslide hazard maps are not comprehensive or accurate enough to rely on solely for effective landuse management and planning strategies. A comprehensive landslide inventory would provide information on susceptibility, landslide triggers, and the frequency and magnitude of events.

TIDES: The storm tide height reached in Wellington Harbour during the 1936 Cyclone event of approximately 1.7 m above the Wellington Vertical Datum–1953 is probably a useful benchmark for a 1% Annual Exceedance Probability (or 100-year return period). Also, wave heights of up to 8.1 m (Te Kaukau Pt) are possible around the Wellington Region coast, based on 20-year hindcast modelling.

SEA-LEVEL RISE: "Most likely" estimates for sea-level rise around the Wellington region by 2050 and 2100 are 0.26–0.30 m above WVD-53 and 0.42–0.62 m above WVD-53, respectively. There is a small chance that sea level might rise by up to 1.0 m above WVD-53 in the year 2100. For tides, a level of 0.9 m above WVD–53 which would currently not be exceeded at all in 100 years, would be exceeded by up to 17% of all High Waters given the predicted rise in sea level by 2050.

WIND STORMS: The maximum 3-second gust speed (km/hr) at 10 m above the ground for low lying areas expected to be equaled or exceeded at an average interval of 142 years for most of the Wellington region is about 198 km/hr and at an average interval of 475 years is about 216 km/hr. These return period wind speeds are higher for escarpments, hills and ridges by between 1.04 and 1.54 times (see Table 6.1 for multiplication factors). Under global warming the mean westerly wind component across New Zealand is expected to increase by approximately 10% of its current value by 2050.

SNOW: Snowfalls (periods when snow is reported as falling, even if it melts upon reaching the ground) are quite rare below about 200 metres above sea level, occurring about once in every 2–5 years in the Wellington region. At about 200 metres and above, on average at least one fall of snow is likely each year and at around 600 metres there are an average of 5 snowfalls a year. Above 800 metres, an average of about 22 days of snowfall have been reported at Makahu Saddle and Ngamatea, in the ranges to the north of Wairarapa.

FROST: The lowland areas exhibiting the highest frost risk are the Hutt Valley, particularly Upper Hutt, the area around Palmerston North, and west of the Tararuas between Masterton and Dannevirke which currently experience around 30 – 40 screen frosts each year. This number varies by year to year, ranging from about 15 to 65. High elevation areas (above 500 m) regularly receive more than 100 screen frosts each year. Climate models indicate about 10 fewer screen frost days per year by 2100 in the Wellington region.

EXTREMELY HIGH TEMPERATURE: The mean annual extreme maximum temperatures are typically around 31–32 °C on the Wairarapa Plains in the vicinity of Masterston and Greytown. The east coast typically receives extreme temperatures up to around 30 °C, while west of the Rimutakas and Tararuas maximum temperatures rarely exceed 27 °C. Higher mean temperatures due to climate change will increase the probability of extreme warm days and decrease the probability of extreme cold days. The expected change between 1990 and 2100 in the number of days per year above 25°C, for the SRES A1 mid-sensitivity emission scenario, and for the HadCM2 and CSIRO9 global climate models, for example, is an extra 15 – 30 days for the Wellington region.

HAIL AND LIGHTNING: The frequency of occurrence of both hail and lightning is relatively low in southern Wairarapa (1 – 2 days of hail/year and 0.15 – 0.25 lightning flashes/km^2/year) and correspondingly higher to the north (2 – 3 days of hail/year and 0.5 – 0.7 lightning flashes/km^2/year) and near the Kapiti Coast (3 – 5 days of hail/year and 0.4 – 0.6 lightning flashes/km^2/year). We expect the frequency is higher still over the Tararua ranges, although the data does not show it because of the lack of observing sites. Climate change is likely to change the risks of hail and lightning, most probably increasing the risk of each because of an increase in convective activity. Some researchers suggest an increase of 1ºC in average wet-bulb temperature might be accompanied in mid-latitudes by a 40% increase in lightning, but this is still quite uncertain.

EX-TROPICAL CYCLONES: These events pose a risk in that they bring both intense rainfall and wind, however the frequency of events is relatively low. Tropical cyclone track data suggest that central New Zealand, including the Wellington region is affected by cyclones of tropical origin once every three to six years. The most extreme ex-tropical cyclone to impact the Wellington region was the Wahine storm in which the strongest winds reached 110 km/h (gusting to 150) at the entrance to Wellington Harbour where the inter-island ferry Wahine was making its arrival.

STORMINESS: While it appears likely that "storminess" will increase in the Southern Hemisphere this century, we cannot yet say whether this will mean more intense storms, or a higher frequency of passing cold fronts, or some combination of these. Moreover, a general increase over the Southern Hemisphere as a whole does not necessarily imply an increase locally in the small sector of the hemisphere that New Zealand occupies. Regional changes will be sensitive to changes in prevailing wind strength and direction, which vary considerably between models. An analysis of current and predicted future changes in storminess requires processing large quantities of daily data from observations and models, and is a topic identified by NIWA for future research.

WILDFIRE: While the occurrence of four wildfires at the same time (January 2001) was an extremely rare event, the chances of similar fire seasons in the future are more likely due to easier access into forested areas, taller trees (more fuel) and a more blurred rural-urban interface. Wildfire frequency is closely related to drought frequency, as lower than normal rainfall is the main proponent for higher than normal fire outbreaks. It is possible that wildfire risk might increase in the future, based on climate change scenarios, particularly in the drier eastern parts of the Wellington region.

IMPACTS: Potential impacts of climate change on Wellington region activities through changes to meteorological hazards are wide ranging. These include but are not limited to: An increased threat to lifelines and services coming from more frequent heavy rainfall events and associated floods; increased drought risk particularly in the east of the Wellington region affecting the suitability for particular crops; sea level rise making groundwater aquifers near the coastline vulnerable to saltwater intrusion; and changes in temperature and rainfall regimes brought about by climate change causing problems for plant and animal pest eradication programmes. Also, climate change has the potential for positive impacts to the Wellington region such as the introduction of sub-tropical or frost-sensitive crop species, and yield increases due to higher carbon dioxide concentrations and extended growing seasons.

1. Introduction

1.1 The Climate of The Wellington Region

The climate of the Wellington region (Figure 1.1) is dominated by the presence of Cook Strait and the rugged local topography. Average annual rainfall for most of the region is in the range of 1200 to 1400 mm, rising steeply to about 2400 mm in the Rimutaka Range and to about 3200 mm in the Tararua Range (Goulter, 1984). East of the ranges there is a rapid decrease in rainfall to a minimum of about 800 mm/year on the plains, where in addition to the sheltering from the main ranges to the west, the Aorangi Mountains provide some sheltering from east and southeast rains (Thompson, 1982). The distribution of rainfall throughout the year shows quite a strong variation, with lower totals in the summer and higher totals in the winter. At the Kelburn meteorological station, average rainfall in January is 81 mm while in July it is 139 mm.

Rainfall records extend as far back as the late 1800's for some sites in the region. In general, there is quite a lot of variability present in the data. Figure 1.2 shows the annual percent of normal rainfall for Wallaceville, for example. It can be seen that some years have been much wetter than normal (1936, 1941, 1977, 1979 and 1980 were all above 120 % of normal rainfall) and others have been much drier than normal (1932, 1933, 1937, 1939, 1950, 1963, 1969, 1970, 1971 and 1973 were all below 80 % of normal rainfall). While in some years there have been rapid changes from the previous year's rainfall (e.g. 1968 = 1507 mm, 1969 = 777 mm), lower than normal or higher than normal rainfall periods can persist for several years, as is shown by the 5-year moving average curve on Figure 1.2.

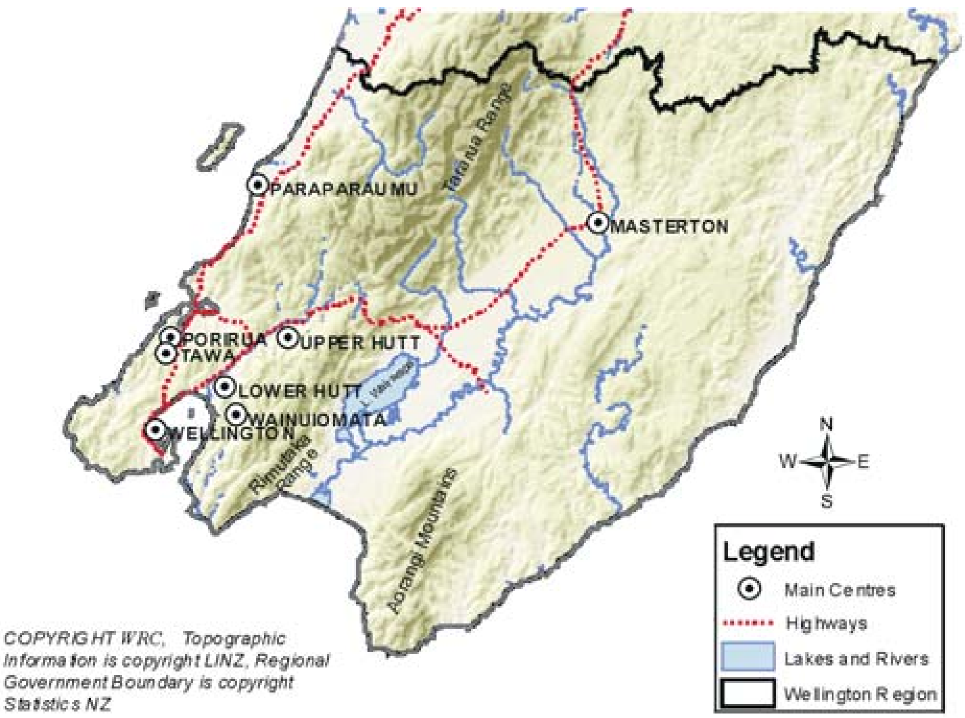


Figure 1.1: Location map of the Wellington region.

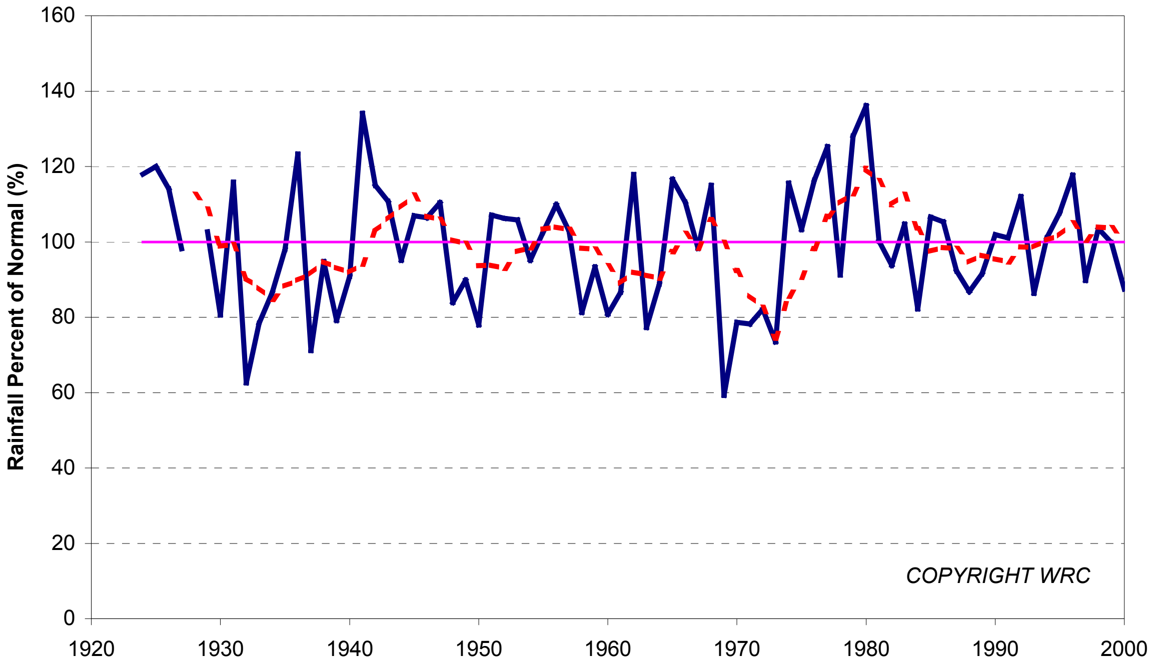
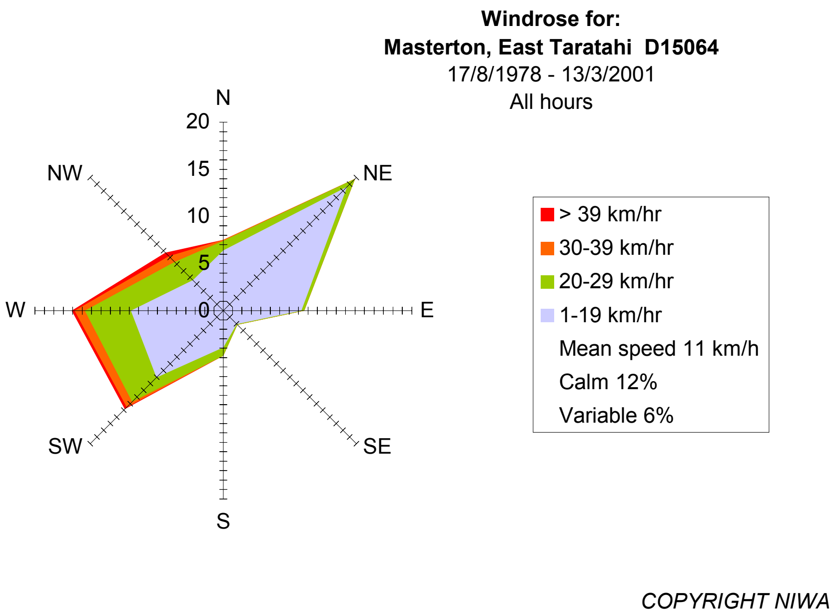


Figure 1.2: Annual percent of normal (1970-2000) rainfall for Wallaceville for the period 1924-2000 (solid blue line). The normal annual rainfall for this location is 1311 mm. A five-year moving average is also shown (dashed red line).

Wellington region's proximity to Cook Strait leads to high frequencies of strong winds, and because the lower level flow is strongly forced by the rugged topography, the winds tend to be very gusty. The anemograph on the 122 m high TV tower on Mount Kaukau (425 m) records a very high (42 km/h) average wind speed. Below hilltop level the winds are disturbed by the terrain and the average speeds are much less, nevertheless gust speeds may be comparable with the higher level winds. Seasonal variation is not large, with a maximum mean wind flow in late spring. However, strong spatial variation is evident, with the mean wind speed at Wellington Airport (27 km/h) much greater than at Wallaceville (10 km/h), Masterton (12 km/h) and Paraparaumu Airport (16 km/h).

Due to the channelling of airflows by the hills and ranges around Wellington, the wind direction is mostly either northerly (most frequently between October and January) or southerly (most frequently between May and August). The Wairarapa is also quite exposed and high winds are not uncommon (Figure 1.3). Strong turbulent winds crossing the ranges from the west can descend to the plains to produce very gusty föhn surface winds. Masterton typically has about 24 days per year with wind gusts greater than 60 km/h. The most frequent wind direction for the Wairarapa is from the northeast, and these winds tend to be quite light (Figure 1.3).

The duration of bright sunshine varies from about 1600 to 1700 hours per year in the Tararua Ranges to over 2000 hours per year in some locations east and west of the ranges. Table 1.1 gives the mean monthly and yearly totals of sunshine hours for eight locations in the region. A strong seasonal fluctuation from a minimum in winter of about 100 hours to around 220 hours in mid-summer is typical, while quite strong local effects of the order of 100 hours annually clearly exist within the region.



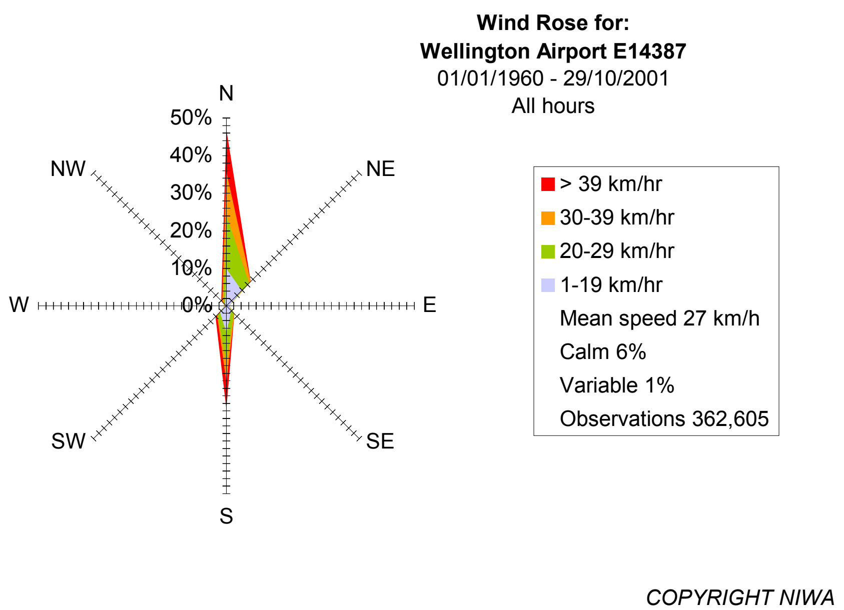


Figure 1.3: Wind roses for Masterton, East Taratahi and Wellington Airport. The scale on the axes represents the percent frequency and the colour depicts the mean speed for winds emanating *from* the direction indicated.

The maritime location and windiness of the Wellington region ensure that temperature extremes are moderate, while the rugged topography leads to quite strong spatial variation. The sheltered Wairarapa plains generally have a larger temperature range (diurnally and seasonally) of temperature than is found on the western side of the ranges. Monthly mean daily temperatures vary seasonally from a summer maximum of about 17 °C (west of ranges) to 22 °C (east of ranges) to a winter minimum of about 8 °C (west of ranges) to 2 °C (east of ranges).

Table 1.1: Monthly and annual average sunshine (hours) and, in parentheses, the annual percent of possible sunshine hours (%). Copyright NIWA.

Location	J	F	M	A	M	J	J	A	S	O	N	D	Year
Kelburn	236	201	186	151	118	104	107	132	162	190	208	224	2019 (48)
Paraparaumu	235	201	184	157	128	114	121	138	158	184	201	222	2043 (48)
Kaitoke	218	191	177	125	93	75	85	95	119	169	204	195	1746 (41)
Wallaceville	226	195	180	145	111	96	98	123	145	171	194	212	1896 (45)
Taita	224	200	169	138	104	86	99	115	131	175	201	214	1856 (44)
Makara	195	172	156	128	102	100	101	102	126	161	170	185	1698 (40)
Waingawa	233	197	188	151	117	106	107	130	163	192	211	212	2007 (47)
Martinborough	245	212	200	160	127	121	119	141	179	194	230	239	2167 (51)

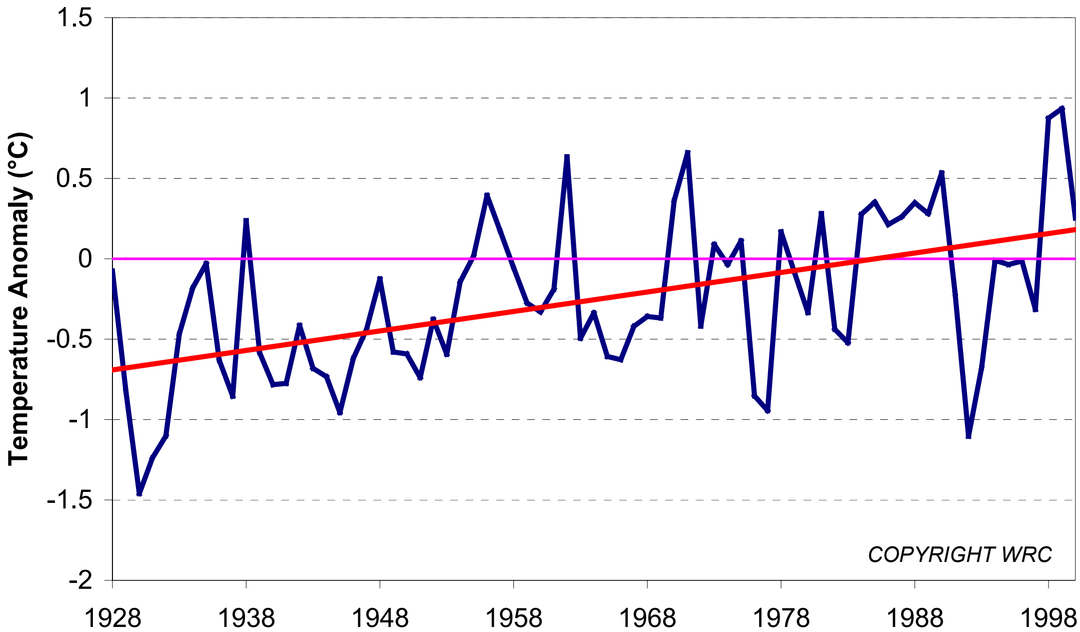


Figure 1.4: Mean annual temperature anomaly (difference from1970-2000 mean of 12.8 °C) for Kelburn for the period 1928-2000 (solid blue line). The solid red line represents the trend of 0.12 °C/decade.

Despite much cooler than normal conditions in 1977, 1978 and 1992, temperatures are generally warmer now than they have been in the last 70 years. The mean annual temperature for Kelburn in 1999 was 0.9 °C above normal, at 13.7 °C, which was the warmest year since records began. Figure 1.4 shows that there has been a general increase in the mean annual temperature for the Wellington region over the last 70 years by about 0.12 °C/decade.

1.2 Overview of Meteorological Hazards in the Wellington Region

Several meteorological hazards and their impacts on the Wellington region are identified and presented in detail in sections 2–11 of this report. A brief overview of each meteorological hazard, areas of high risk, methods of amelioration and knowledge gaps is presented here.

1.2.1 Floods

Floods represent one of the most important hazards the Wellington region faces. Damage from flooding occurs through inundation, wind damage, land slides and through extraneous causes such as car crashes. The Tararua Ranges acts to enhance precipitation and severe flooding can occur "simultaneously" on both sides of the Tararua's during the passage of a single storm. Rainfall return period maps suggest that as much as 600 mm is likely to fall in a 24-hour period in the Tararua Ranges with a return period of 142 years and as much as 800 mm with a return period of 475 years. 1-in-100 year flood inundation maps for the Hutt, Otaki and Waikanae Rivers and a 1-in-50 year flood map for the Wairarapa indicate that large areas are at risk. For example, it is estimated that 100 utility services (communications, water, waste, energy) and 126 transport services (road, rail, pipelines, parking) are within the flood prone area of the Hutt Valley.

Several flood amelioration schemes are in force around the region. These include stopbanks, channel management work such as bed and beach re-contouring (or cross blading) and gravel extraction, bridge upgrades, and non-structural measures including land use planning regulations, and steps that floodplain residents, groups, businesses, and utility and emergency services can take to prepare for floods.

There is some interim guidance available on likely climate change impacts on heavy rain and flood frequency, but this is very general and based on limited research. Interim projections are that the intensity of heavy rainfall could increase by up to about 7% by 2050. By 2030 the return period of heavy rainfall events and associated floods could be reduced by up to a factor of 2, and by 2070 by up to a factor of 4, but also the possibility cannot be ruled out that there will be no discernible reduction in return periods. Further scientific study on likely impacts of climate change on heavy rainfall and floods is therefore a high priority for all New Zealand regions including Wellington. Detailed maps of lifeline services within the defined flood prone areas should be drawn up. Rainfall and flood forecasting skills need improving and investigation into flood effects on smaller rivers and streams needs to be considered.

1.2.2 Droughts

The issue of drought is a major concern in the Wellington region. Drought occurs during a sustained period of low rainfall, which has persisted long enough to produce serious hydrological imbalances. It is usual for the Wellington, Hutt, Kapiti and Wairarapa districts to experience at least one extended period of low rainfall each year, especially during the warmer months from November through March. For the Wellington region the potential for severe drought is highest in Wairarapa, where there are on average about 15 days a year when soil moisture deficits exceed 130 mm. On average 10 days with a deficit of that nature can currently be expected in Kapiti, Wellington and the Hutt Valley. The extent and severity of drought can be affected by significant El Niño or La Niña events. During El Niño, drought becomes more prevalent in the Wairarapa than elsewhere in the region, while during La Niña's areas west of the Tararua Ranges can experience prolonged periods of drought.

The consequences of drought include shortages or restrictions on water supplies, damage to horticulture, feed shortages, stress to evergreen trees and shrubs and an increased potential for wild fire. Water supply is the main lifeline at risk from drought. The metropolitan water supply systems in the Wellington region have relatively little storage capacity. Extended periods of low rainfall restrict the amount of water available from rivers, while causing the amount of water used to increase.

The principal amelioration method is the efficient use of water. This is true for horticultural, agricultural and metropolitan uses. Local authorities and WRC operate water conservation programmes over the summer and autumn months and regularly check distribution systems for leaks. Good information about long-term drought risk, up-to-date information on soil moisture and rainfall, long-range (1 – 2 week) weather forecasts, and seasonal climate outlooks can help farmers manage for drought. Various agencies such as WRC, NIWA, and MetService offer seasonal forecasts thus allowing a degree of forward planning for agricultural and water supply needs. However, seasonal forecasting cannot give a categorical prediction of drought or rain - it can only produce guidance on the "odds" of a coming season being drier or wetter than normal.

Further research into the impacts of climate change on droughts in the region needs to be undertaken. Investigations looking at the shallow groundwater resource and studies to determine the moisture requirements of soils, crops, and varying land uses will be of benefit in the development of efficient use/irrigation of water in the region.

1.2.3 Landslides and Erosion

For lifeline considerations, landslides and erosion that threaten infrastructure of the Wellington region are of importance. The nature of the region’s terrain–steep, geologically young, undergoing tectonic uplift, and with the soil mantle exposed by vegetation clearing–means that landslides will occur. The most obvious and common lifeline to come under threat from landslides in the region is transportation systems. Many of the region’s roads and rail lines are cut through the underlying hard but closely fractured greywacke bedrock. Also, landslides cause significant damage to structures such as houses. Other impacts of landslides are on power supply, water supply, telecommunications, the stormwater network and gas supply.

In 1994, WRC produced a map for earthquake induced slope failure for the Wellington region. The map assigns susceptibly ratings to slope stability factors. The areas of susceptibility defined in the map are also applicable to landslides brought about by rainfall. To date this is the best method the WRC has to determine the rainfall induced landslide hazard for a particular area.

However, the current landslide hazard maps are not comprehensive or accurate enough to rely on solely for effective landuse management and planning strategies. A comprehensive landslide inventory would provide information on susceptibility, landslide triggers, and the frequency and magnitude of events. This information would be important in developing land management policies and guidelines for the avoidance and mitigation of landslide hazard and risk.

1.2.4 Coastal Flooding

Key coastal hazards for the Wellington region relate to either coastal erosion (shoreline retreat) or occasional coastal flooding, due to extreme tides, storm surge, heavy seas or a tsunami. Key drivers of coastal flooding (inundation), coastal erosion and maritime/recreational hazards are extreme tides, waves, atmospheric pressure, winds, and coastal currents, while tsunami can be generated by earthquakes and/or underwater landslides.

The coastal topography around the Wellington region's coastline is mostly rugged with few very low-lying areas. However there are populated low-lying areas that are vulnerable to coastal flooding hazards, either at present or in the future as sea level continues to rise. Also, infrastructure such as roading is vulnerable to coastal flooding in some locations despite the adjacent rugged terrain.

Coastal erosion hazards in the Wellington region have had a high public profile at various times, particularly when coastal dwellings have been threatened. One memorable event was the 11–13 September 1976 storm that caused rapid erosion at Raumati and Waikanae Beaches on Kapiti coast, threatening to undermine several dune-top dwellings. Other high-profile areas for erosion have been on the east coast at Castlepoint, Riversdale Beach and Te Kopi.

Continued rigid adherence to planning mechanisms under the NZ Coastal Policy Statement, the Regional Coastal Plan, and District Plans to ensure sufficient coastal buffers to absorb most of the consequences of coastal erosion and coastal flooding is the key process for coastal hazard amelioration. Also, a simple storm-surge/wave warning system could be set up based around wave and sea-level monitoring systems, which along with evacuation street maps based on extreme storm tide and wave run-up, would provide a faster response to an event and ease the risk of damage and injury.

1.2.5 Severe Winds

Winds in the Wellington region are influenced by several meteorological factors leading to a very complex regime. The western part of the region is subject to frequent high winds associated with Cook Strait while the eastern part of the region in the Wairarapa has some areas subject to extreme downslope winds but other areas have remarkably benign wind climates. The Tararua range is a high wind part of the region.

One of the most devastating storms of the last century to impact the Wellington region was the Wahine storm in April 1968. Wind speeds of 110 km/h (gusting to 150) were recorded at the entrance to Wellington Harbour at the time the inter-island ferry Wahine was making its arrival (see section 10 on ex-tropical cyclones).

Maximum 3-second gust speed (km/hr) at 10 m above the ground for low lying areas expected to be equaled or exceeded at average intervals of 142 years for most of the Wellington region is about 198 km/hr and at average intervals of 475 years is about 216 km/hr. These return period wind speeds are higher for escarpments, hills and ridges by between 1.04 and 1.54 times (see Table 6.1 for multiplication factors). Wind damage can be ameliorated by design of structures for their particular locations. Much progress has been made in recent years by recognising that design is not just a question of geographical location but that design against winds requires micro-zoning so that crests of ridges lying across the winds and local areas with channelling are identified.

Knowledge of instrumentation characteristics is important and recording of instrument characteristics and siting could be improved. Changes of extreme wind associated with natural and human induced climatic variations are also important but are difficult to determine with much certainty. Knowledge of the spatial variation of extreme wind speeds due to terrain may be advanced in the next few years due to improved numerical models and is an area of potentially fruitful research.

1.2.6 Snow and Frost

Snowfall (a period when snow is reported as falling, even if it melts upon reaching the ground) is a relatively uncommon event at sea level in the Wellington region, although visual records of snow falling are reported most years. In the hill country and mountains, snowfalls are more common, typically occurring during winter and early spring. Frosts are more common in the region, particularly in non-coastal areas like the Hutt Valley. As hazards, snow and frost have a significant impact on transport systems, particularly roads, with slippery roads often causing major traffic problems.

Below about 200 metres, snowfalls occur about once in 2–5 years. At about 200 metres above mean sea level and above, on average at least one fall of snow is likely each year. At around 600 metres there are an average of 5 snowfalls a year. Above 800 metres, an average of about 22 days of snowfall have been reported at Makahu Saddle and Ngamatea, in the ranges to the north of Wairarapa.

While snowdays are a standard meteorological variable, snow depth is not measured at New Zealand climate stations. Hence, there is no way of knowing from the records whether 1 cm or 20 cm of snow fell on a particular snowday. This has obvious implications for hazards analyses, as snow becomes more hazardous (affecting transportation, communications, damaging power lines and roofs due to snow loading) the more of it that falls and settles on the ground.

The high frost risk lowland areas are the Hutt Valley, particularly Upper Hutt, east of the Tararuas along State Highway 1 between Paraparaumu and Palmerston North, and west of the Tararuas between Masterton and Dannevirke. These areas currently experience around 30 – 40 screen frosts each year, although this number varies by year to year, ranging from about 15 to 65. High elevation areas (above 500 m) regularly receive more than 100 screen frosts each year.

The Meteorological Service of New Zealand issues frost and snowfall warnings, which are very useful. To reduce the hazardous impacts of frost and snowfall, residents should be advised to stay indoors, monitor those at high risk (particularly the elderly), cover sensitive plants and drive with extreme caution. Also, the application of salt and/or grit to roads speeds up the melting process and hence reduces the potential for accidents.

1.2.7 Excessive Temperature

The climate of the Wellington region is relatively mild and excessive temperatures are generally rare and short-lived compared with continental locations. Nevertheless, extreme temperatures can still pose a hazard in the region, as the health of residents, particularly the elderly, can be detrimentally affected by significantly above average temperatures.

The mean annual extreme maximum temperatures are typically around 31–32 °C on the Wairarapa Plains in the vicinity of Masterston and Greytown. The east coast typically receives extreme temperatures up to around 30 °C, while west of the Rimutakas and Tararuas maximum temperatures rarely exceed 27 °C. However, the health dangers associated with extremely high temperatures (e.g., heat stroke) are not limited to the highest temperature regions, rather it is the relative difference between average and extreme temperatures which is important. The highest health risk area, with respect to extreme heat, is eastern Wairarapa in the hills around Gladstone extending northwest to include Masterton.

1.2.8 Lightning and Hail

Lightning and hail are weather elements associated with severe convective storms. They cause damage directly as well as being associated with the other damage caused by such storms through for example severe wind and rain. This direct damage can include, for lightning, the destruction of electrical and electronic installations providing power and communications, and for hail the destruction of crops and damage to infrastructure. Lightning and hail also pose a health risk to people and animals.

The frequency of occurrence of both hail and lightning is relatively low in southern Wairarapa (1 – 2 days of hail/year and 0.15 – 0.25 lightning flashes/km^2/year) and correspondingly higher to the north (2 – 3 days of hail/year and 0.5 – 0.7 lightning flashes/km^2/year) and near the Kapiti Coast (3 – 5 days of hail/year and 0.4 – 0.6 lightning flashes/km^2/year). We expect the frequency is higher still over the Tararua ranges, although the data does not show it because of the lack of observing sites. The risk from lightning is greatest for communications towers, power and telephone cables. Damage resulted from hail, or from the inundation into buildings of rainwater failing to flow down hail-filled gutters can include damage to orchard and vineyard crops, plastic roofing, skylights and guttering, car bodies and windscreens, and bird deaths.

There is substantial uncertainty in our knowledge of the frequency and distribution of lightning. To resolve the discrepancies in the data will involve a more detailed study than has been possible here. Further data is becoming commercially available from a new lightning detection system which could assist this analysis, at some cost. Resolution of this issue is important in the planning of new communications and power infrastructure. There is also some uncertainty about the detailed distribution of hail, which would be relevant in the planning of sensitive structures such as glasshouses.

1.2.9 Ex-Tropical Cyclones

Ex-tropical cyclones are often the cause of New Zealand's most extreme weather leading to extensive flooding and wind damage and this damage (and also the naming of the storms) leads to them being well remembered by the public. Ex-tropical cyclones pose a risk in that they bring both intense rainfall and wind, which as detailed previously in this report, can cause major damage. Far from being confined to wind damage and flooding, there is also the potential for storm surges and waves to exacerbate the situation.

These cyclones can generally be forecast quite reliably, usually allowing for a number of days warning before it reaches New Zealand. Amelioration measures for these cyclones are the same as for intense rainfall and floods (section 2), coastal flooding (section 5), and severe winds (section 6).

1.2.10 Wildfire

Wildfires in the Wellington region can result in the burning of large areas of bush and forest and the consumption of hundreds of thousands of dollars worth of man-hours and fire-fighting equipment usage. For example, this was the case in January 2001 when there were four significant wildfires in the Wellington region, three of which were the result of arson. The four fires were in Porirua, Plimmerton and two in Silverstream.

Wildfires of the size of the above fires are not uncommon in the Wellington region. However, while the occurrence of four fires at the same time was an extremely rare event, according to David Etchells, Upper Hutt City Council Principal Rural Fire Officer, the chances of similar fire seasons in the future are likely to increase due to easier access into forested areas, taller trees (more fuel) and a more blurred rural-urban interface.

The estimated fire hazard risk for the Wellington region has been mapped by WRC. The greatest fire risk areas are characterised by gorse and scrub type vegetation, on steep slopes, with relatively low rainfall, and close to areas frequented by people. Approximately 20% (165,500 ha) of land in the Wellington region is at 'high', 'very high' or 'extreme' risk from wildfire.

Mitigation measures include: increasing the size of and maintaining defensible space around buildings; replacing flammable vegetation with less flammable species; managing vegetation to speed floral succession at the boundaries of defensible space; use of fire resistant building materials and structures such as stone walls to reduce flammability of buildings; matching of building design, siting, and materials to perceived hazard; and land use planning for new subdivision development.

An accurate meteorological forecast is vital for real-time analyses of the probable spread of the fire and its heat intensity. These estimates help determine the best method of fire fighting, whether it be hoses, bulldozers, helicopters or some combination of these. Current knowledge gaps include a lack of high quality statistics on wildfire occurrence and a lack of appropriate models for fire behaviour in New Zealand vegetation types.

1.3 Overview of Climate Change Impacts in the Wellington Region

Projecting climate changes and assessing their impacts on the Wellington Region depend on downscaling the best available predictions of global and continental-scale changes such as those reported in the recent Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001). Even global-scale projections contain uncertainties – not least because the greenhouse gas emissions over the next century, which drive climate changes, will depend on how the world's population and economics develop and on choices which are made about energy generation and use. Downscaling these global projections to estimate likely changes at the scale of the Wellington region introduces further uncertainties.

To deal with these uncertainties, scientists typically consider an ensemble of climate change "scenarios", which between them span most of the likely greenhouse gas pathways and incorporate some of the climate modelling uncertainties. The climate change projections in this report come either from a range of scenarios, or from near the midpoint of such a range. Thus they are statements about what "could" happen, rather than definite statements about what "will" happen.

1.3.1 Climate Change Impacts on Specific Meteorological Hazards

When it comes to considering the effect of climate change on extremes, there is very little information available directly from the models at the New Zealand scale. The global climate models (GCM) have much too coarse a resolution to provide a reliable spot value for, say, an extreme daily rainfall or temperature. However, local effects can be inferred through the use of a high resolution model "nested" within a GCM, or through "statistical downscaling" which makes use of statistical relationships between local climate and larger scale climate patterns, or through the generalisation of extreme changes analysed for other parts of the globe. This report draws predominantly on information from statistical downscaling.

According to the IPCC, more intense precipitation events are "very likely, over many areas", however this does not necessarily apply to an area as small as that of the Wellington region. Nevertheless, a warmer atmosphere can hold more moisture (about 8% more for every 1°C increase in air temperature), and so the potential for heavier extreme rainfalls is present. Interim projections are that the intensity of heavy rainfall could increase by up to about 7% by 2050. An alternative way of viewing these systematic increases in average rainfall intensity is to say that a reduction in the return period of heavy rainfall events is expected. By 2030 the return period of heavy rainfall events and associated floods could be reduced by up to a factor of 2, and by 2070 by up to a factor of 4, but also the possibility cannot be ruled out that there will be no discernible reduction in return periods.

Increased drought risk is related to a combination of both increased evapotranspiration and reduced precipitation. Systematic changes in evapotranspiration cannot readily be deduced from model simulations at this point. Obviously, reduced rainfall is likely to increase the risk and severity of drought, particularly if the rain that does fall is more unevenly distributed in time (i.e., falls on fewer days). An index computed by Salinger and Griffiths (2001) relevant to low rainfalls is the maximum number of consecutive dry days in a year. Over the last 50 years, this index shows a trend in Wellington region for an increase in Wellington and a decrease in Masterton.

Mullan *et al.* (2001) assessed future river flow changes using the latest scenarios of temperature and precipitation change coupled to a detailed hydrological model of a river catchment. Although none of these catchments was in Wellington region, the reduction in river flow was shown to be twice as large in percentage terms as the rainfall reduction. River flow could also decrease for small (5% or less) increases in precipitation. Thus, it is likely that the east of the Wellington region could experience increased drought risk through a combination of higher temperatures, reduced mean rainfall, a changed rainfall distribution, and more westerlies.

Based solely on sea-level rise, present beaches which are in dynamic equilibrium or eroding are likely to experience increased rates of erosion. Accreting coasts are likely to continue to build seawards, but at a slower pace. Gravel beaches will continue to roll back, but build higher berms. There is no sign yet of any definitive acceleration in the rise of sea level from any New Zealand sea-level gauges. However, based on the Third Assessment Report of the IPCC, our "most likely" estimates for sea-level rise around the Wellington region by 2050 and 2100 are 0.26–0.30 m above WVD-53 and 0.42–0.62 m above WVD-53, respectively. There is a small chance that sea level might rise by up to 1.0 m above WVD-53 in the year 2100. For tides, a level of 0.9 m above WVD–53 which would currently not be exceeded at all in 100 years, would be exceeded by up to 17% of all High Waters given the predicted rise in sea level by 2050.

Coastal erosion is affected by a complex interaction of many other factors in addition to a rising mean sea level. These include waves, wind, storm surge, frequency of storms, and local and regional sediment supply to the coast. Some or all of these factors could also be influenced both by natural climate variability and by greenhouse gas induced climate change. For example, it is likely that beaches respond to interdecadal fluctuations such as the 30-year Interdecadal Pacific Oscillation cycle, or to a lesser extent the 2 - 5 year El Niño - Southern Oscillation cycle, so that some decades have a higher risk of coastal retreat than others. Unfortunately the current knowledge of likely climate change impacts on waves, winds and currents, and of the impacts of interdecadal natural changes on Wellington region shorelines, is insufficient for us to provide projections of their future impacts on coastal erosion or accretion in this report.

Under global warming the mean westerly wind component across New Zealand is expected to increase by approximately 10% of its current value in the next 50 years. Strong winds are associated with intense convection (expected to increase in a warmer climate) and with intense low pressure systems which might also become more common. Thus an increase in severe wind risk could occur.

Higher mean temperatures obviously increase the probability of extreme warm days and decrease the probability of extreme cold days. The IPCC also notes that climate models forecast a decrease in diurnal temperature range at many locations; that is, the night-time minimum increases faster than the day-time maximum. Clear evidence exists of decreasing number of frost days in the past record at many New Zealand sites. The evidence for increasing numbers of very warm days is less clear, with regionally varying patterns that can be related to circulation fluctuations. Based on results from climate models, there is some indication of large increases in the number of warm days (at least a 50% increase in the number of days with temperatures greater than 25 °C by 2100) in the lower North Island, with bigger increases in the Wairarapa than in the west of the Wellington region. Climate models also indicate about 10 fewer frost days per year by 2100 in the Wellington region, for the mid-range scenario.

Lightning and hail are small-scale phenomena, very sporadic in time and space, and it will be difficult to establish statistically significant changes in their frequency. However, both lightning and hail are associated with intense convection, which is generally expected to become more frequent in a warmer and moister atmosphere.

Therefore, one would have to conclude that the risk of these phenomena is more likely to increase than decrease. It has been estimated that an increase of 1 ºC in average wet-bulb temperature may be accompanied in mid-latitudes by a 40% increase in lightning.

The IPCC Third Assessment indicates that the peak wind intensities of tropical cyclones are "likely" to increase in some areas. However, tropical cyclones have changed their characteristics by the time they reach New Zealand, and very few of those affect the Wellington region. In the Southern Hemisphere, the meridional temperature gradient and latent heating are predicted to increase under global warming. It would therefore be reasonable to infer that "more storminess" was likely. However, we cannot yet say whether this would mean more intense storms, or a higher frequency of passing cold fronts, or some combination of these. Moreover, a general increase over the Southern Hemisphere as a whole does not necessarily imply an increase locally in the small sector of the hemisphere that New Zealand occupies. Regional changes will be sensitive to changes in prevailing wind strength and direction, which vary considerably between models.

Wildfire risk is clearly related to drought risk, and additionally can be aggravated by strong winds and lightning occurrence. Thus, it is possible that wildfire risk might increase in the future, particularly in the drier eastern parts of the Wellington region.

1.3.2 Impacts of Climate Change on the Wellington Region

Based on the possible increase in frequency and intensity of extreme weather events, the biggest threat to lifelines and services is likely to come from heavy rainfall and associated floods. Increased peak flows in urban catchments will put pressure on stormwater and wastewater infrastructure. Lifelines and services that are currently near riverbanks are also likely to become more prone to floods. Structures such as bridges may need to accommodate higher flood peaks in their design. Lifeline utilities and infrastructure throughout the region will be exposed to a higher risk of landslides than currently if rainfall totals increase.

Areas near the coast may become increasingly prone to erosion due to rising sea levels. There is potential for considerable damage to the region's low lying coastal settlements and infrastructure where population, tourism, and capital investment are large and predicted to expand. Infrastructure such as roads, bridges, water mains, stormwater and sewerage systems needs to be assessed to determine its suitability, with respect to location and future operating potential. Rising sea levels will increase the risk of storm surges leading to breaches of sea defences and coastal flooding.

An increase in drought conditions may result in increased competition for water uses between agricultural irrigation, domestic and industrial use. Water supply to the four territorial authorities of Upper Hutt, Lower Hutt, Porirua and Wellington cities is collected and distributed by WRC. WRC has put much work into predicting future water use to guarantee supply for the years to come. Problems have arisen on the Kapiti Coast during recent droughts when demand has exceeded what can be supplied from current sources. More frequent droughts on the Kapiti Coast along with growing population will exacerbate this problem.

Changes in temperature and rainfall regimes brought about by climate change may cause problems for plant and animal pest eradication programmes. Furthermore, under a scenario of 20% more regional rainfall an additional 32,000 ha of land could qualify for soil conservation measures that would be subject to even more severe slippage or erosion than experienced under current rainfall regimes (Green, 1999). However, a blanket increase in rainfall such as this is not predicted, as there are expected to be decreases in some eastern areas and increases in some western areas. Nevertheless, it is likely that erosion would increase under increased rainfall with reductions in water quality and productive pasture base, increases in damage to roads and other utilities, and increased sedimentation in rivers on adjacent land.

Climate change is expected to result in rising sea levels. This could make groundwater aquifers near the coastline vulnerable to saltwater intrusion, and also give a reduction in recharge due to possible lower rainfall in some areas. Also, an increase in the magnitude and frequency of high intensity rainfall events would increase the number of significant flood events which would in turn require increased maintenance to ensure the integrity of flood protection works is retained.

Changes in temperature and rainfall regimes that affect the suitability of districts for particular crops, changes in crop and pasture performance, changes in water availability for irrigation, changes in soil fertility, stock health issues, and problems with weeds, pests, and diseases are likely to be the most significant effects on agriculture and horticulture of climate change. Impacts will vary widely between districts, crops, and decades, as the change in climate becomes more pronounced. Also, climate change has the potential for positive impacts to the Wellington region such as the introduction of sub-tropical or frost-sensitive crop species, and yield increases due to higher carbon dioxide concentrations and extended growing seasons.

In responding to climate change, the biota in the Wellington region may face a greater rate of long-term change than ever before. Also, changes in soil characteristics, water and nutrient cycling, plant productivity, species interactions (competition, predation, parasitism etc), and the composition and function of ecosystems are highly likely responses to increases in atmospheric CO_2 concentration and temperature, and shifts in rainfall regimes. These changes would be exacerbated by any increases in fire occurrence and insect and weed outbreaks. Aquatic systems will be affected by disproportionately large responses in runoff, river flow and associated nutrients, wastes, and sediments that are likely from changes in rainfall and rainfall intensity, and also by sea level rise in estuaries and other low lying coastal areas (McGlone, 2001).

Many of the potential changes in aquatic ecosystems under climate change start with the effects on surrounding vegetation and altered amounts of runoff to streams and rivers. Freshwater ecosystems will be impacted by higher temperatures which will affect lake mixing and associated eutrophication processes, decrease the available habitat for native species, and increase the habitat and growth of undesirable exotic species. Climate change is also expected to bring about changes in the magnitude and seasonality of river flows, which will reduce the habitat for native species and increase nutrient loading, and the further loss of the region's wetlands and associated wildfowl populations.

1.4 Information Needs of Key Stakeholders

There are numerous stakeholder groups in the Wellington Region with an interest in the risks posed by meteorological hazards and climate change. Potentially, everyone in the Region could be affected by meteorological hazards. Some of the key stakeholders have been identified.

- Wellington Regional Council

WRC holds assets and governance across the Region. Information such as the predicted effects of climate change could impact on flood protection works that are undertaken. WRC supplies bulk water to four territorial authorities and drought planning is essential. WRC also undertakes environmental monitoring, soil conservation, and is the consenting authority for activities such as water abstraction, therefore knowledge of the potential impacts of meteorological hazards on these areas would be useful. The Emergency Management capabilities of the council require knowledge of the likely hazards.

- City and District Councils

These councils also hold assets and governance. Operation of their emergency management offices is critical to response and recovery. Information on potential hazards and the effects of climate change is needed for responsibilities such as sewage and stormwater disposal, local water distribution, building/landuse consents, and flood protection works in smaller catchments.

- Central Government

There is a need to know, depending on the severity of any event, whether central government headquarters in Wellington could still be operated.

- Lifelines

All utility services and industries involved with water supply, sewage disposal, stormwater disposal, gas supply, electricity supply, telecommunications, broadcasting network, transportation systems (including road, rail, ferry, air), and building services need to know the hazards as well as their priorities and dependencies upon each other.

- Local Tangata Whenua

Local tangata whenua need to be informed of the actions that need to be taken in the event of any of the meteorological hazards or climate change.

- Emergency Services

These services (police, fire, ambulance) are critical and must have adequate information enabling them to be prepared for all events.

- Hospitals

There is potential for hospital facilities to suffer damage or be without water or power for periods of time.

- Schools

Schools provide a heavy density of young people during opening hours. Information on potential hazards is essential to provide for preparedness.

- Port Authority

The port authority requires information on the threat posed by meteorological hazards and climate change on major infrastructure in the Region's ports and harbours.

- Department of Conservation

DOC manages a large estate of land within the Region. Meteorological hazards could impact on sensitive species as well as the land itself.

- Marinas/Sailing Clubs

Information would be desired on impacts of events such as storm surges, high winds, cyclones, and rising sea levels due to climate change.

- Primary Industries

Areas such as agriculture, horticulture and forestry would be impacted by climate change and knowledge of any potential changes (for example changes in climate or water availability) can help with future planning.

- Hazardous Substances Storage Facilities

Companies will need to take steps to ensure reasonable precautions have been made to minimise any hazards.

- All Residents

All regional residents need to have access to information on any potential hazards by means such as hazard maps prepared by councils. Coastal residents will need to be aware of any increase in coastal hazards such as erosion, surges, or rising sea levels. People not on reticulated water supply will need to be aware of any potential changes to water availability or quality. All residents should have access to ways of identifying areas of risk due to all meteorological hazards.

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2. Floods

Floods and droughts represent two of the most important hazards the Wellington region faces. Floods in New Zealand over the last 25 years have led to 75% of all insurance claims from natural hazards with loss estimates as high as $500m over that period (NIWA, 2000). The cost to regions of droughts is difficult to assess, but research suggests that, nationwide, recent droughts cost as much as $500m each (MAF, 1999).

The region is an important area from a hydrometeorological perspective, because severe flooding can occur on both sides of the Tararua Ranges during the passage on a single storm system (Thompson et al., 1997). This section and the following section of the report aim to assess the significance of floods and droughts to the Wellington region by describing several examples, estimating return periods of extreme events, listing areas of risk and hazards to lifelines, and presenting opportunities for research and amelioration (MAF 1999, NIWA 2000, Porteous et al., 1999).

2.1 An Historical High Rain Event: 27-28 October, 1998

In this section we will describe a significant flooding event. Where possible, contrasts with an event that occurred a week earlier will also be made.

2.1.1 Description of the weather

A strong moist, northwesterly flow covered the Tararua Ranges ahead of a slow moving front (Figure 2.1, right). This front was associated with a deepening low in the mid Tasman Sea. The development of the low further delayed the progress of the front across New Zealand. As the low moved southeast towards the South Island, a secondary cold front developed. This moved onto the North Island around 6 a.m. on the 28th, producing a second pulse of rain.

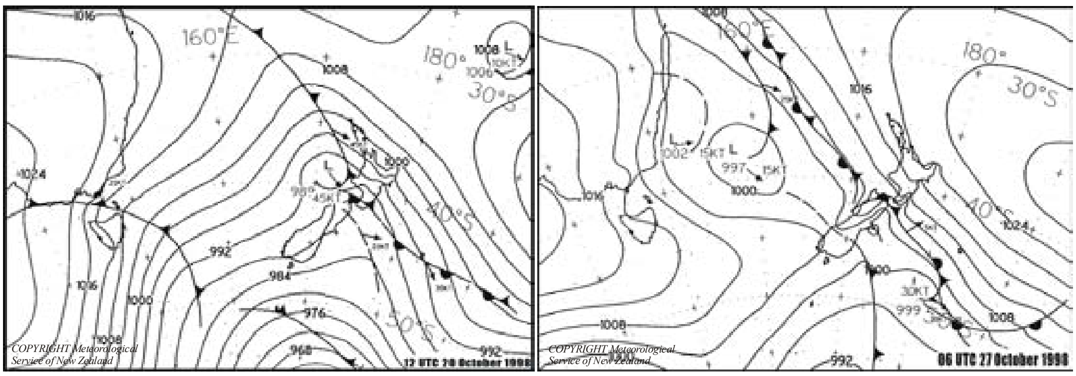

Figure 2.1: Synoptic maps at midnight NZST, 21st October 1998 (left) and 6pm NZST, 28th October 1998 (right).

This synoptic pattern of a 75–110 km/h moist northwesterly resulted in the Tararua ranges being subject to rain falling for over 24 hours. This strong wind impinging on the ranges led to a large component of the rainfall being orographically enhanced. For example, the storm total rainfall at Otaki depot (30m amsl) was 27 mm whereas at Oriwa (1080m amsl) a total of 434 mm was recorded.

In contrast, for the event of the 20–21 October 1998, the strong moist northwesterly lay ahead of a northeastward moving cold front (Figure 2.1, left). This front progressed quickly over the South Island, but became almost stationary over the south of the North Island as a wave developed on the front. This wave led to a complex set of "fluctuations" in the position of the front over the lower North Island, and led to a series of pulses of rain. The winds for the 20–21 October event peaked early at 110 km/h, but for most of the storm the winds were between 35–55 km/h (WRC, 1998).

Another notable difference in this event (20–21 October) to the one that occurred 7 days later was that the lower wind speeds in the storm led to a smaller component of orographic enhancement in the rainfall falling at the hilltops. Though the coastal gauge totals were generally higher (102 mm at Otaki depot compared with 27 mm), and the duration similar, the wind speed was often only around 35 km/h, thus supplying less moisture leading to smaller orographic enhancement (Gray and Austin, 1993).

2.1.2 Storm return period 27-28 October

As part of the WRC report on these two floods, assessments were made of the return periods of the rainfall and flow. The long steady nature of this event resulted in only the longer duration rainfall statistics being notable. For example, at Taungata, the 1-hour rainfall return period was assessed at 1 year, whereas the 24-hour rainfall total was likely to occur only once in every 40 years. With the unusually large orographic enhancement component to this rainfall, only the high-altitude gauges showed notable return period statistics. In gauges with altitudes below 100m the return periods range from 1–6 years. Gauges on the ridge tops (>1000m), had 24-hour return periods that ranged from 8–40 years (WRC, 1998).

Return periods assessed from the peak of flow records showed that this was an extreme event (> 20 year return period) for the, Akatarawa (75 year), and Whakatiki (59 year) Rivers. The combined flow for the Hutt arriving at Taita Gorge had a return period of 26 years, while measurements further upstream were less extreme. The flow on the Otaki River was assessed as having a return period of 9 years, yet much of the damage from this storm occurred in that region.

Of interest is that the return periods for the flows are generally more extreme than that seen in the gauge data. This reflects the long duration of this event, and its occurrence in an unusually damp season. This led to catchments that were already well water laden and that would return much of the incident rainfall as runoff rather than being stored.

2.1.3 Damage

Damage from such flood events occurs through inundation, wind damage, land slides and through extraneous causes such as car crashes. Listed here is some of the damage, as reported in newspaper clippings. Not included in this will be costs such as loss of earnings, due to injury, inability to trade, as well as more esoteric issues such as trauma. The following paragraphs provide information on the type and extent of damage during the two October 1998 storm events.

Wind: Wind felled trees, ripped off roofs, cut power, and felled a pine tree closing Seatoun tunnel.

Flood: Otaihunga domain flooded, as did several businesses, a 56 year old man drowned, State Highway 1 closed at Waitohu bridge, St Peter's school closed, and 15 families were evacuated near Otaki. Flood defenses were damaged, golf courses eroded, and a service bridge washed away including sewer and water pipes, gas and telephone. Six houses were flooded (Hutt River).

Slips: Road closures occurred in Carterton, a slip closed Paekakariki hill road, western Hutt road was reduced to 1 lane with a slip. Akatarawa road was closed with multiple slips. Near Otaki, the river undermined 2 houses, and 14 houses were rendered uninhabitable.

Other: Several car crashes were reported. Road repairs from the 27–28 Oct storm were estimated at $350k, ($1.2m for the 20–21 Oct. event). Insurance claims were expected to be near $5m. Firth closed business after $50,000 losses.

2.1.4 Photos

The WRC flood report contains a good selection of photos as reproduced in the press. See also the WRC flood plans for examples of the damage floods can cause.

2.2 Rainfall Return Period Maps

High intensity rainfalls for 24 hours and for average recurrence intervals (ARI), or more commonly known as return periods, of 142 and 475 years over the south of the North Island are shown in Figures 2.2 and 2.3. The maps are based on climatic conditions experienced through the 20th Century, and do not take account of any changes that might occur due to climate warming. The return periods have been computed from a regional frequency analysis of extreme rainfalls for New Zealand, using an index-rainfall method described by Thompson (2002). This procedure involves mapping the median annual maximum rainfall, which is also the 2-year ARI event, and the derivation of regional growth curves that relate rainfalls at different ARI to the index value. Regional growth curves are developed from generalised extreme value distributions by combining rainfall data series from sites within some prescribed and "homogeneous" region.

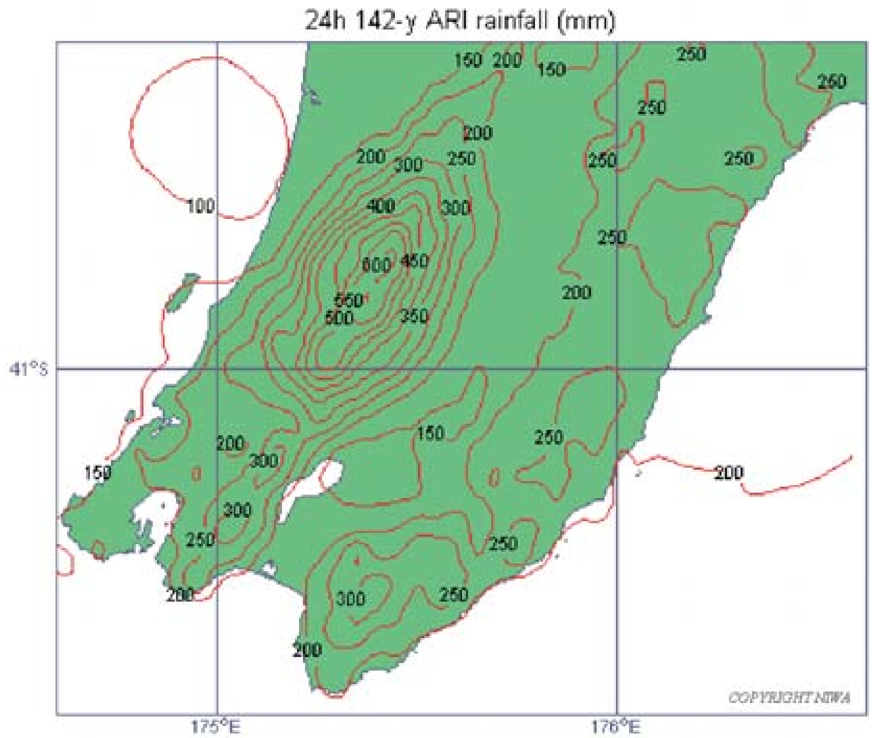

Figure 2.2: Twenty-four hour 142-year return interval rainfall (mm).

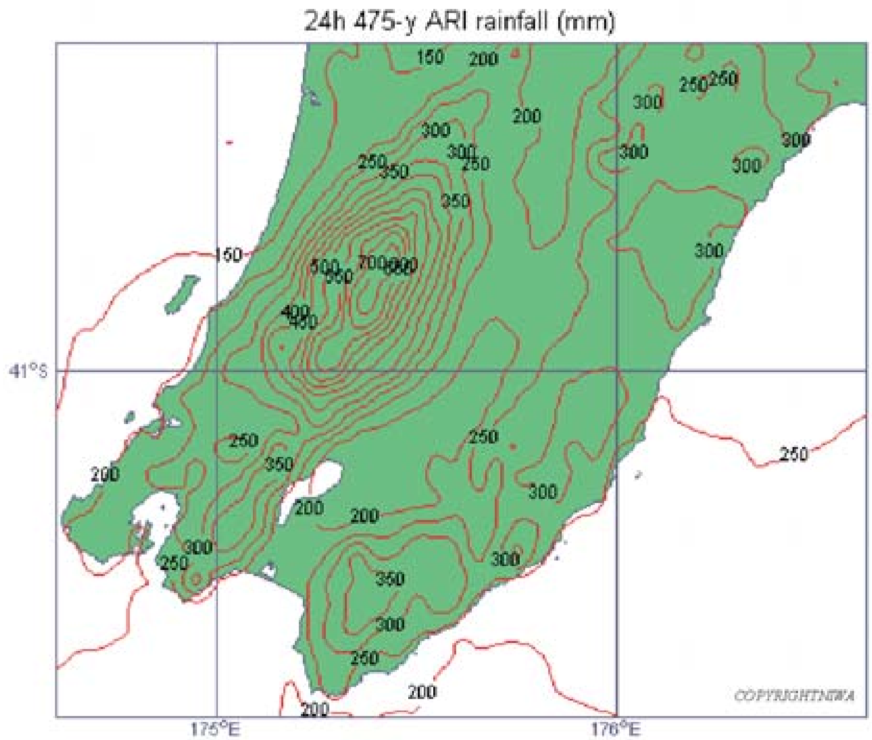

Figure 2.3: Twenty-four hour 475-year return interval rainfall (mm).

2.3 The 100-Year Flood maps

Figures 2.4–2.7 show the areas (and depths) of inundation expected from a flood with an ARI of 100 years. Also, Figure 2.8 shows the area of inundation expected from a flood with an ARI of 50 years for catchments in the Wairarapa (there is currently no 100-year flood map available for the Wairarapa). Assumptions have been made in preparing these figures, including the caveat that none of the currently installed protection works fail. Considerably greater areas could be at risk if, for example, stopbanks are breached in key places. The WRC floodplain management plans report on the likely consequences of several levels of stopbank breaches.

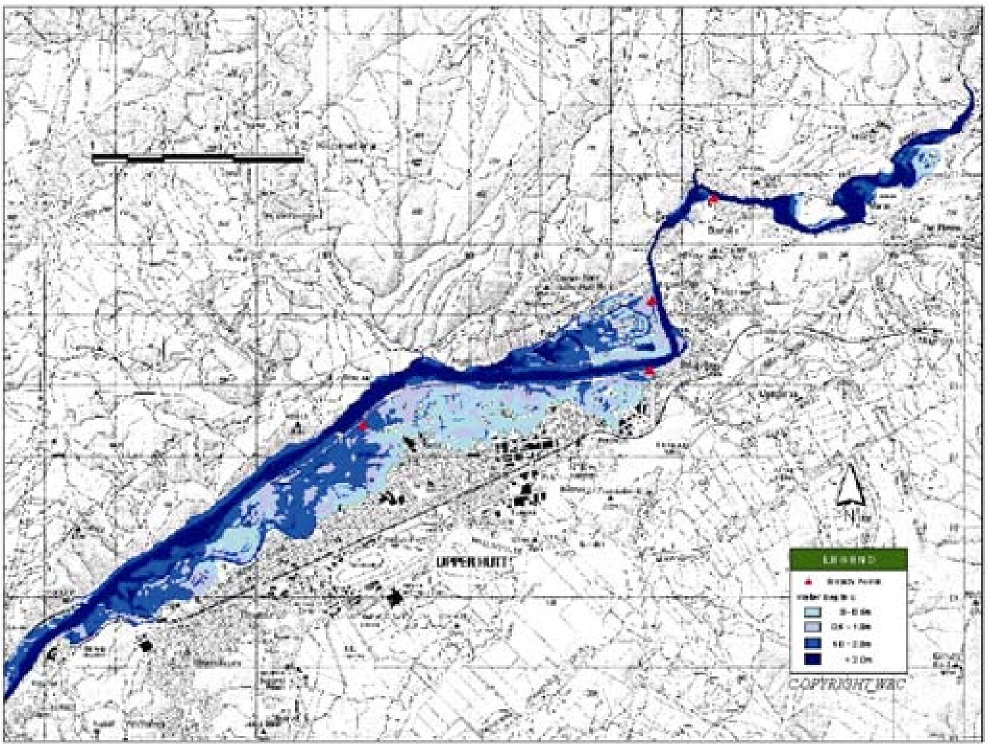

Figure 2.4: 100-Year flood inundation map for Upper Hutt (Source: WRC).

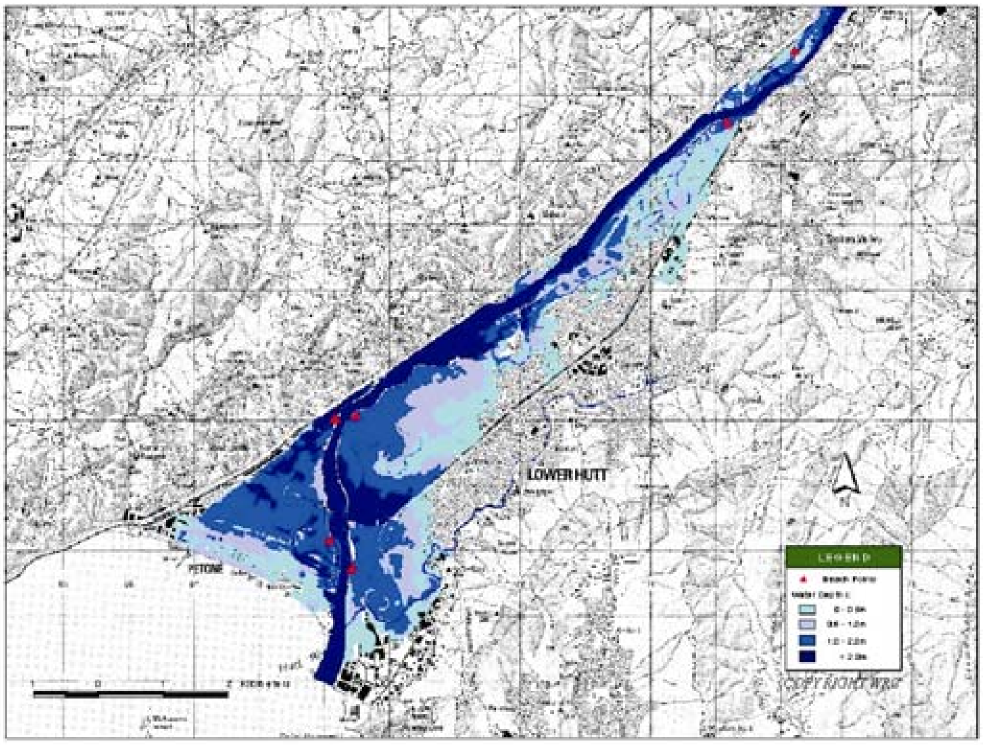

Figure 2.5: 100-Year flood inundation map for Lower Hutt (Source: WRC).

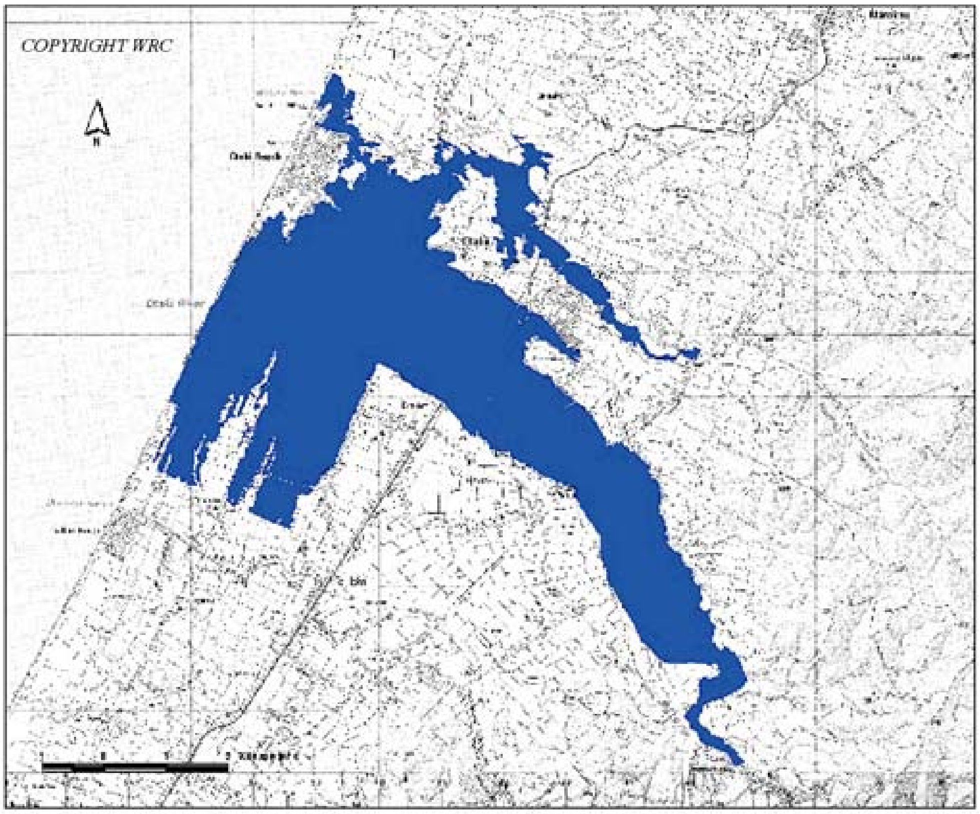

Figure 2.6: 100-Year flood inundation map for Otaki (Source: WRC).

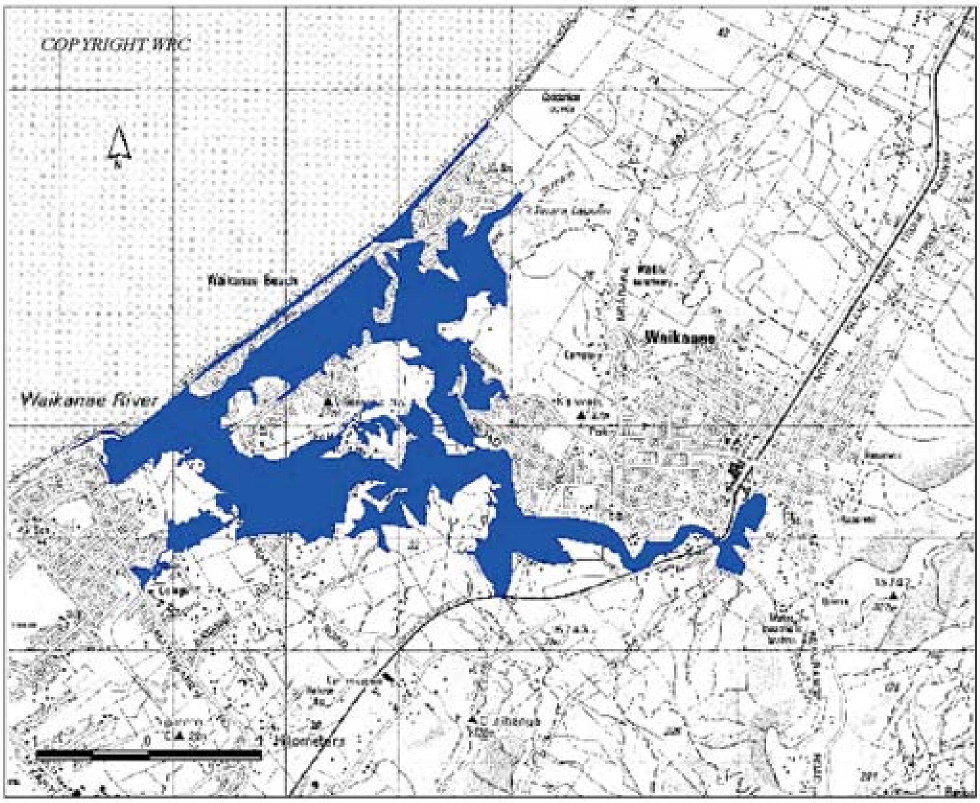

Figure 2.7: 100-Year flood inundation map for Waikanae (Source: WRC).

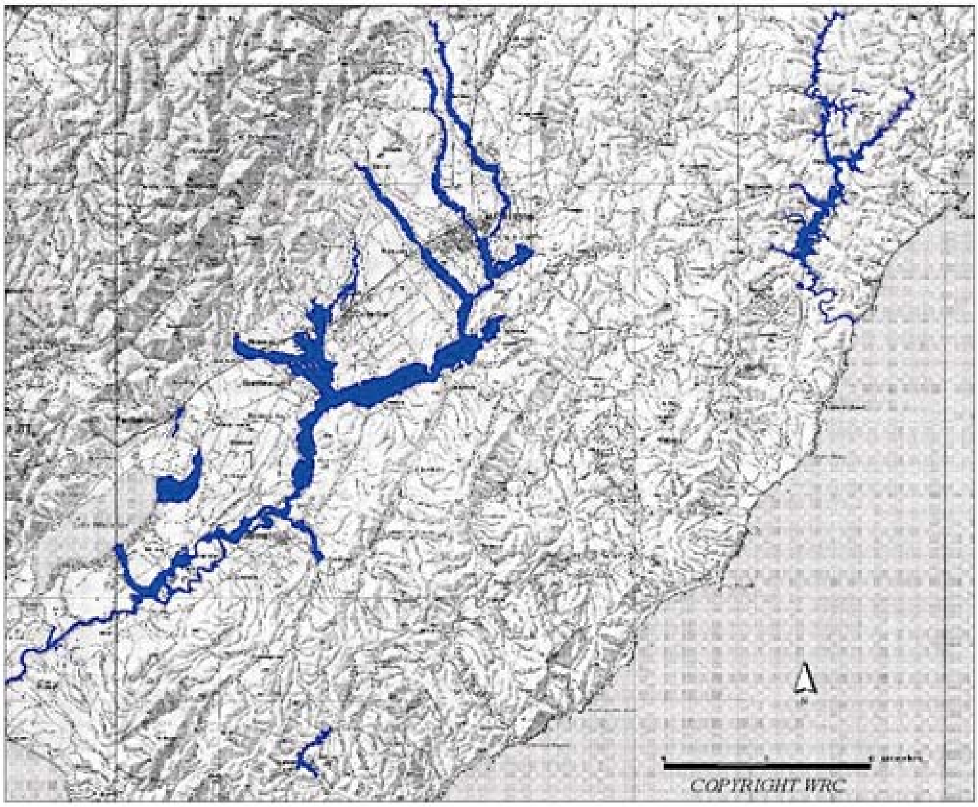

Figure 2.8: 50-Year flood inundation map for the Wairarapa (Source: WRC).

2.4 Knowledge Gaps

Further research into the area of climate change or climate variability impacts is necessary to ascertain any changes in the frequency or magnitude of flooding. For example, are there significant differences over the Wellington Region in the frequency and severity of flooding due to the phase of the El Niño-Southern Oscillation? Another research avenue would be to look at the uncertainties associated with the implications of climate change on the frequency and magnitudes of floods. Some discussion is provided in a later in this report (see section 12).

Detailed maps of lifeline services (e.g. flood inundation maps) within the defined flood prone areas should be drawn up where this has not already been done. These would be of benefit when planning for flood preparedness.

Forecasting skills can be further improved. Quantitative rainfall and flow forecasting is now becoming available and will enable improved warnings to be made of imminent danger, and suitable action to be taken.

Investigation into flood effects on smaller rivers and streams has rarely been considered. Most focus has been on the larger catchments. Urban hydrology should also be looked at closer, particularly in regards to intense rainfall in urban areas, due to the potential problems associated with drainage and sewerage systems.

2.5 High Risk Areas

The flood hazard risk has been assessed for various rivers in the region as part of the WRC floodplain management process. The extent of a 1 in 100 year flood is mapped for the Hutt, Otaki and Waikanae rivers (Figures 2.4–2.7) and a 1 in 50 year flood for catchments in the Wairarapa (Figure 2.8).

The flooding detailed in the maps covers a wide area and shows the potential for a number of lifeline services and utilities to be affected.

WRC (1996) estimates that 100 utility services (communications, water, waste, energy) and 126 transport services (road, rail, pipelines, parking) are within the flood prone area of the Hutt Valley. Estimates of the number of utility and transport services in the flood prone area of the Otaki River are 6 and 16 respectively, and 7 and 1 respectively for the flood prone area of the Waikanae River (WRC, 1992).

Potential damages to property, production, public services and utilities in a 100-year flood in the Waiohine River have been estimated at $9.9 million (Kloosterman and Baker, 1993).

A cause for concern in a major flood event is the lack of alternative routes to the SH1 bridges across the Otaki and Waikanae rivers.

Alternative routes can be made around the SH2 bridges over the Tauherenikau, Waiohine and Waingawa rivers if necessary, although these could also be affected by flooding within the Ruamahanga River.

In a major flood event communities could be expected to be without power for a number of days, and also to be isolated as transport routes are gradually repaired over a period of days. Telephone lines brought down by the floodwaters would affect landline phone systems but cellphone coverage should remain, as cellphone towers are generally sited on higher ground away from flood waters (GNS, 2000).

WRC estimates flood damages to property in the flood prone areas when the stopbanks fail or are overtopped to be $190m in Upper Hutt and $700m in Lower Hutt (WRC, 1996), $124m in Otaki (WRC, 1992b), and $45m in Waikanae (WRC, 1992).

Not accounted for in these figures are intangible losses associated with:

- Personal loss, tragedy and possible loss of life
- Family stress, tension and trauma
- Loss of income and accommodation
- Longer term psychological effects and domestic tension
- Cost and time involved in the major cleanup
- Monetary costs resulting from lost working days
- Loss of productivity and loss of general business through delays

Intangible flood losses are expected to be as large as tangible losses and therefore the totals given for potential flood damages can be considered to be conservatively low.

Areas not affected by major river systems also face flooding risks. Thunderstorm activity can bring very intense rainfall and areas such as parts of Lower Hutt and Wellington were adversely affected by the 20 December 1976 storm. Many roads were blocked by the resulting flooding, including SH2 for long periods, power and telephone lines were brought down bringing disruption to services, water supply pipes were undermined, and the stormwater system totally failed to cope with the floodwater and debris.

Intense rainstorms over Wellington City in June 1998 and January 2002 caused problems, most associated with flooding due to the incapacity of the stormwater system to deal with the runoff.

Ecosystems, both in the coastal and stream environments, are affected by flooding. Most at risk are those near urban areas. Runoff from roads and building services, and the seemingly quite common sewage overflows into the stormwater system, enter the marine environment depositing harmful pollutants and silt.

2.6 Amelioration Methods

WRC has developed floodplain management plans for various rivers around the region that set a foundation for implementing structural and non-structural amelioration measures, recording how they have been developed and when they will be implemented.

2.6.1 Structural Methods

Structural measures are the physical flood protection structures and channel management works that are the first defence against the flood hazard. Structural measures are designed to contain floods to keep water away from existing development, and to limit erosion from the river. Physical protection from the flooding in many areas, such as the Hutt Valley, has been built up over time and therefore the structural measures remain the dominant way of managing flood hazard today.

Stopbanks are the most obvious examples of a structural amelioration measure. This is done using rock linings, vegetation buffers and groynes built up along the banks of the river to maintain the channel position and protect stopbanks from erosion. Active channel management such as bed and beach re-contouring (or cross blading) and gravel extraction also help to reduce the chance of a river eroding its banks and damaging structural works.

Bridge upgrades improve the flood capacity of a river and avoid the risk of debris dams forming. As part of the WRC Hutt River Floodplain Management Plan, existing bridge structures will be investigated to determine if they meet flood design standards. Where possible such investigations should take account of the possible climate change impacts on the design standard.

The Lower Wairarapa Valley Development Scheme is a large-scale flood mitigation scheme that benefits nearly 400 square kilometres of fertile farmland (WRC, 1998c). A combination of overland floodways and the ability to hold water in Lake Wairarapa and release it gradually through a barrage gate system has greatly reduced the flood hazard to the lower Wairarapa Valley. Figure 2.8 shows the effect that the flood mitigation measures have in the lower valley. A 50-year flood is largely confined to the channel in the lower reaches of the Ruamahanga River while overflow travels through the floodways and into Lake Wairarapa.

2.6.2 Non-Structural Methods

Non-structural measures are less obvious aspects of flood protection. Rather than building structures to keep the rivers away from people and property, they focus on keeping people away from floodwaters and helping the community to cope when flooding occurs. Non-structural measures include land use planning regulations, and steps that floodplain residents, groups, businesses, and utility and emergency services can take to prepare for floods.

Land use planning measures can offer flood protection by:

- Controlling earthworks in upper catchment areas
- Developing policies in district plans that recognise flood hazard management
- Discouraging construction of buildings in river corridors and encouraging buildings and structures to be sited outside river corridors
- Discouraging subdivision where resulting land uses could expose people and assets to an increased flood hazard.

Emergency management measures try to ensure that residents know about the flood hazard, are prepared, and can manage themselves in a flood. Emergency management groups work to spread messages about the risks of flooding and the advantages of being prepared. Regular hazard awareness meetings and seminars are held for councillors, council managers, businesses, community groups and schools, and have prepared information kits that explain how individuals can reduce their risks of exposure. Also, generic floodplain management planning guidelines for New Zealand are used to manage flood risk as it relates to floodplains (Berghan and Westlake, 2001).

The WRC undertakes flood-warning duties across the region. A network of raingauges and river level recorders are linked to council headquarters and are monitored directly. The WRC can issue predictions of how high river levels will rise in response to rainfall during a storm event and information is passed on to those responsible for managing the various flood prone areas of the region.

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3. Droughts

The issue of drought is a major concern in New Zealand. Drought occurs during a sustained period of low rainfall, which has persisted long enough to produce serious hydrological imbalances. These may result in shortages or restrictions on water supplies, crop failure and loss of productive land, damage to horticulture and lack of feed and consequences for agriculture, as well as increased potential for wild fire, and other socio-economic factors.

There are many ways of measuring or defining "drought". Agricultural drought is based on estimates of the soil moisture balance, where drought is said to occur when there is insufficient soil moisture to sustain plant growth. Crops become stressed as the readily available water capacity of the pasture root-zone has become depleted and incipient wilting occurs. In summer (December through February) it can take as little as two or three weeks with insufficient rainfall to meet this criterion. The drought ends when rainfall has finally restored the soil moisture sufficiently above the wilting point level.

Another useful climatological definition of drought assumes that water shortages may often affect an area for short periods, in which case provisions are usually made or are already in place to cope with those events, but hazard conditions might be said to occur when at least the seasonal (3-month) rainfall in the area affected falls below the ten-percentile value, and a severe event falling below the five-percentile value, i.e. an event that occurs on average less than once in twenty years.

It is usual for the Wellington, Hutt, Kapiti and Wairarapa districts to experience at least one extended period of low rainfall each year, especially during the warmer months from November through March, when temperatures are highest and rainfall is least, some of which may extend into a drought. For the Wellington region the potential for severe drought is highest in Wairarapa, where there are on average about 15 days a year when soil moisture deficits exceed 130 mm. On average 10 days with a deficit of that nature can be expected in Kapiti, Wellington and the Hutt Valley, since there are higher mean seasonal rainfalls and fewer hot days there. Significant variability from these averages can occur from year to year: as many as 74 days have occurred in this category in the Wairarapa (1997/98) and 122 days occurred in part of Wellington (2000/01) in the most extreme cases. Brief statistics comparing the drought of summer-autumn 2000/01 with other significant events appear at the end of this section.

Over the past few years research by WRC staff have presented results into the relationships between seasonal low rainfalls and ENSO for the Wellington Region (see for example WRC, 2000, and the references contained within). For example in the Wairarapa, the chances of low rainfall during summer are increased if an El Niño episode was underway in the preceding spring. Likewise during a La Niña, autumn rainfall is likely to be low if there was already a La Niña summer. These WRC reports play an important role towards mitigating the drought hazard, by providing councils with the necessary tools to be better prepared for drought and its consequences.

Therefore, good and timely information about how frequent and severe droughts have been in the past in various areas, up to date information on soil moisture and rainfall, long range weather forecasts, and seasonal climate outlooks can help farmers and providers and users of water manage for drought. Seasonal climate forecasting is a topic of continuing research. It provides guidance on the "odds" of a coming season being drier, wetter, warmer or cooler than normal, rather than a categorical prediction of drought or rain.

3.1 An Historical Drought Period: Summer–Autumn 2000/01

The summer–autumn 2000/01 drought was the most severe to affect parts of Wellington city in more than a century. It was also severe in the Hutt Valley, and on the Kapiti coast, being a potentially hazardous event. Although the drought was not as significant in Wairarapa, some water restrictions were still imposed there. A month-by-month chronology of the drought, from start to end, is given in the following section. Some advance warning of low autumn rainfalls in the Wairarapa would have been available using the WRC ENSO-based prediction scheme, since a La Niña existed during the summer months.

3.1.1 A month-by-month chronology of the drought

October 2000: Westerlies were more frequent than average, with both average rainfall and soil moisture levels. River flows were above average.

November 2000: Rather cool with more frequent southerlies than usual. Rainfall was less than 50% of normal in Wellington, Kapiti, and western Wairarapa, with moderate soil moisture deficits in places. River flows were below average, particularly in Wellington.

December 2000: Sunny, rather warm conditions with ridges of high pressure, and frequent hot northwesterly conditions in Wairarapa. Rainfall was less than 75% of normal in Wellington, Kapiti and western Wairarapa. Significant soil moisture deficits developed, with low river flows.

January 2001: Rather cool, with frequent, although dry, southerlies. Rainfall was extremely low being less than 25% of normal in Wellington, Kapiti, and southern and western Wairarapa — many locations recorded only 5–20 mm. Severe soil moisture deficits developed throughout the region (Figure 3.1). River flows were below average.

February 2001: Warm weather, with many more hot days than normal prevailed. Rainfall was less than 50% of normal in Wellington, Kapiti, and southern and western Wairarapa, with continued widespread severe soil moisture deficits (Figures 3.2 and 3.3). River flows were well below average and groundwater supplies were under pressure in places. Irrigation restrictions were imposed in some localities. Many small creeks in southern Wairarapa stopped running, some for the first time in many years.

The extremely low summer (1 December 2000 to 28 February 2001) rainfall total of 82 mm (36% of normal) at Kelburn, Wellington was exceeded only in 1907/08 (52 mm) and 1886/87 (78 mm). Paraparaumu Airport measured 96 mm (45% of normal) — the lowest there since 1977/78, and Wallacville 114 mm (45% of normal) — exceeded only in 1972/73 (106 mm), records began in 1924. Fire risk was very high to extreme throughout the region.

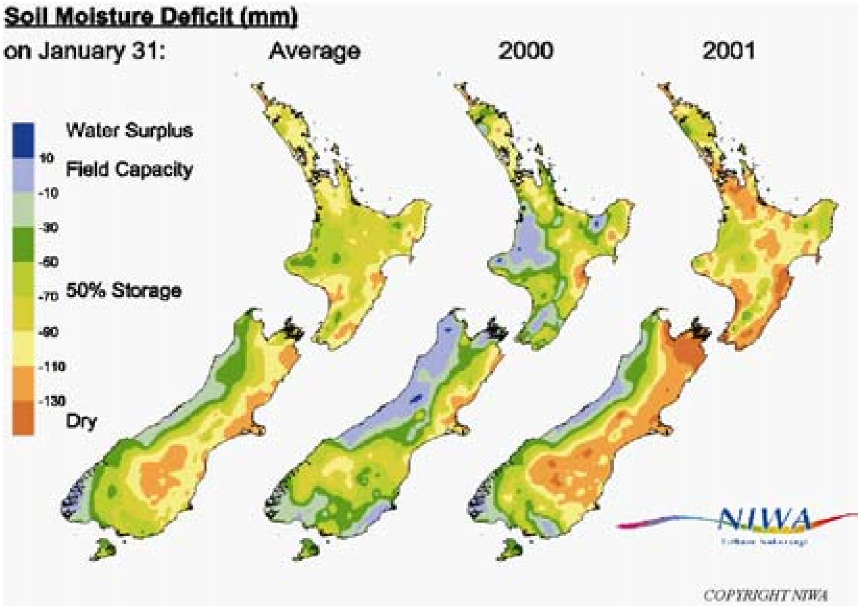


Figure 3.1: Soil moisture deficit in the pasture root zone at the end of January 2001 (right) compared with the deficit at the same time in the previous year (centre) and the long-term end of January average (left). The water balance is run for an average soil type where the available water capacity is taken to be 150 mm. The readily available water capacity is taken as 75 mm.

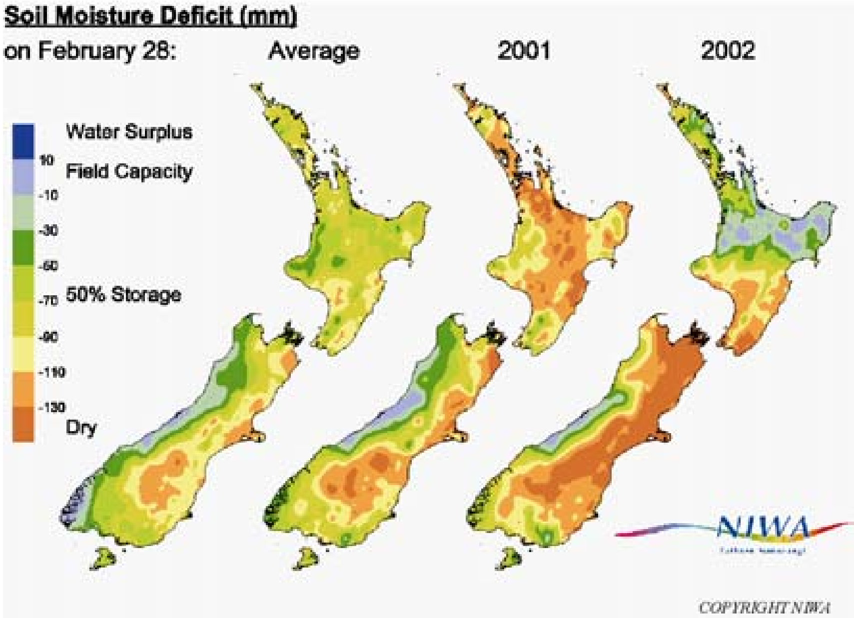


Figure 3.2: Soil moisture deficit in the pasture root zone at the end of February 2001 (right) compared with the deficit at the same time in the previous year (centre) and the long-term end of February average (left). The water balance is run for an average soil type where the available water capacity is taken to be 150 mm. The readily available water capacity is taken as 75 mm.

Figure 3.3: Scorched Earth - The surface of a dried up dam on an Ohariu Valley Farm, near Wellington. Courtesy of the Evening Post, 22 February 2001.

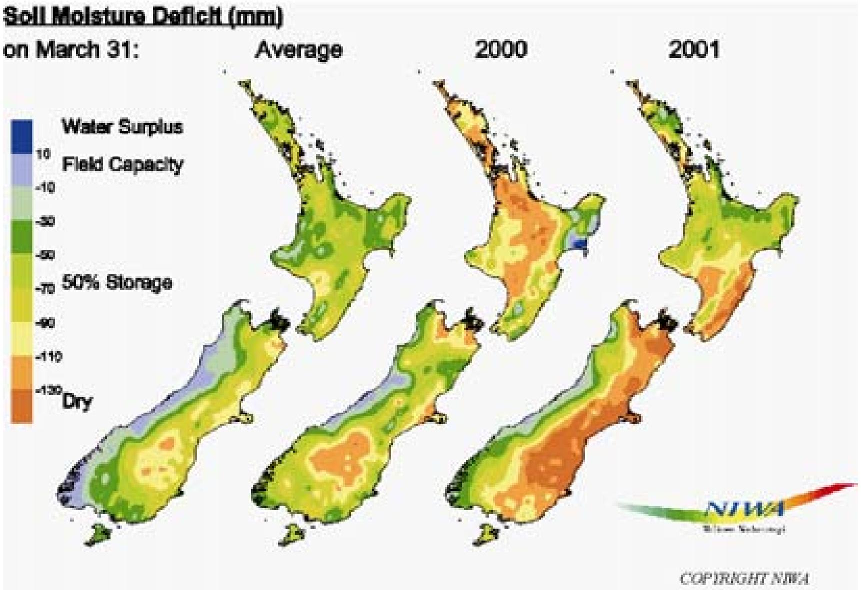


Figure 3.4: Soil moisture deficit in the pasture root zone at the end of March 2001 (right) compared with the deficit at the same time in the previous year (centre) and the long-term end of March average (left). The water balance is run for an average soil type where the available water capacity is taken to be 150 mm. The readily available water capacity is taken as 75 mm.

March 2001: Anticyclonic conditions continued. It was also very sunny. Rainfall failed to keep up with pasture demand, being extremely low with totals less than 25% of normal in Wellington, less than 50% of normal throughout Wairarapa, and less than 75% of normal in Kapiti. There was no respite from the drought, with widespread severe soil moisture deficits persisting in Wellington and Wairarapa (Figure 3.4) where river flows remained very low. Rainfall in Kapiti on 26 March led to an easing of some water restrictions there. Streams around Wellington were still running well below normal levels. Wellington had recorded its lowest January to March rainfall (61 mm), in records that began in 1863.

April 2001: Further sunny anticyclonic conditions. Rainfall was less than 25% of normal in Wellington and throughout southern Wairarapa, and less than 50% of normal in Kapiti. The low rainfall during the month was generally insufficient to alleviate the very dry soil conditions, but enough to lift soil moisture levels a little from the extreme low experienced at the end of March. River flows remained very low. At this stage Wellington had recorded its lowest January to April rainfall for over 100 years (77 mm).

May 2001: This was a changeable month with higher rainfall than in previous weeks (but still less than 75% of normal throughout the region); finally enough to lift soil moisture levels and bring relief from the very dry soil conditions. River flows remained below average. Rainfall in Wellington totalled 20 mm on 25 May, the first day with a total of at least 15 mm since 1 October 2000.

3.1.2 Some consequences and effects of the drought

- Shortages or restrictions on water supplies:
  22 February: Garden hosing and watering restrictions applied throughout Wellington, and Kapiti. Water needed to be tanked to some rainwater dependant homes on the Kapiti coast. Groundwater supplies were under pressure in places, and many small creeks stopped flowing in southern Wairarapa.

  22 March: Total sprinkler and hose bans were enforced in Waikanae, Paraparaumu and Ruamati, with hose restrictions at Paekakariki. Irrigation bans were placed in Wairarapa.

  23 March: The Waikanae River was running critically low, flowing at a rate of 728 litres per second. The Kapiti Coast District Council closed all school swimming pools, including a public pool to conserve water. Irrigation bans applied for use of water from the Waikanae River and Waitohu Stream.

  26 March: Rainfall was enough to end pool closures and alleviate some of the water restrictions in Kapiti, but unattended sprinklers and garden hosing was still banned.

- Damage to horticulture:
  23 March: More than 50% of the 12,000 new plants planted during the winter of 2000 died on Somes-Matiu Island. Many native trees were suffering from water-stress. The Island was closed to the public due to fire risk.

- Consequences for agriculture:
  22 February: A shortage of drinking water resulted in an Ohariu Valley farmer selling almost 300 stock and sending 1300 sheep to graze in other parts of the North Island. He quoted it as “one of the worst summer’s ever”. “ This is hurting us… and we’re really on the back foot”.

  March: In Makara there were feed shortages for deer and other stock from parched paddocks that hadn’t revived after grazing.

  5 April: Some southern Wairarapa farmers had already significantly reduced stock numbers to winter proportions, due to anticipated pasture shortages.

  30 April: Many Wellington evergreen trees and shrubs were showing signs of stress; some shedding leaves to compensate for the lack of water. Others were weakened and had become more susceptible to disease.

- Increased potential for wild fire:
  22 February: A total fire ban was enforced over the whole of the Wellington region due to extreme fire risk potential. 250 scrub fires had already occurred in the greater Wellington region since 1 October 2000.

1 March: The Wellington region was now at the same level on the Fire Service's drought code (an index used to monitor soil and fuel moisture) as Marlborough was when severe fires raged in the hills around Blenheim during Christmas 2000.

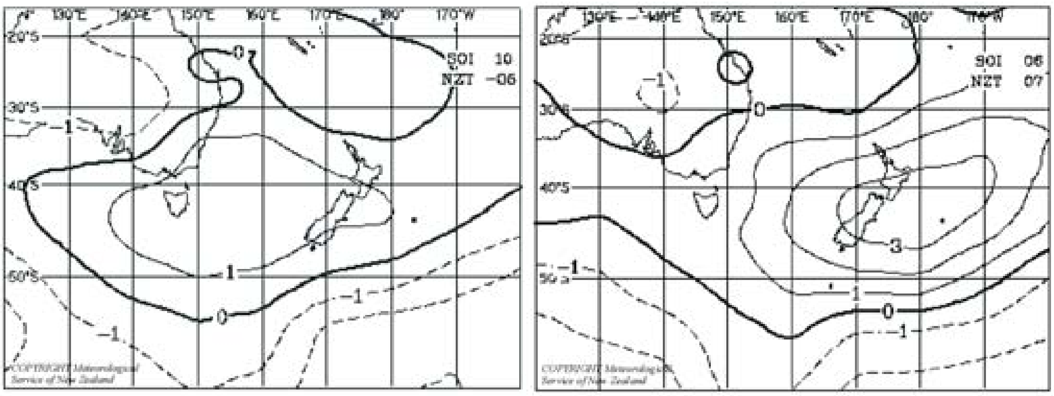
3.1.3 How the drought occurred and why it persisted

Very few depressions or active rain-bearing systems developed or tracked across the mid-Tasman Sea to affect central New Zealand in the seven month period from October 2000 through April 2001, and the frontal bands that did affect the lower North Island produced relatively small amounts of precipitation. Anticyclones, or ridges of high pressure, predominated over the southern North Island (Figure 3.5a).

This pattern was particularly noticeable at the height of the drought from February through April 2001 (Figure 3.5b).

3.1.4 How unusual was the summer–autumn 2000/01 drought?

New all-time records were set for accumulated extremely low rainfall totals at Kelburn for selected three, four, five and six month periods during the drought (Table 3.1). Brief statistics relating the summer–autumn 2000/01 drought (based mainly on periods of severe soil moisture deficit), to previous events are listed below (Table 3.2). These show that in parts of Wellington this was easily the most extreme drought in records dating back to the 1860s, more than 60 years in the Hutt Valley, and the worst since the late 1970s in Kapiti. The drought, although associated with some irrigation bans, did not stand out as extreme in Wairarapa records.



a) October 2000 though April 2001 b) February through April 2001

Figure 3.5: Mean sea level pressure anomalies during the 2000/2001 drought.

Table 3.1: Kelburn rainfall totals during the drought of 2000/01 compared to previous events. Copyright NIWA.

Location	Rainfall period	Period (months)	Total rainfall mm and (percent of average)	Rank and comments
Wellington, Kelburn	Nov 2000 - Apr 2001	6	187 (36)	Lowest for any 6-month period
1861-2002	Nov 1872 - Apr 1873	"	280 (54)	4th lowest for Nov–Apr
	Nov 1914 - Apr 1915	"	278 (52)	3rd
	Nov 1920 - Apr 1921	"	236(46)	2nd
	Dec 2000 - Apr 2001	5	127 (30)	Lowest for any 5-month period
	Dec 1886 - Apr 1887	"	177 (41)	2nd lowest for Dec- Apr
	Dec 1920 - Apr 1921	"	209 (49)	3rd
	Dec 1997 - Apr 1998	"	218 (51)	4th
	Jan - Apr 2001	4	77 (23)	Lowest for any 4-month period
	Jan - Apr 1887	"	140 (41)	2nd lowest for Jan–Apr
	Jan - Apr 1939	"	142 (42)	3rd
	Jan - Apr 1981	"	156 (46)	4th
	Jan–Mar 2001	3	61 (25)	3rd lowest for any 3-month period and lowest for Jan–Mar
	Jan - Mar 1887	"	89 (37)	3rd lowest for Jan–Mar
	Jan - Mar 1939	"	67 (28)	2nd
	Jan - Mar 1982	"	97 (40)	4th
	Feb - Apr 1867	"	30 (11)	Lowest for any 3-month period
	Dec 1906 - Feb 1907	"	52 (21)	2nd lowest for any 3-month period

Table 3.2: Days with severe soil moisture deficit over summer of 2000/01 compared to previous events. Copyright NIWA.

Location	Period of severe soil moisture deficit	Days with severe soil moisture deficit; at least 130 mm (and departure from average).	Rank	Soil moisture data period
Wellington, Kelburn	Jan - May 2001	79 (+69)	1st	1928-2002
	Nov 1934 - Feb 1935	60 (+50)	2nd	
	Feb - Apr 1939	45 (+12)	4th	
	Jan - Mar 1982	47 (+37)	3rd	
Wellington Airport	Jan - May 2001	122 (+102)	1st	1961-2002
	Jan - Mar 1973	61 (+41)	3rd	
	Dec 1997 - Apr 1998	67 +47)	2nd	
Maungarakei	Jan - Mar 2001	26 (+11)	1st	1969-2002
	Feb 1971	21 (+6)	3rd	
	Feb - Mar 1973	24 (+9)	2nd	
Wallaceville	Jan - Mar 2001	47 (+42)	1st	1940-2002
	Jan - Mar 1970	39 (+34)	2nd	
	Jan - Mar 1973	35 (+30)	3rd	
Paekakariki	Jan - Mar 2001	22 (+18)	2nd equal	1955-2001
	Jan - Mar 1970	31 (+27)	1st	
	Dec 1974 - Mar 1975	22 (+18)	2nd equal	
Paraparaumu Airport	Jan - Mar 2001	58 (+46)	2nd	1951-2002
	Jan - Mar 1970	46 (+34)	3rd	
	Jan - Mar 1978	73 (+61)	1st	
Waikanae Waterworks	Jan - Mar 2001	22 (+13)	3rd	1969-2002
	Jan - Mar 1970	40 (+31)	2nd	
	Jan - Mar 1978	61 (+52)	1st	
Orongorongo Station	Jan - May 2001	53 (+37)	2nd	1969-2002
	Dec 1971 - Mar 1972	36 (+20)	3rd	
	Dec 1972 - Mar 1973	54 (+38)	1st	
Masterton, Bagshot Stn.	Mar - Apr 2001	23 (+8)	Not significant	1942-2002
	Jan - Apr 1943	65 (+50)	3rd equal	
	Jan - Mar 1973	65 (+50)	3rd equal	
	Jan - Mar 1978	69 (+54)	1st	
	Dec 1997 - Mar 1998	68 (+53)	2nd	
East Taratahi	Feb 2001	12 (-3)	Not significant	1972-2002
	Dec1972 - Mar 1973	72 (+57)	2nd	
	Dec 1997- Mar 1998	74 (+59)	1st	

3.2 High Risk Areas

Water supply is the main lifeline at risk from drought. The metropolitan water supply systems in the region have relatively little storage capacity. Extended periods of low rainfall restrict the amount of water available to from rivers, while causing the amount of water used to increase.

The WRC storage lakes at the Te Marua water treatment plant can store 3,400 million litres of water, or enough to meet 20 days of average use for the cities of Upper Hutt, Lower Hutt, Porirua and Wellington.

Extended periods of dry weather can cause the Wainuiomata treatment plant to close (e.g. summer/autumn 2001) because minimum flows set on the river sources can make it uneconomical to treat the small quantities of water left for abstraction.

Areas of the Kapiti Coast regularly come under stress through low water availability. The Waikanae River, that supplies Paraparaumu and Waikanae, often drops to a level where abstraction must be cut back and the Kapiti Coast District Council must impose water use restrictions on the community.

There is potential for a public health issue if the water available for supply drops to such a low level that adequate amounts can not be supplied to maintain community health and cleanliness.

Low rainfall and limited water supply will have an adverse effect on agriculture and horticulture. Earnings will be lost due to reductions in stock size and numbers, and in crop harvest. Farm gate losses, due to recent droughts, have been estimated at around $40000-$50000 per farm (Porteous, pers. comm., 2002)

A period of drought is often accompanied by some days of high temperatures. In the past, extreme temperatures have been known to cause buckling of railway tracks, causing derailments in the worst cases and closing the line until repairs are made. The region has a high proportion of railway tracks — both suburban and main trunk lines.

3.3 Amelioration Methods

Efficient use of water, in horticultural, agricultural and metropolitan uses is beneficial at all times, and particularly so in drought periods. A limited amount of work has been done investigating moisture requirements of soils and land use for crops in the Te Horo area. Results from studies like this will lead to more efficient irrigation practices and potentially a large saving in water used and more investigation should be encouraged.

Local authorities and WRC operate water conservation programmes over the summer and autumn months and regularly check distribution systems for leaks. The Kapiti Coast District Council's water restriction and conservation programme has a high presence in the community and keeps people informed of any restrictions that are in force and also when they are lifted. Savings in water use can easily be made when asked for and when communication is good.

Alternative sources should be promoted in areas like the Kapiti Coast where shortages are often experienced. Taking of water from groundwater sources is preferred to taking from streams and rivers. Promotion of methods such as using tanks to collect rainwater from roofs for garden use should be undertaken more strenuously and financial incentives provided for installation.

Long-range weather forecasting can help to ameliorate the effects of drought. Various agencies such as WRC, NIWA, and MetService offer seasonal forecasts thus allowing a degree of forward planning for agricultural and water supply needs. Seasonal climate forecasting is a topic of continuing research. It provides guidance on the "odds" of a coming season being drier, wetter, warmer or cooler than normal, rather than a categorical prediction of drought or rain.

The pressure put on the freshwater ecology of the region is increased during drought periods when flows that are decreasing naturally are further depleted by abstraction. The Regional Freshwater Plan specifies minimum flows for some rivers in the region, which allows people and communities to use the water while ensuring flows are sufficient to maintain their natural and amenity values. Stepdown levels are used in most cases so that as the flow drops, abstractions are gradually decreased until the minimum flow is reached and all abstraction must cease. WRC has the power to issue water shortage directions on waterways in the region that prohibit the taking of water when stream or river health is compromised.

As resource consents to abstract surface water are renewed, new conditions are attached by WRC that restrict the amount of water that can be taken from this rivers once stepdown levels or minimum flows are reached.

Checks of railway tracks during extreme high temperatures are needed to ensure buckling and bending does not occur. Drivers need to be aware to look for track abnormalities in such warm periods.

3.4 Knowledge Gaps

The issue of climate change impact on drought in the Wellington Region will require further research effort, as simulations of day to day rainfall and soil moisture under changed global climate scenarios become available from regional climate models. However, interim guidance on the possible impacts of climate change and drought can be found in section 12.2.2, where increases in drought are likely in the east of the region.

Investigations have been started looking at the shallow groundwater resource of the Kapiti Coast. This resource is coming under increasing pressure from numerous new abstraction bores and little is known of the effect this is having and what the sustainable limit is.

Studies similar to the Wairarapa Irrigation Study (Hawke *et al*., 2000) to determine the moisture requirements of soils, crops, and varying landuses will be of benefit in the development of efficient use/irrigation of water in the region.

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4. Landslides and Erosion

For lifeline considerations, landslides and erosion that threaten infrastructure of the Wellington region are important. The nature of the region's terrain — steep, geologically young, undergoing tectonic uplift, and with the soil mantle exposed by vegetation clearing — means that landslides will occur.

Deep-seated landslides are generally not a problem in the Wellington region but shallow debris avalanches or regolith slides are. These are often initiated by intense rainfall events or during less intense rainfall that has been preceded by a long wet period.

The most obvious and common lifeline to come under threat from landslides in the region is transportation systems. Many of the region's roads and rail lines are cut through the underlying hard but closely fractured greywacke bedrock.

Erosion is most often a problem during intense rainfall or flood events. Erosion of channels and surfaces can lead to deposition of debris over lifelines such as road and rail networks, and even electricity sub stations. The erosive nature of flooded rivers during floods can be a problem, e.g. cutting into bridge abutments or breaking through stopbanks.

4.1 Historical Landslide Events

4.1.1 December 1976

An unusually severe rainstorm on 20 December 1976 affected part of the Wellington region. Two moist airstreams, one from the north and the other from the south converged over the Hutt Valley. The resulting rise of the mass of moist air and its subsequent cooling led to extremely heavy rainfall that led to severe flooding in the Wellington and Hutt Valley areas.

The area of heaviest rainfall in the storm extended from Pinehaven and Stokes Valley through the Hutt Valley and its hill suburbs to the western suburbs of Wellington as far as Karori. In total, an area of 400 km^2 was affected. In the 24 hours between 19 and 20 December many places received more than 300 mm of rain. Most of Wellington and Hutt Valley received over 100 mm. Most of the intense rain fell in the first 12 hours, and the storm is estimated to have a return period in excess of 100 years, and possibly in excess of 500 years (Tomlinson and Dyke, 1977). Figure 4.1 shows the 12-hour maximum rainfall isohyet map of the 20 December 1976 storm (Tomlinson and Dyke, 1977).

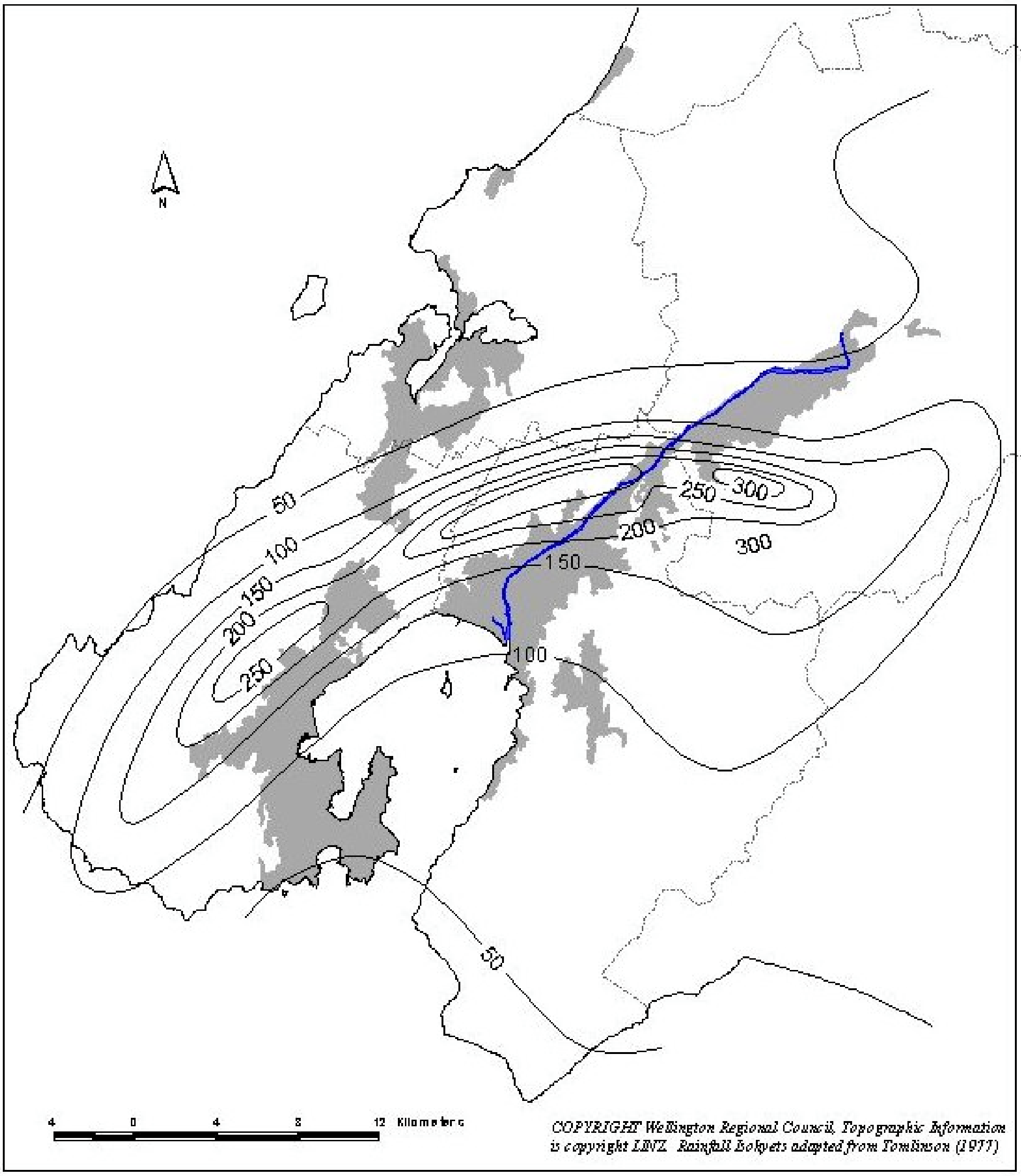

Figure 4.1: 20 December 1976 maximum 12-hour rainfall totals. Adapted from Tomlinson and Dyke (1977). (Source: WRC).

As a result of the high intensity rainfall over a long period the soil and weathered rock mantle became super saturated leading to hundreds of landslides and debris flows. Not only did the landsliding cause direct damage and disruption to infrastructure, but trees and debris brought down by landslides entered already overloaded watercourses, completely blocking culverts or forming debris dams. This led to stormwater and debris leaving the normal channels and flowing uncontrolled over roads and private properties. Debris dams formed in stream channels allowing water to build up behind them until such time as they were overtopped or gave way sending a large wave of water and debris downstream. Landslides undermined roads, footpaths and buildings, while slips from hillslopes and cuttings smashed structures and blocked roads. There was one fatality during the storm when a landslide crushed part of a building in the Wellington suburb of Croften Downs.

Figure 4.2 details the location of the landslides that occurred over Wellington and the Hutt Valley as a result of the intense rainfall. The landslides were identified from aerial photographs taken in 1977.

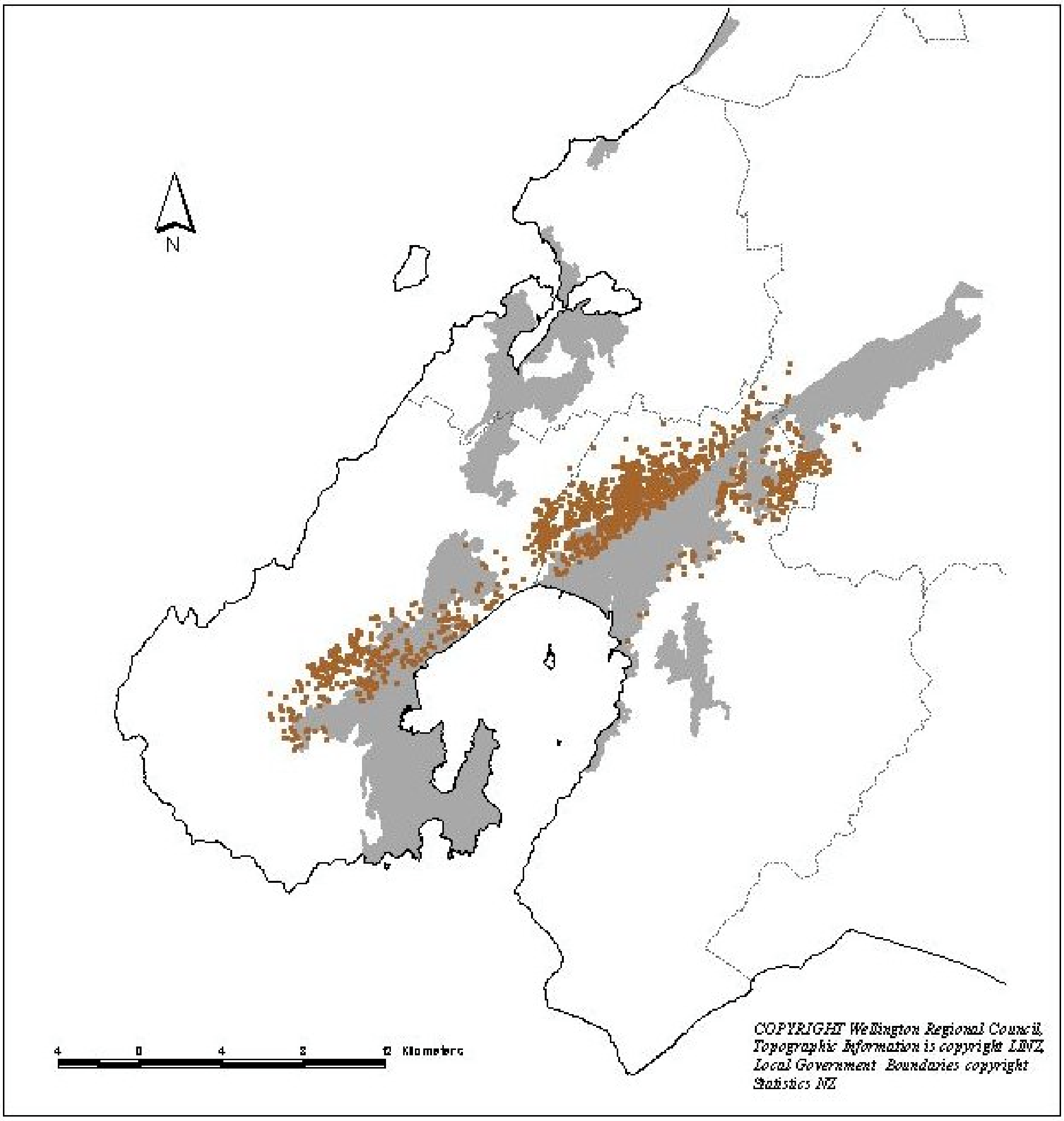

Figure 4.2: Landslides triggered by the 20 December 1976 storm. (Source: WRC).

The following paragraphs describe the effects of landsliding during the event on various lifelines.

- Roads

State Highway 2 (SH2) was closed or partially closed in various places along the western hills fault escarpment in Lower Hutt and Petone. Major slips occurred in the steep, narrow valleys of these hills that resulted in the complete blockage of most of the culvert systems under SH2 forcing a considerable amount of debris and water onto the road leading to its closure. The main area of disruption was where the Korokoro Stream crosses under SH2. All culverts were blocked and the stream flowed across the road depositing tonnes of debris over the road and the main Hutt Valley railway tracks, where ballast was eroded and signal cables damaged.

SH2 was closed at Korokoro from 9am on Monday until Tuesday afternoon and the railway line between Wellington and the Hutt Valley closed from the same time until Wednesday afternoon.

Further north at almost every stream channel coming down the western hills of Lower Hutt, SH2 was covered with silt, gravel and trees ensuring this section of the road was closed until late Monday night and then only partially opened over the next two days.

In Wellington City, Hutt Rd was closed practically all day at the Ngaio Gorge intersection, as the bridge over the Kaiwharawhara Stream could not handle the huge amount of flow and debris coming down it.

Minor flooding resulted from blocked drains and sumps in many areas of Upper Hutt, Lower Hutt and Wellington that lead to many cars being trapped and access limited to many areas.

Collapses of unsupported road batters (above and below road surfaces) occurred. The most disruptive being two slips near the top of the Ngaio Gorge Road that occurred below the road. This resulted in the road being limited to one lane at these points. However, this problem was not noted on any of the major arterial routes where some extremely high cut batters were able to cope with the minor landslides and erosion on their faces.

The only public bridges to suffer any erosive undermining were on the Mangaroa Valley/Whiteman’s Valley Rd, but this was only minor. However, many private bridges proved to be inadequate in many areas and access to many private properties was cut off for a period.

Local authorities, the Ministry of Works and Development, and NZ Railways cleared the many kilometres of roads and rail of debris and water in a mammoth effort and all services were completely restored by Christmas Eve.

- Power

Slips in Wellington brought down approximately four power poles. There were no widespread power cuts and any interruptions to power were quickly restored.

In the Hutt Valley apart from a six-hour power cut to Belmont there was no general disruption of the electricity supply.

- Water

A direct effect on water supply by landsliding and erosion was evidenced by a subsidence under the Orongorongo/Karori water main on Petone Esplanade. Two joints in the main were damaged. Indirectly, the Wainuiomata water main on Hutt Rd was damaged as heavy machinery cleared culverts blocked by landslide debris two days after the storm.

A report on the storm by Bishop (1977) states that the main problem with the damage to the water supply installations was the main roads being blocked with debris, flooding and traffic which prevented service vehicles reaching the site of the damage.

- Telecommunications

Landslides affected about 30 telephone cables on 20 December and three-quarters of these were repaired within two days. Only one cable fault was considered to have been a major fault when a cable linking Wellington and Hutt Valley was broken near the Korokoro Stream. Considerable delays in repairing the cable were experienced, as it became buried under debris and the re-opening of SH2 and the railway line took precedence.

For a time telephone communications were not available between Upper Hutt, Lower Hutt and Wellington and with SH2 impassable at several places for long periods, the radio network was the only means of contact between service staff in the areas.

Commercial radio stations broadcast significant news during the event.

- Stormwater

The stormwater network was overwhelmed in many areas not only by the intense rainfall and runoff but also by culverts and sumps becoming blocked leading to floodwater and debris migrating over roads and private properties. The storm was of such a magnitude that the amount of rainfall alone would have caused major disruption to stormwater disposal. The numerous landslides choking the system with debris only made the situation worse.

- Gas Supply

The gas supply network could have expected to face similar disruptive effects as those experienced by the water supply system. There was potential for buried gas pipes to be broken in landslide movements or undermined and exposed by erosion during the event. No mention can be found of any damage to the gas supply network.

It must be noted that the 20 December 1976 storm was an extreme event. Tomlinson and Dyke (1977) concluded that the storm had a return period in excess of 100 years and possibly in excess of 500 years. It is justified to examine such an event for Emergency Management and Lifelines considerations as it provides useful indications of what can be expected in extreme meteorological events.

4.1.2 1974

During 1974 a large number of landslides occurred within the Wellington region. Rather than confined to one intense rain event as on 20 December 1976, the landslides were distributed throughout the year. 1974 was very wet in a number of ways, with (at that time): the highest recorded annual rainfall in many stations in Wellington, the highest four-monthly total on record, the wettest April and October and the second wettest July in the 98 year record at Karori Reservoir, the highest total runoff and number of raindays at Kelburn, and finally the greatest increase (1118 to 1862 mm) over a previous year's rainfall (Eyles *et al*., 1978).

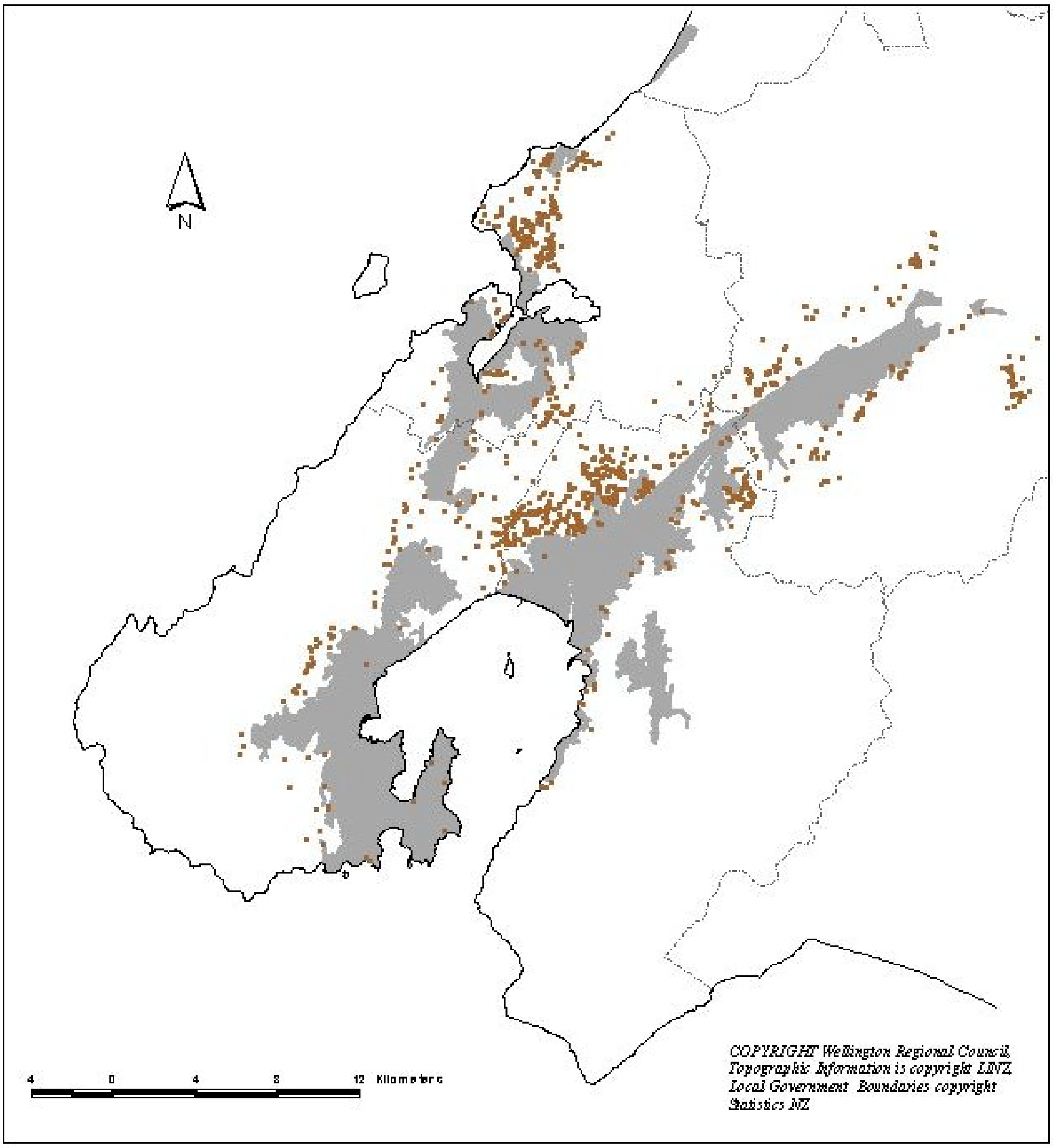

Figure 4.3: Landslides triggered during 1985. (Source: WRC).

However, most of the landslides occurred during storms of moderate intensity and 1974 was characterised by a relatively large number of storms with return periods of 2.9 to 4.1 years, occurring in the seven-month period April to October when total rainfall and number of raindays was the highest on record (Eyles *et al*., 1978).

1149 landslides were identified in 1974 (Eyles *et al.*, 1978), with only two of these located on natural slopes. The remainder being on over-steepened cut and fill slopes associated with road cuts, house platforms, sports fields, and school grounds. The majority of these landslides occurred in hill suburbs that generally have narrow winding roads. These tend to be earlier developed suburbs where intensive development has been carried out on steep terrain.

4.1.3 1985

1985 was another year when numerous landslides occurred. June was particularly wet with 221 mm of rain falling, and most of this within a two-week period. Figure 4.3 shows the locations of the landslides surveyed at the end of 1985.

4.1.4 Other landslide events

Historical reports on landslides obtained from Wellington's Evening Post have been searched and the excerpts detailed below are taken from a report by Eyles *et al.* (1978).

- July 1955:
  "…yesterday's excessive rain brought down more than 200 slips of varying sizes in the city and suburban streets. The worst of the slips was in the Terrace where, being 30 feet wide by 60 feet long. The other most serious subsidences were in Fairlie Crescent and Maida Vale Road, the latter being closed to traffic until noon." (Evening Post, 21 July 1955).

- 14 October 1943:
  "…with the ground already thoroughly saturated by over four months of incessant rain, this latest deluge, one of over 2 inches, has had the effect of starting a number of slips in the city and suburbs…serious damage occurred….as a result of the rain, particularly as it followed the record rainfall in September, when small slips occurred by the dozens, said city engineer, Mr K. E. Luke today… Reference was also made to the extraordinary difficulties before the council in removing slips caused by the long spell of bad weather. The work of removal will involve an expenditure of about £15,000" (Eyles *et al*., 1978).

- 3 October 1943:
  "…practically all the main traffic and vehicular routes in the suburban area had been subjected to slipping….There were hundreds of slips all over Wellington, some being quite extensive" (Eyles *et al*., 1978).

- 4 October 1941:
  "…I have never known the position to be as bad for 35 years, said the city engineer Mr K. E. Luke…. Cost of restoration of roads and streets may reach from £10,000 to £15,000, said the chairman of the works committee" (Eyles *et al*., 1978).

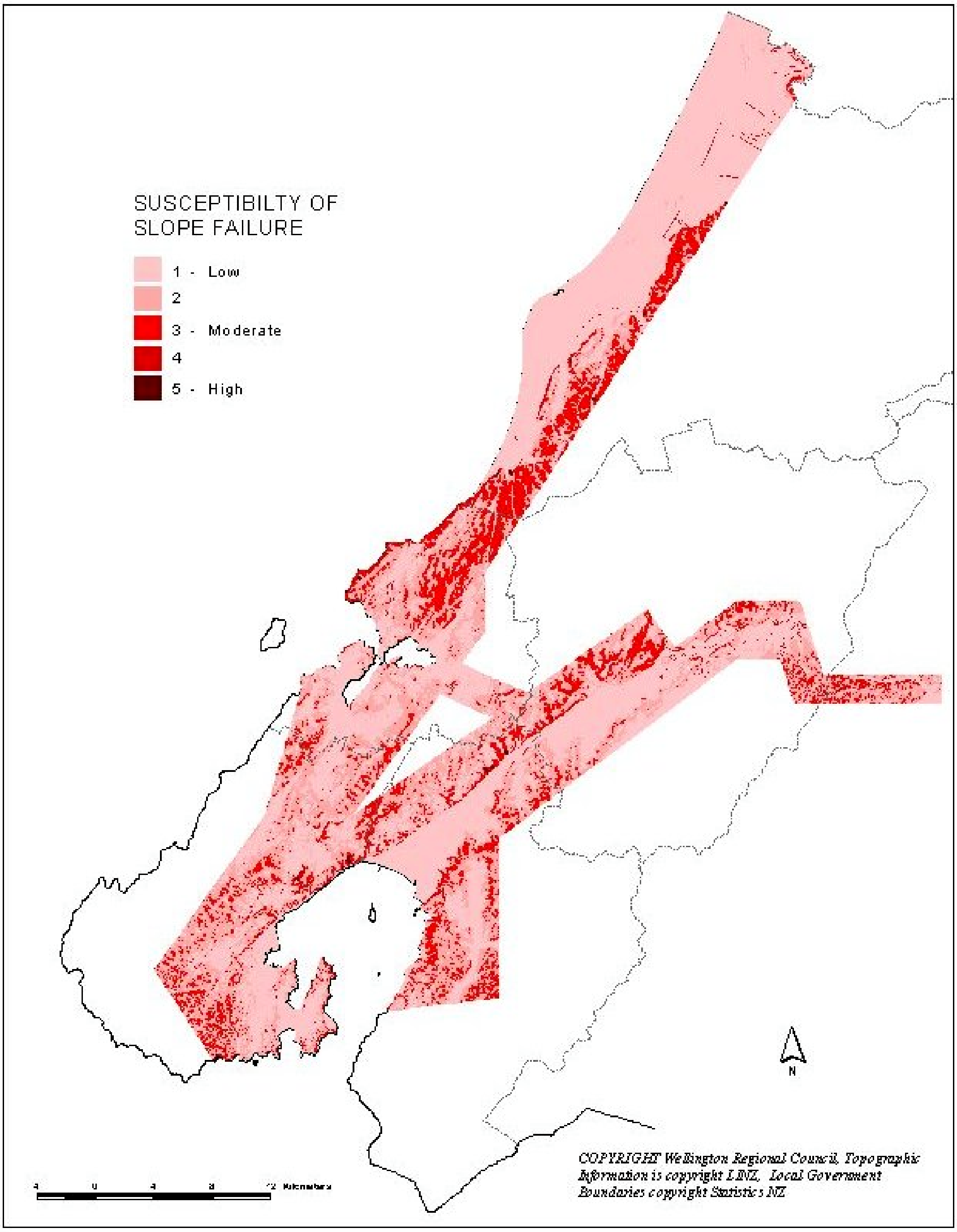

Figure 4.4: Landslide hazard map. (Source: WRC).

4.2 High Risk Areas

The Wellington Regional Council has made a number of attempts to define the landslide hazards in the region, focussing on both rainfall and earthquake induced landslides.

Early studies looking at rainfall induced landslide hazards have dealt with small, rainstorm generated slope movements on natural slopes near urban areas, with most of the work concentrated on slope failures associated with the wet winter of 1974 and the severe rain storm of 20 December 1976. The results of these studies were criticised for various factors and were never adopted.

The Policy and Planning department of the WRC developed the Landslip Hazard Assessment Menu System (LHAMS) in 1993. This GIS based method was developed from historic landslide data from the 20 December 1976 storm and the terrain characteristics of slope angle and landform. LHAMS runs within ARC/INFO software and can produce maps of landslide hazard assessment for a particular area. LHAMS is not regularly used by WRC.

In 1994 WRC produced a map for earthquake induced slope failure for the Wellington region (Figure 4.4). The map assigns susceptibly ratings to slope stability factors. The areas of susceptibility defined in the map are also applicable to landslides brought about by rainfall. To date this is the best method the WRC has to determine the rainfall induced landslide hazard for a particular area.

The landslide hazard map for the region shown in Figure 4.4 covers Wellington, Porirua, Hutt Valley, Kapiti and the SH2 corridor from Upper Hutt to Featherston. Five slope failure susceptibility zones from very low to very high are detailed.

A landslide hazard planning guide was developed for Eastbourne (Lawrence *et al*., 1982) using criteria such as rock jointing, depth of weathering, slope stability and vegetation. Three suitability classes were derived and mapped that allow planners to decide on what extent of professional opinion is required before building can take place.

A recent study (Hurndell, 2001) focuses on Wellington City using slope angle, slope aspect, and road density to create landslide susceptibility zones on modified slopes. The encouraging results obtained show that a more extensive and wide reaching hazard study should be completed for the region. The landslide susceptibility zones were overlain with important lifeline road links to produce the following results:

> "The entire length of the motorway from Wellington city to the Johnsonville off-ramp lies in Moderately to Highly susceptible terrain. The majority of Makara Rd lies in a low susceptibility zone, except for three small areas. The first of these is at the southern end of the road, where it connects to Karori Road. This area shows High to Moderate susceptibility. The second portion of this road with High to Moderate susceptibility is ~1.6 km to the northwest of the latter area. A third, small, moderately susceptible area lies ~3.6 km west of Johnsonville. The road connecting the south coast to Wellington Central crosses terrain of varying degrees of susceptibility. This

> road shows Low susceptibility from the coast to ~2 km inland. From that point the terrain it covers becomes a mosaic of all three degrees of susceptibility classes. The Mt Victoria Tunnel connection also shows varying degrees of susceptibility to landsliding, with approximately a third of the route falling into each susceptibility class" (Hurndell, 2001).

Eyles *et al.* (1978) identify three threshold values of rainfall above which serious slipping seems to occur in Wellington: (i) A four-month rainfall of between 750 and 800 mm, with susceptibility increasing towards the end of the wet period; (ii) with relatively dry antecedent conditions typical of summer and autumn, a 24-hour rain storm above about 120 mm; and (iii) on natural slopes under grass, scrub or forest a 24-hour fall of 200 to 250 mm.

4.3 Amelioration Methods

The landslide hazard maps discussed above are not comprehensive or accurate enough to rely on solely for effective landuse management and planning strategies.

A comprehensive landslide inventory (if it were to exist for the region) would provide information on susceptibility, landslide triggers, and the frequency and magnitude of events. This information would be important in developing land management policies and guidelines for the avoidance and mitigation of landslide hazard and risk.

The current landslide hazard maps WRC holds can provide a broad view of the hazard for a particular area and provide a guide to landuse planning and disaster management. However, for individual sites (e.g. subdivisions) a detailed site engineering study is necessary.

The rainfall thresholds described by Eyles *et al.* (1978) would be very hard to ameliorate against. And with the possibility of an increase in high intensity rainfall events under global climate change then the thresholds could be attained more often.

4.4 Knowledge Gaps

The Wellington region has a long recognised problem with slope stability and landslides and as number of attempts have been made to derive models of hazard and susceptibility.

These attempts have had limited success. More effort needs to be made to come up with a detailed landslide hazard assessment map or model.

A lack of a comprehensive landslide inventory for the region has been identified (Hurndell, 2001). Several noteworthy inventories for particular landslide events exist, however a standardised regional/national database is required to succeed with the management of land for the reduction of hazard and risk to people, property, and services.

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5. Coastal Flooding and Erosion

Key coastal hazards for the Wellington region relate to either coastal erosion (shoreline retreat) or occasional coastal flooding, due to extreme tides, storm surge, heavy seas or a tsunami. The risk of coastal flooding is limited to areas of low-lying coastal margins that are only a few metres above the mean level of the sea. However, erosion is not limited to low-lying areas, but rather many of the erosion hazards in the Wellington region impact shorelines with coastal cliffs (Wairarapa coast) or relatively high frontal dunes (Kapiti coast).

Key drivers of coastal flooding (inundation), coastal erosion and maritime/ recreational hazards (Figure 5.1) are extreme tides, waves, atmospheric pressure, winds, and coastal currents, while tsunami can be generated by earthquakes and/or underwater landslides. Climate-change effects are covered in section 12.

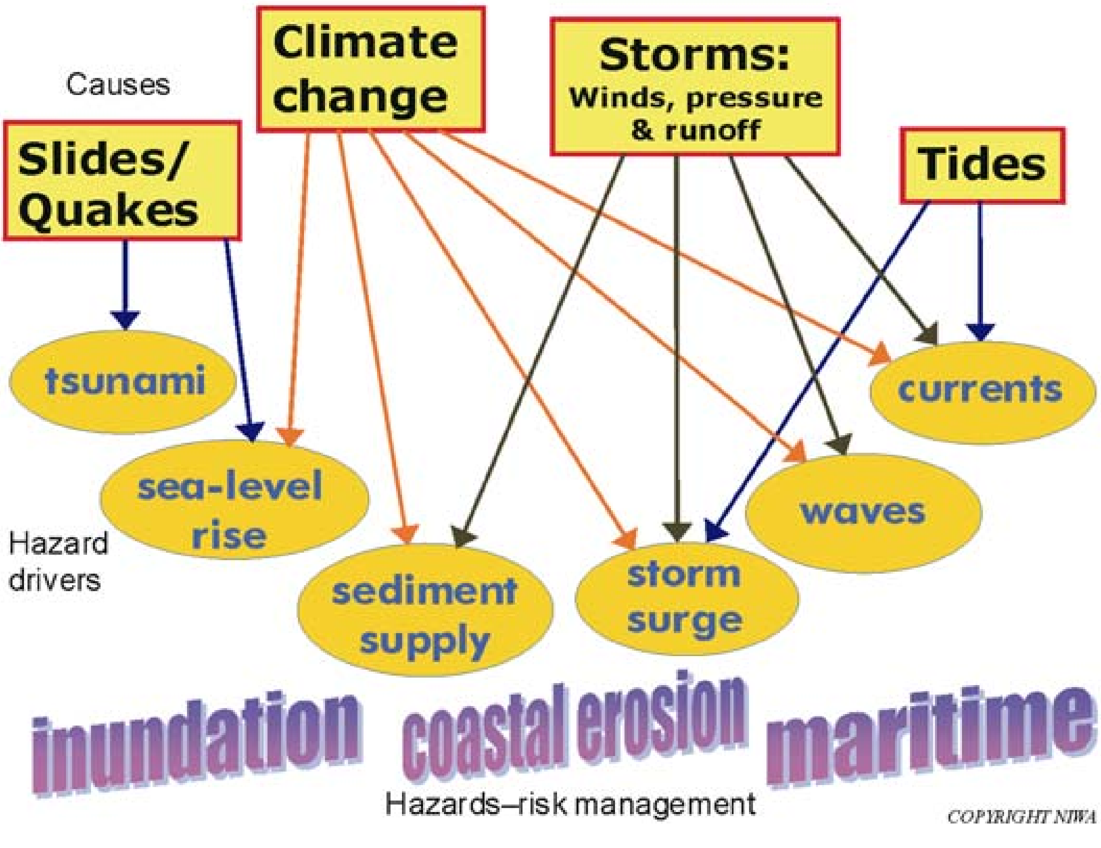

Figure 5.1: Interactions of the cause and drivers of the main coastal hazards that require risk management. "Maritime" hazards cover navigation, search & rescue, oil-spill operations, surf rips and recreational activities, but are not covered by this report.

This section of the report describes some of the latest information on hazard drivers (tides, waves, atmospheric pressure, storm surges) for the Wellington region, and relates them to examples of known coastal-hazard hotspots for coastal flooding and erosion. More detailed investigations of local hotspots, such as recent Kapiti coast studies (Lumsden, 2001; Boffa Miskell, 2001), will then be required to determine the risks, especially the likelihood of occurrence or return periods of damaging consequences.

A recent scoping report on tsunami hazards for the Wellington region was prepared by GeoEnvironmental Consultants, ArchResearch, NIWA and GNS (GeoEnvironmental Consultants, 2001), so no further information is considered here on the coastal flooding and erosion risk from local or remote tsunami.

Long-term climate change will be manifest as a rise in sea level, relative to the landmass, but also through changes in other drivers such as wave climate, storminess, and factors affecting coastal sediment supply (e.g., from rivers, coastal cliff erosion, and the inner continental shelf). Global warming will tend to cause more erosion problems for areas already susceptible to erosion or in a delicate state of equilibrium with dwindling modern sediment supplies. An increase in sea-level rise (without invoking increased storminess) will significantly increase the probability (or lower the return period) of storm surge and spring tides exceeding a fixed datum level, such as a coastal bund or dune. The possible modification by climate change to the risks associated with existing coastal hazards is discussed in more detail in section 12.

This section covers coastal flooding and coastal erosion hazards, but not maritime or recreational hazards. Some historic events are described and an attempt is made to estimate the risk where sufficient monitoring data is available, such as the Wellington CBD where the Queens Wharf tide gauge is situated. Gaps in the knowledge or suggested steps forward are then discussed along with amelioration approaches.

5.1 Coastal Flooding

The coastal topography around the Wellington region's coastline is mostly rugged with few very low-lying areas. However there are populated low-lying areas that are vulnerable to coastal flooding hazards, either at present or in the future as sea level continues to rise. Also, infrastructure such as roading is vulnerable to coastal flooding in some locations despite the adjacent rugged terrain.

Some examples of known areas at potential risk of coastal flooding are: Castlepoint Beach, SH1 between Paekakariki and Pukerua Bay, Plimmerton, Porirua Harbour margins, populated bays along the south coast of Wellington City (Owhiro Bay, Island Bay, Lyall Bay, Breaker Bay), and some of the margins around Wellngton Harbour, especially the CBD area around Te Papa and Lambton Quay, the Hutt–Eastbourne Rd and Petone.

Coastal flooding results from combinations of all or some of the following "drivers" (Figure 5.1):

- Extreme high tides (that provide the high sea-level platform for other "drivers" to piggy-back on);
- Large waves or swell (causing local water-level set-up and run-up inside the surf zone);
- Low atmospheric pressure, with the so-called inverted barometer effect causing regional water-level set-up of approximately 1 cm rise per 1 hPa drop in atmospheric pressure below the mean pressure of around 1014 hPa;
- Winds blowing either onshore or alongshore with the coast on their left, cause a set-up in sea level as seawater piles up against the coast;
- Long period sea-level fluctuations at seasonal (annual), El Niño–Southern Oscillation (2–5 year), and Interdecadal Pacific Oscillation (20–30 year) timescales can cause higher background sea levels of up to 0.15 m in some years or seasons than others (Bell *et al.*, 2000; 2001)
- High river water levels at river mouths, which at high tide can greatly exacerbate river flooding upstream and cause flooding of low-lying adjacent coastal margins.

Some of these basic drivers are now well monitored in some localities, such as tides, winds and atmospheric pressure, while waves, wave run-up and long-period sea levels are not very well known. Ultimately, to estimate the risk of coastal flooding for vulnerable areas, there is a need to combine the risks of "drivers" acting together in a realistic joint-probability approach that splices in with the local coastal topography. This is an area currently being researched by NIWA. Simply combining all the worst-case sea level set-ups for each "driver" is not helpful as it produces unrealistically conservative results.

"Storm surge" needs some definition, as confusion often accompanies the term. Storm surge is the temporary elevation in sea level at the shoreline above the predicted tide height caused by a combination of both low atmospheric pressure (inverted barometer) and set-up by adverse winds, and breaking surf waves during a storm. An additional component that needs to be considered for each site is wave run-up, which varies locally with the topography of the coastal margin. Another term used in this section is "storm tide" (i.e., the level of the predicted high tide plus storm surge) which conveys the important point that high tides play a critical role in determining the elevation of coastal sea levels during a storm, and whether coastal margins or a river mouth sustains flooding.

Recent information has become available on the occurrences of extreme tides, atmospheric pressure, ocean waves, and long-period sea-level fluctuations, which are now described.

5.1.1 High tides

A 100-year tide forecast from 1-Jan-2000 to 1-Jan-2099 was carried out for Wellington Harbour at Queens Wharf, based on the set of tidal constituents used to generate the Tide Tables each year. Of most interest is the height distribution and occurrences of High Waters (HW's) over the 100-year period. Figure 5.2 shows the distribution of the 69,874 HW's over the 100 years relative to Wellington Vertical Datum–1953.[1] The Highest Astronomical Tide reached by a HW in the next 100 years (excluding any non- tidal effect) will be 0.90 m above WVD–53. This won't occur until 7-Apr-2091, but HW's on the 10-Apr-2012 will reach a similar height of 0.89 m.

Mean High Water Spring (MHWS) is the statutory boundary delineating the Coastal Marine Area under the RMA-1991. A key point demonstrated by the distribution of HW's in Figure 5.2 is that MHWS is exceeded by 46% of all HW's! The reason for this lies in the definition used traditionally for navigation, which is to add the main twice-daily lunar and solar tide ranges together.

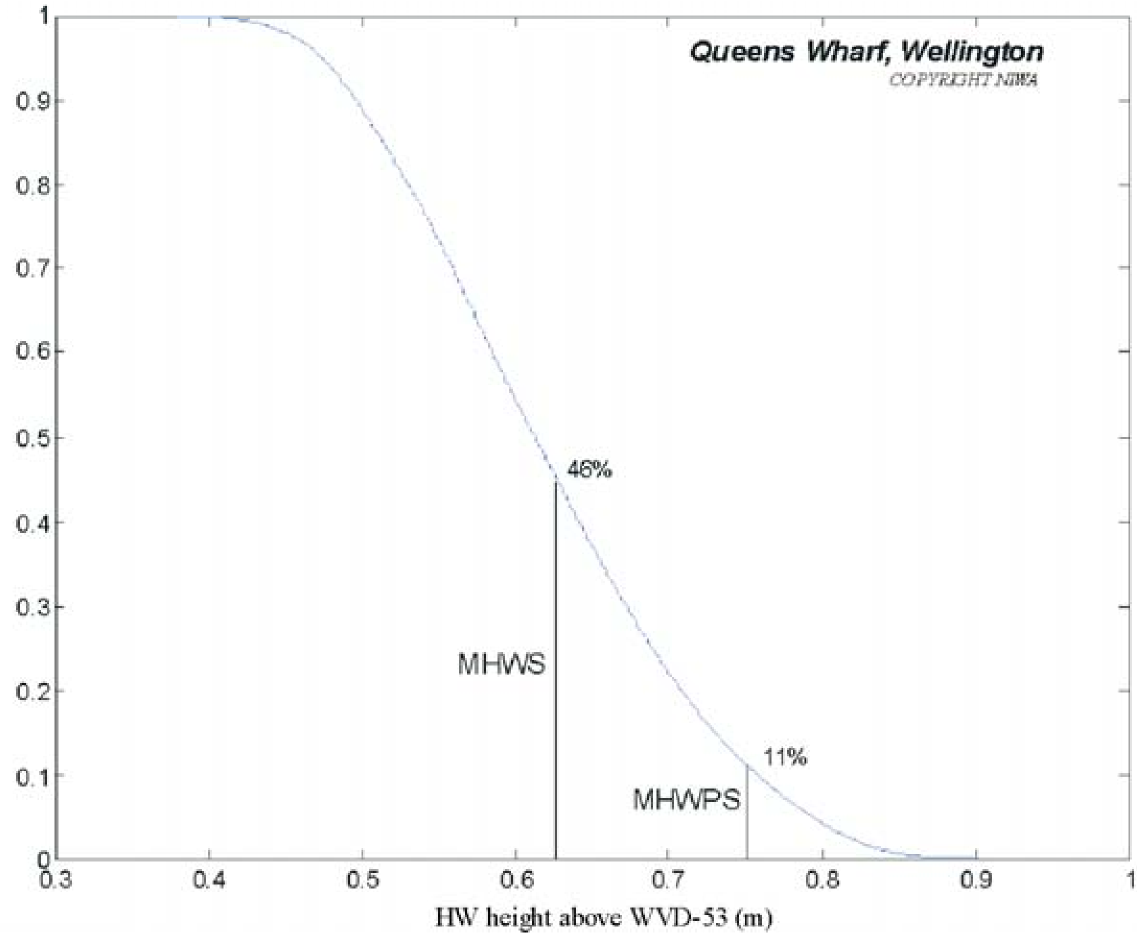

Figure 5.2: Probability of exceedance curve for High Water (HW) heights based on tide predictions for Queens Wharf (Wellington) over the next 100 years, but excluding sea-level rise and meteorological effects. The Mean High Water Spring (MHWS) level is exceeded by 46% of HW's, while only 11% of HW's exceed the Mean High Water Perigean-Spring (MHWPS) level. The datum is Wellington Vertical Datum–1953.

[1] Based on survey control for BM K 80/1 (LINZ code ABPB) in Featherston St. near Lambton Quay.

However, the twice-daily solar tide virtually disappears in mid-eastern coasts of New Zealand as shown by recent tidal modelling of the ocean around New Zealand by Walters *et al*. (2001). Rather, the higher HW's are caused by the combination of the main twice-daily lunar tide and when the Moon is in its perigee each month i.e., when it is closest to the Earth during its monthly elliptical orbit. When spring tides coincide with the Moon in its perigee higher perigean-spring tides are generated, shown by MHWPS in Figure 5.2. In deliberations on the matter of defining high water springs, the Environment Court has taken a more pragmatic approach, so a "pragmatic" definition of a HW height that is exceeded say only 10% of the time, is a better base to work from when relating to vulnerable low-lying coastal margins. For Queens Wharf (i.e., inner Wellington Harbour), the MHWPS is only exceeded by 11% of all HW occurrences and is therefore a much better definition to work with rather than MHWS.

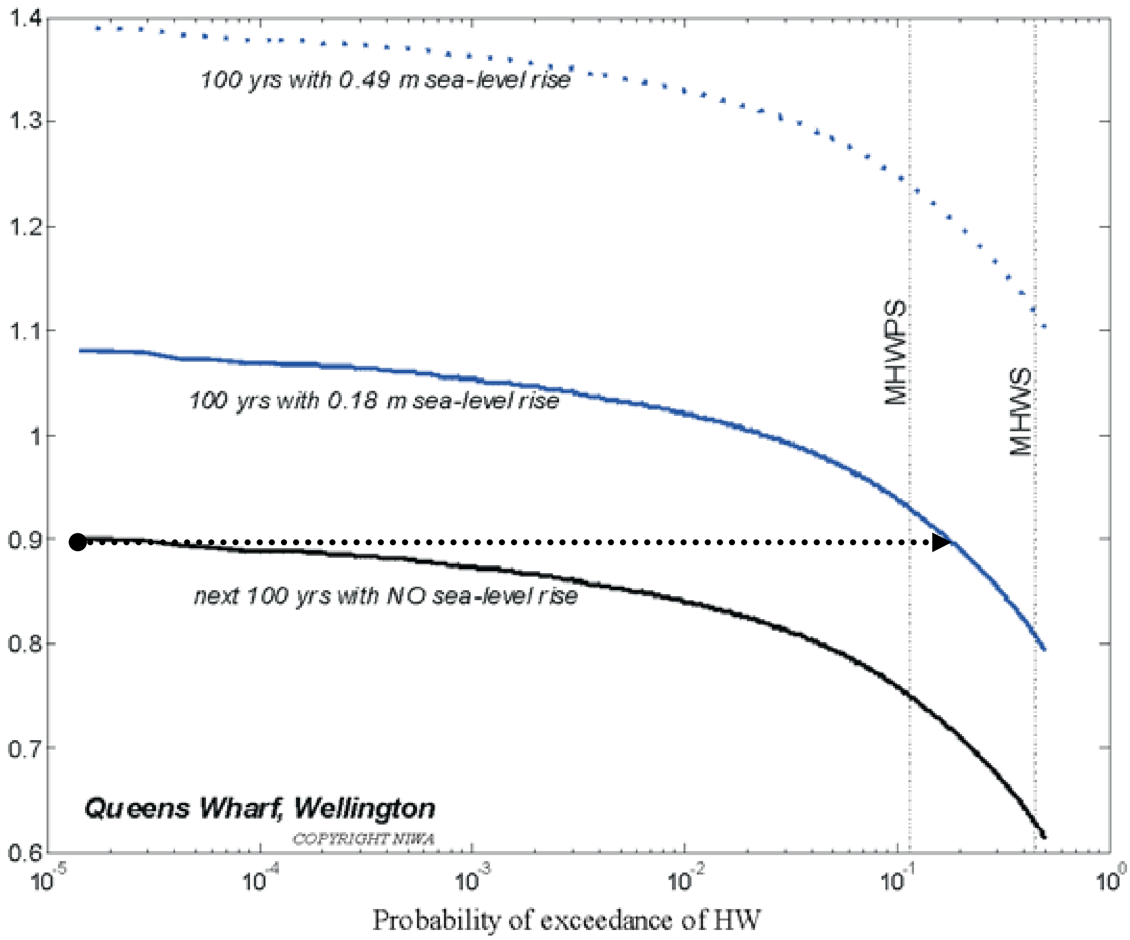

Figure 5.3: Probability of exceedance curves for extreme High Water (HW) levels based on tide predictions for Queens Wharf (Wellington) over the next 100 years. The bottom curve is without sea-level rise, the middle curve is for a 0.18 m sea-level rise (akin to the projections for 2050) and the top curve is for a rise of 0.49 m (projected for 2100). The dotted arrow shows the large change in probability of exceedance with just a small change in sea-level rise (+0.18 m), where the most extreme 100-year HW level of 0.9 m eventually becomes a commonly exceeded level for around 16% of HW's. The datum is Wellington Vertical Datum–1953.

Now looking more closely at the extreme HW's, Figure 5.3 shows a semi-log plot of the height distribution versus the probability of exceedance of that HW (based on 69,874 high tides over the next 100 years). The lower curve shows the distribution without sea-level rise. Section 12 discusses sea-level rise projections in more detail, but Figure 5.3 shows the resulting 100-year high tide distributions[1] riding on the back of sea-level rises of 0.18 m and 0.49 m, which are projected for 2050 and 2100 respectively. The dotted arrow shows the dramatic effect on the exceedance of a specific extreme tide level with even a small rise in sea level. The example shown, means that for tides only, a level of 0.9 m above WVD–53 which would not be exceeded at all in 100 years, would be exceeded by up to 17% of all HW's for a 0.18 m rise in sea level.

The tide range varies markedly around the Wellington region coastline, as shown on the Kapiti coast (Laing *et al*., 2000). For example, the Highest Astronomical Tide varies from 0.80 to 1.26 m above WVD–53 in a 40 km distance from Paekakariki to Otaki. This has important implications for determining coastal flooding heights and risks for each locality. The tidal model of the ocean around New Zealand (Walters *et al*., 2001) has been used to supply district councils with GIS-based pragmatic levels of MHWPS and Highest Astronomical Tide at locations along the coastline.

5.1.2 Atmospheric pressure

Most sea-level records are too short (apart from Queens Wharf) to estimate return periods of storm surges on the open coast. However, there are longer records available of atmospheric pressure and to a lesser extent, winds, which can be used as surrogates for estimating storm surge. Of interest are minimum atmospheric pressures as most storm-surge events have common elements to varying degrees — low atmospheric pressure, high tides, adverse winds and high seas.

One of the longest atmospheric pressure records in the region is available from Paraparaumu Airport. The record analysed was from January, 1962 to June, 2000. Of most relevance to storm-surge levels is the frequency of deep low-pressure systems passing through the region. The minimum daily pressures were sorted in ascending order and the lowest values plotted as a frequency (probability) plot (Figure 5.4). The equivalent inverted barometer set-up in sea level (cm) is plotted along the top axis.

Two well-known events in recent time are marked, being Cyclone *Giselle* (the so-called *Wahine* storm of 9–10 April 1968, and the storm of 11–13 September 1976 which caused severe erosion along the Kapiti coast (Gibb, 1976; 1978a). Interestingly, the barometric pressure of 980.8 hPa was not excessively low during the devastating 1976 storm. This low pressure was surpassed by 19 other lower events during the 38-year period. This illustrates the issue of joint occurrence and probability of several "components" combining together when attempting to derive return periods of various storm-surge levels and then including the wave set-up and run-up. The lowest

[1] The assumption is that tidal characteristics will change little with sea-level rise because of the relatively deep harbour.

pressure recorded was 973.6 hPa on 15 April 1962, yielding an equivalent sea-level set-up (inverted barometer) of just over 0.4 m due to the low pressure alone.

5.1.3 Storm surge

An approximate rule of thumb is that inverted barometer contributes half the set-up in ocean storm surge (above the predicted tide), while the other half comes from wind set-up and other coastal trapped-waves that propagate out from the storm centre (Bell *et al*., 2000). This rule is only approximate, as the two contributory processes can vary considerably. Given these limitations, doubling the highest inverted-barometer set-up from Paraparaumu Airport of 0.4 m, would suggest a large ocean storm surge could be 0.8 m above predicted tide levels. Then at the shoreline, wave set-up through the surf zone and wave run-up can at least double the ocean storm surge set-up.

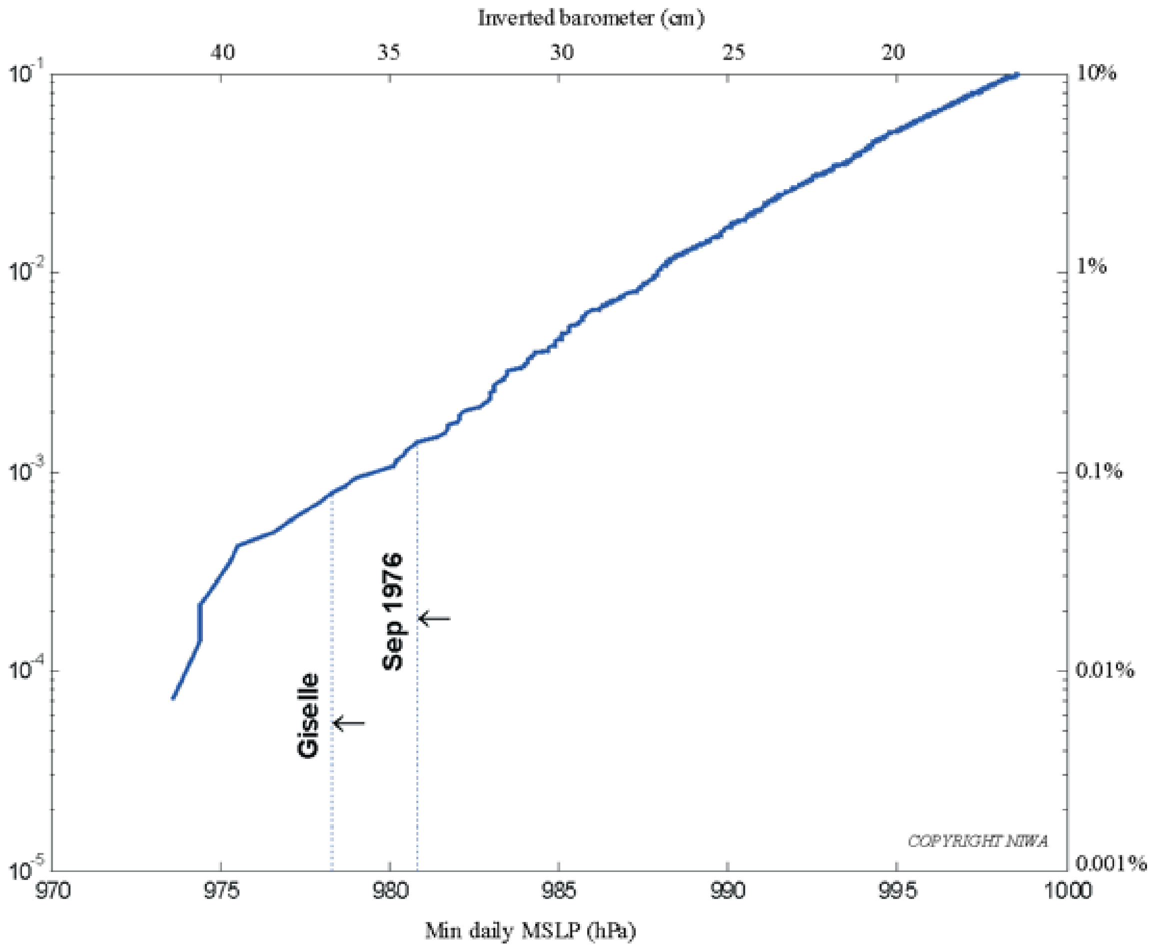

Figure 5.4: Frequency distribution of minimum daily mean sea-level atmospheric pressure (MSLP) for the Wellington region. It is based on hourly measurements at Paraparaumu Airport from January 1962 to June 2000. The right axis gives the percent of days in the 38-year period that pressures were lower than a selected pressure. The top axis is the equivalent set-up in sea level (cm) due to the inverted-barometer effect.

Firstly, looking at some historic events in the Wellington region will at least enable the magnitudes of storm surges and coastal flooding risk to be assessed. More is known about coastal storm events since the 1950's, but recorded observations of historic storm surges are patchy, and rely mainly on semi-quantitative information.

- The "Cyclone of 1936", as it is known, occurred on 2nd February 1936, generated by a deep depression reaching 970 hPa that passed over the North Island (Brenstrum, 2000). The storm generated strong easterly and south-easterly winds that slammed into the Wairarapa and South Wellington coasts respectively, with similar strength to those experienced during the later *Wahine* storm. Large tides coincided with the storm. Back predictions for Queens Wharf show that high tides on 2 February were expected to be nearly 0.8 m above WVD–53, which from Figure 5.3 is higher than the mean high-water perigean-spring tide (MHWPS). These high tides, coinciding with a deep depression (inverted barometer set-up of approx. 0.45 m), and strong wind set-up, could have produced an ocean storm surge of around 0.9 m above the tide in Wellington Harbour. At high tide, this translates to an estimated storm-tide height of ~1.7 m above WVD–53. This explains why in Wellington, the sea flooded the waterfront roads[1] (Brenstrum, 2000), particularly if wave run-up is included. On the open exposed coast at Castlepoint, the sea washed away the sandhills and reached houses up to 100 m inland (Brenstrum, 2000), again suggesting the storm surge plus surfzone wave set-up and run-up could have been at least 2 m above the predicted high tide. An easterly gale occurred a few weeks later on 26–27 March of the same year (1936) in the upper North Island. It is not known what the effect on storm surge was in the Wellington region, but this event caused extensive coastal flooding of the Hauraki Plains and areas of Auckland because of the extreme high tides. The back-predicted high tides at Queens Wharf for those days were very high at 0.86–0.87 m above WVD–53, very close to the 100-year extreme high tide of 0.9 m in Figure 5.3.

- On 19–20 June 1947, very high "tides" were recorded in Wellington Harbour (SCRCC, 1957). On 20 June 1947 at 1805 hrs, the highest ever "tide" up to that date was recorded at 6 ft (1.83 m) above the level marked at the Wellington Harbour Board office, compared with a normal spring tide of 4 ft 6in (1.37 m). Taking into account that the gauge datum is now lower, and that the back-predicted tides were only just above the MHWPS level (0.79 m above WVD–53), means the storm surge in the Harbour that day was approximately 0.3 m. The 19–20 June 1947 storm tide is estimated then at 1.1 m above WVD–53. It caused water to seep into basements of many waterfront buildings and waves were breaking over the Hutt to Eastbourne road around high tide.

- Two historic events in the 1950s caused severe erosion along the Kapiti coastline from Paekakariki and Raumati (Donnelley, 1959) and coastal flooding or heavy seas. No climate data is available for this period, but newspaper articles and observations provide some indications:

[1] To put the storm tide in context, Lambton Quay is around 2 m above WVD–53.

- 9–10 July 1954 Southerly Gale. Minimum low pressure of around 990 hPa with north-west winds, followed by a southerly gale that gusted to nearly 90 kt at Rongotai Airport. Tide ranges were low (neap), with the predicted high tide at Kapiti Island only reaching 0.4 m above the mean level of the sea. It appears that the storm-surge component was probably small to moderate, coinciding with neap tides and therefore the erosion was largely the result of heavy seas. Other consequences of the heavy seas, reported by the *Evening Post* (10 July 1954), were: (i) a dressing shed at Lyall Bay was moved off its foundations, with a portion floating out to sea; (ii) waves were observed breaking over Taputeranga Island that protects Island Bay; and (iii) waves were breaking on the Petone foreshore and running up onto The Esplanade.

- 12–13 October 1957. Minimum low pressure of 988 hPa (inverted barometer set-up of 0.27 m) accompanied by gale-force north-west winds (gusts up to 57 kt recorded at Kelburn). Tide ranges were high (spring), with the predicted high tide at Kapiti Island reaching 0.9 m above mean level of the sea. The *Evening Post* reported that on Sunday morning (13 October, 1957), “heavy seas pounded a mile of Paekakariki Beach, cutting several feet into the sandhill”. Further, “all residents could do at the height of the gale at midday was to watch the waves, estimated to be 20 to 30 feet (6–9 m), slash their way through flimsy protective walls.” Obviously, the damage was mainly due to wave set-up and run-up, but was supported by a spring tide that peaked locally soon after midday and a moderate storm surge (estimated to be 0.4–0.5 m from the inverted-barometer and wind set-up), elevating the local sea level and exposing the toe of the foredune. Other *Evening Post* reports of coastal flooding came from Plimmerton, where “old residents had never seen such a storm. The seas were breaking right up against the houses and water was pouring through the gates into their yards.”

- 10 April 1968—Cyclone *Giselle* (or the *Wahine* storm). The minimum atmospheric pressure reached 978 hPa in the Wellington region and was accompanied by a short 8-hour period of gale-force southerly winds along the south Wellington coast and SSW winds (210°) along the Kapiti coast. At Paraparaumu and Wellington Airports, the average 10-minute wind speeds reached over 60 kt, with peak gusts up to 100 kt at Wellington Airport. The peak inverted-barometer set-up in sea level alone would have been ~0.37 m, however sustained winds of this speed would have contributed markedly to storm surge on the South Wellington coast. An analysis by Heath (1977, 1979) has shown that the storm surge at Queens Wharf was about 0.5 m above predicted tides. It is somewhat complicated by the fact that wind set-up within Wellington Harbour from a southerly wind will tend to set-down sea level at the southern gauge site and pile water up at the northern Petone shore. Therefore the storm surge at Petone may have reached around 0.7 m, to which wave set-up from breaking waves could have added a further 0.3 m to produce a 1 m storm tide set-up at the shoreline. An additional component is wave run-up, which is locally dependent on beach slopes and coastal topography. Fortunately, the Wahine storm coincided with smaller mean to neap tides and the storm had begun to subside before high water was due at 2 pm. In summary, the storm tide level in the Wellington CBD during the *Wahine* storm would have been 1.1 m above WVD–53 (excluding waves), which is similar to the 1947 extreme tide event. On the Petone foreshore, the storm tide may have reached 1.6 m above WVD–53 (including wave set-up, but not run-up).

- 11–13 September 1976 storm that caused severe erosion at Raumati and Waikanae Beaches on Kapiti coast (Figure 5.8). The minimum pressure at Paraparaumu reached 981 hPa on 13 September, hovering at very low pressures below 987 hPa for two days on 12–13 September. The situation was set up by a slow-moving depression (970 hPa) west of Taranaki (Gibb, 1978a). The equivalent inverted-barometer set-up would have been sustained at approximately 0.30–0.35 m over both days. The local winds at Paraparaumu Airport reached 34 knots (10-minute average) from NNW (330°), while out at sea in the South Taranaki Bight, ships recorded 50-knot NW winds and 11–13 m swells (Gibb, 1978a). The wind-stress set-up component would have been approximately 0.25 m. From Kapiti coast beach surveys, Gibb (1978a) concluded that the total storm surge set-up was 0.72 m above the predicted spring-tide high waters for the two days of 0.75 m above the Mean Level of the Sea (MLOS). This means the storm tide elevation at high water (excluding wave run-up) would have been nearly 1.5 m above the MLOS (or 1.62 m above WVD–1953).[1] Gibb (1978a) also deduced from the driftwood line that the wave run-up reached a vertical elevation of 2.6 m higher than the normal driftwood line.

- Waitangi Day storm (6 Feb 2002). An intense depression centred 800 km southeast of Wellington generated huge seas along the south Wellington and Wairarapa coasts. Peak waves reached 13 m, with significant wave heights of 8 m. However, it was a generally fine day in Wellington with moderate southerly winds up to 30 kt, while inverted barometer set-up was no more than 0.1 m. Consequently, most of the coastal flooding was due to wave set-up and wave run-up along the south coast.

Secondly, and a more difficult question, is the likelihood of occurrence for a given storm-surge height. This will require further joint-probability analysis of sea-level gauge records and atmospheric pressure after a few more years of record, but a preliminary assessment on return periods is made for the interim. The above events point to the highest storm surge during the Twentieth Century to be around 1 m above the predicted tide i.e., the 1936 Cyclone. However, what is critical for coastal flooding is the joint occurrence of the storm surge with the state of high tide i.e., the storm tide. Table 5.1 is a summary of storm tide levels that have been reached at Queens Wharf from known events (which exclude any wave contribution). From the known historic events around Wellington, and an analysis of New Zealand-wide records suggest that storm surge (excluding wave effects) would rarely exceed 1 m (Bell *et al.*, 2000), being limited by the depth of depressions we get across the North Island. Consequently, the storm tide height reached in Wellington Harbour during 1936

[1] Based on the present mean level of the sea (MLOS) being 0.12 m higher than the geodetic MSL Datum (1953) at the Port of Wellington.

Cyclone event of approximately 1.7 m above WVD-53 is probably a useful benchmark for a 1% Annual Exceedance Probability (or 100-year return period). Further analysis of Queens Wharf tide-gauge data is required, along with a joint-probability analysis that combines predictable tide events with stochastic storm-surge events.

Table 5.1: Predicted High Water (HW), and estimated storm surge set-up (excluding waves) and resulting storm-tide heights reached at Queens Wharf during known storm-surge events ranked in descending order. Copyright NIWA.

Storm event	Date	Predicted HW (m WVD-53)	Storm surge (m)	Storm tide height (m WVD-53)
1936 Cyclone	2 Feb 1936	0.80	~0.9	~1.7
Wahine storm	10 Apr 1968	0.63	0.5	1.1
HRT* (Queens)	20 Jun 1947	0.79	0.3	1.1

* HRT=Highest Recorded Tide in Port of Wellington records

5.1.4 Waves

Local and remote winds can generate sizeable waves in Cook Strait and along the exposed Wairarapa coast. Fortunately historic wave-buoy and visual-observation records are available for Cook Strait off Wellington Harbour. The wave height in Cook Strait off Wellington exceeds 2.5 m for around 8% of the time, based on visual observations and recent Baring Head wavebuoy data. Similar wave conditions are likely to occur along the Wairarapa coastline, which is also exposed to southerly swells. However, the Kapiti coast is more protected from swell arriving from Cook Strait or the Tasman Sea, with less than 15% of swell energy reaching this coast, nevertheless local winds in the South Taranaki Bight can generate heavy seas (Harris, 1990; Laing *et al*., 2000).

- Kapiti Coast
  For the Kapiti Coast, wave climate statistics have been derived from a 20-year record of regional winds for the period 1975 to 1995, using fetch-limited and duration-limited wave growth formulae (Laing *et al*., 2000). The largest computed significant wave height[1] (H_s) over the 20-year wave hindcast period was 4.5 m in deep water. This is equivalent to an $H_{1/10}$ (the average wave height of the highest 10% of the waves over a measurement period) of 5.8 m. Historically, during the 13 October, 1957 storm, residents estimated the waves to be 6–9 m near the shoreline.

- South Wellington Coast
  Wave conditions in Cook Strait were monitored by Central Laboratories (Ministry of Works) for the extension of the Wellington Airport runway into Lyall Bay in 1971, then again for one year in 1978–79 for the Moa Point outfall investigation at a site 2 km off Lyall Bay, and later in the late 1980s for the Hutt City Council outfall investigations. A wave buoy is currently moored due west

[1] Significant wave height (H_s) is the average of the largest 33% of waves in a measurement period

off Baring Head, which is a cooperative effort by Wellington Regional Council, TranzRail and NIWA.

Six-hourly visual observations were observed by Wellington Harbour Board staff from an observatory on Beacon Hill starting in 1969.

Some of this information was summarised by Beca Carter–Caldwell Connell (1980) in a report on the Moa Point outfall study, and also by Harris (1990). Based on the Beacon Hill visual observations over a 7-year period from 1969 to 1976, the 1% AEP wave height was estimated to be 15.5 m, while a 10% AEP wave height was around 8.5 m. (Note: "wave height" was not defined).

$H_{1/10}$ measurements from wave buoy data (with measurement periods of 20-minutes) for 1978–79 produced a 1% AEP $H_{1/10}$ wave height of 14.5 m and a 10% AEP wave height of 10.5 m.

The recent heavy seas in Cook Strait on Waitangi Day (6 Feb 2002) prompted many to ask how often such waves occur — was this the biggest since the *Wahine* storm? Roads and properties along the south Wellington coastline were littered with debris from wave wash-over. The wave buoy at Baring Head measured significant wave heights (H_s) of 8 m and a single maximum wave height of 13 m at the peak of the sea storm. The equivalent $H_{1/10}$ wave height was around 10.3 m.

During the *Wahine* storm on 10 April 1968, waves were estimated at between 12 and 14 m, probably maximum wave heights (Harris, 1990). A wave-model back-prediction of waves for the *Wahine* storm indicate that significant wave heights were 6–8 m high. These results suggest the *Wahine* storm (1968) and the Waitangi Day seas (2002) were in a similar league. A 12 m maximum wave height was also recorded by a wave buoy off Fitzroy Bay during an unnamed storm during 1989. Again similar wave conditions probably occurred during the Southerly Gale of 9–10 July 1954.

In summary for Cook Strait, events with significant wave heights of around 8 m, $H_{1/10}$ heights of 10.5 m and maximum wave heights of 12–13 m have occurred between 8 and 14 years apart, which supports the return-period analysis that such heights represent a 10% AEP (10-year return period) event along the south Wellington coastline. The 1% AEP wave height $H_{1/10}$ is estimated to be 15.5 m.

- Wairarapa Coast

  Little is known of the wave climate along the Wairarapa coast, apart from sporadic ship observations. However, a 20-year hindcast of deep-water wave conditions around the New Zealand coast has been completed by Gorman and Laing (2001) for the period 1979 to 1998 inclusive[1]. Wave climate statistics were extracted for four points on the 50 m isobath around the Wellington region coast, including two sites off the Wairarapa coast (Figure 5.5). The figure shows the directional frequency of deep-water waves. The dominant wave direction for the

[1] This is a different approach and hindcast period than that carried out for the Kapiti coast by Laing et al., 2001)

Wairarapa coast is from due south, but waves can arrive from a window ranging from due east around to south-southeast. This compares with the much narrower wave windows for the Kapiti and south Wellington coasts (Figure 5.5). The distribution of significant wave heights off the Wairarapa coast over the 20-year period are shown in Figure 5.6.

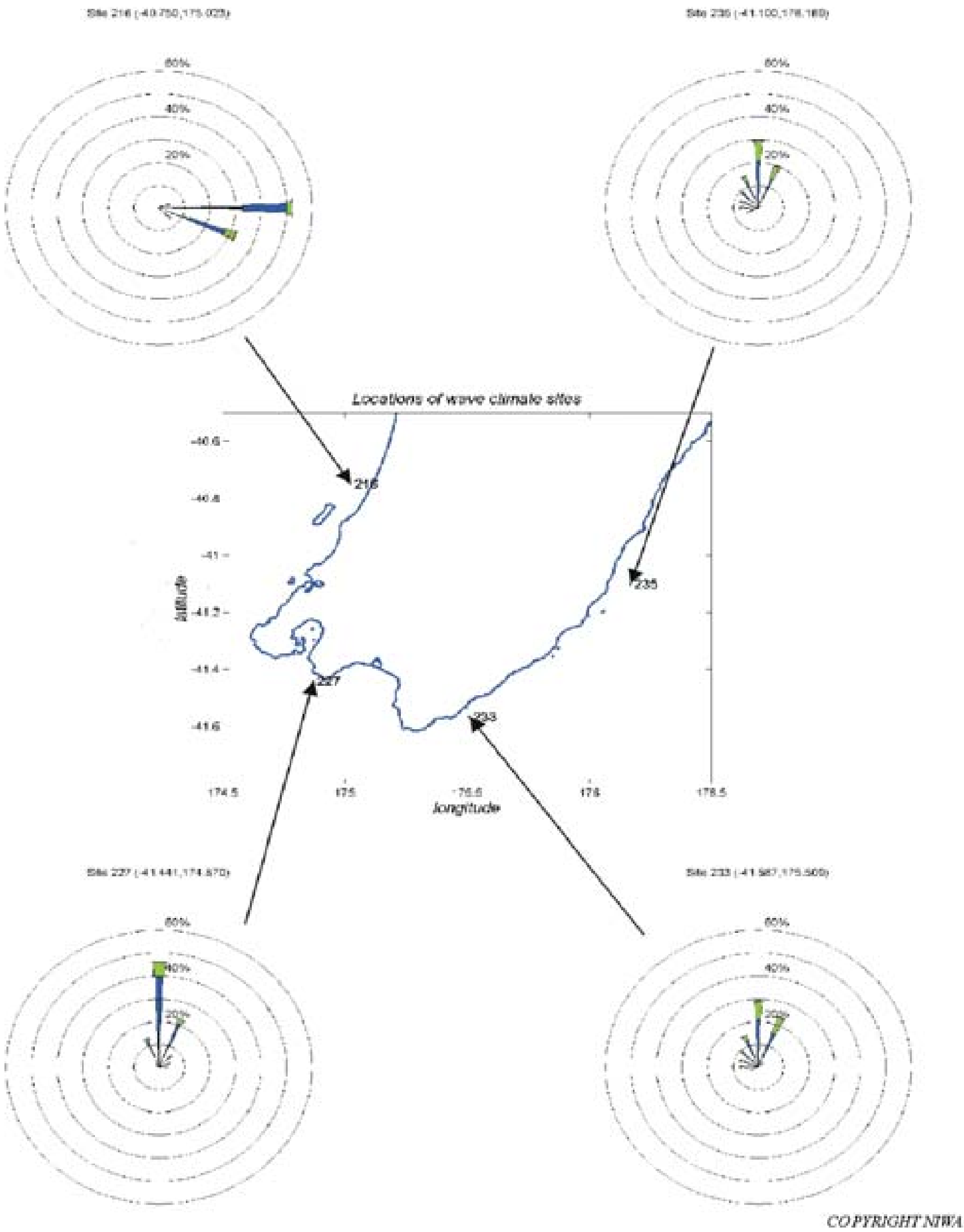

Figure 5.5: Directional frequency roses of the significant wave heights (H_s) around the Wellington region coast for a 20-year wave climate from 1979 to 1998 inclusive. Wave direction bars point in the direction waves move towards and are scaled in thickness in bands of 0–1 m, 1–2 m, 2–4 m, and >4 m. Results are based on the NIWAM wave model using wind model output from the European Centre for Medium-Range Weather Forecasts (Gorman and Laing, 2001).

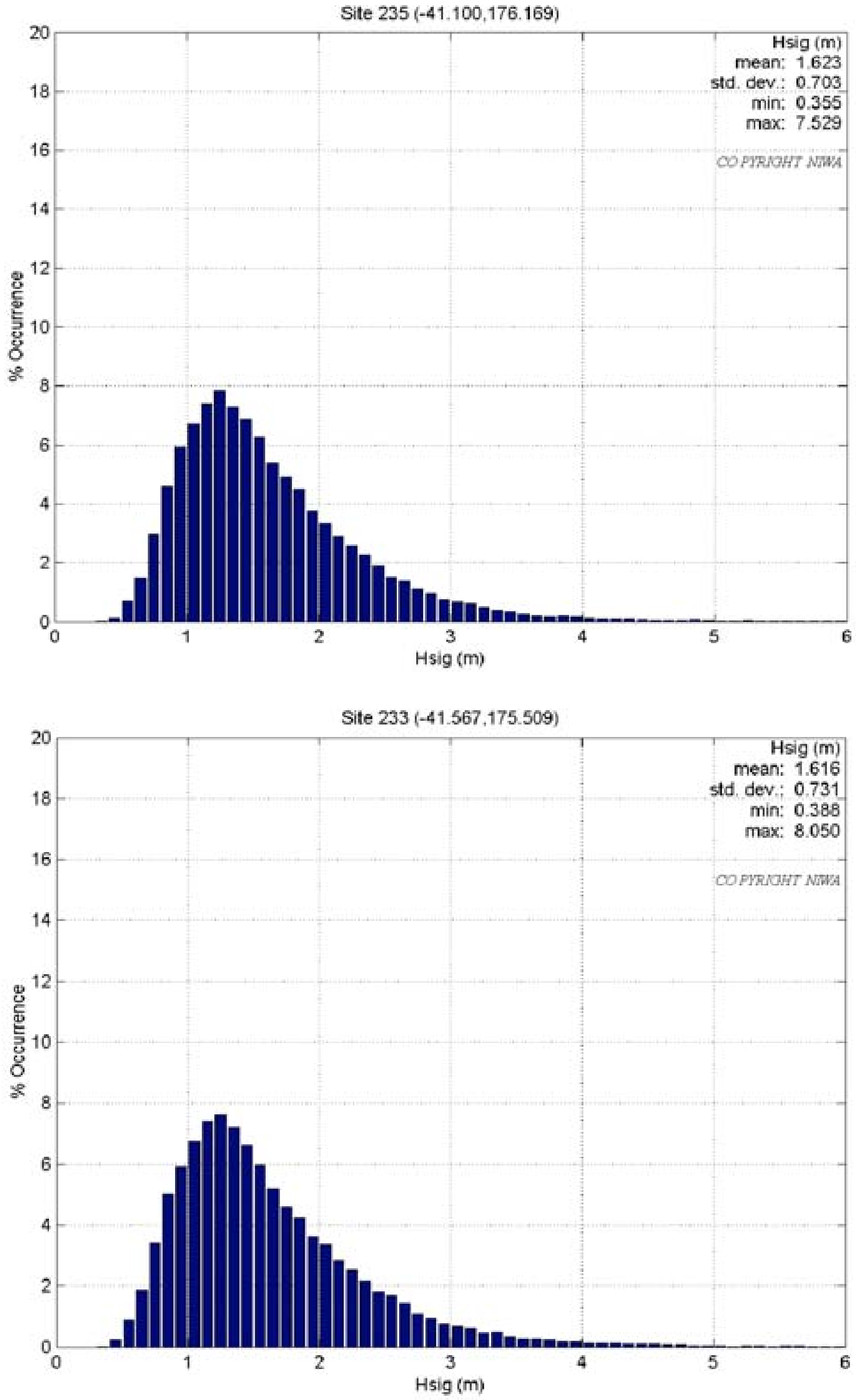

Figure 5.6: Distribution of significant wave height (H_s) for sites off Riversdale (top) and Te Kaukau Pt. (bottom). Based on a wave model hindcast for 1979–98 inclusive (Gorman & Laing, 2001).

For comparison with the Cook Strait site off Turakirae Head (Site 227) in Figure 5.5, the mean and maximum significant wave heights are greater off the Wairarapa coast as shown in Table 5.2. These values correspond to deepwater waves, interpolated and corrected where the wave fetch is limited, but not accounting for refraction of waves near the coast. The modelling procedure appears to smooth out the extreme waves, mainly because the wind modelling does not pick up the intense winds that can be generated around the complex New Zealand landmass, such as Cape Palliser. Nevertheless, the wave hindcast provides a consistent picture of relative wave climate around the Wellington region.

Table 5.2: Significant wave height statistics from the 20-year wave hindcast modelling comparing four sites around the Wellington region coast. Based on Gorman and Laing (2001). Copyright NIWA.

Location	Site No.	Mean H_s (m)	Max H_s* (m)
Otaki	216	1.1	6.3
Turakirae Head	227	1.2	6.4
Te Kaukau Pt	223	1.6	8.1
Riversdale	235	1.6	7.5

* This is an underestimate due to smoothing in model winds and waves for storm events.

5.2 Coastal Erosion

Coastal erosion hazards in the Wellington region have had a high public profile at various times, particularly when coastal dwellings have been threatened. One memorable event was the 11–13 September 1976 storm that caused rapid erosion at Raumati and Waikanae Beaches on Kapiti coast, threatening to undermine several dune-top dwellings (Figure 5.7). Other high-profile areas for erosion have been on the east coast at Castlepoint, Riversdale Beach and Te Kopi.

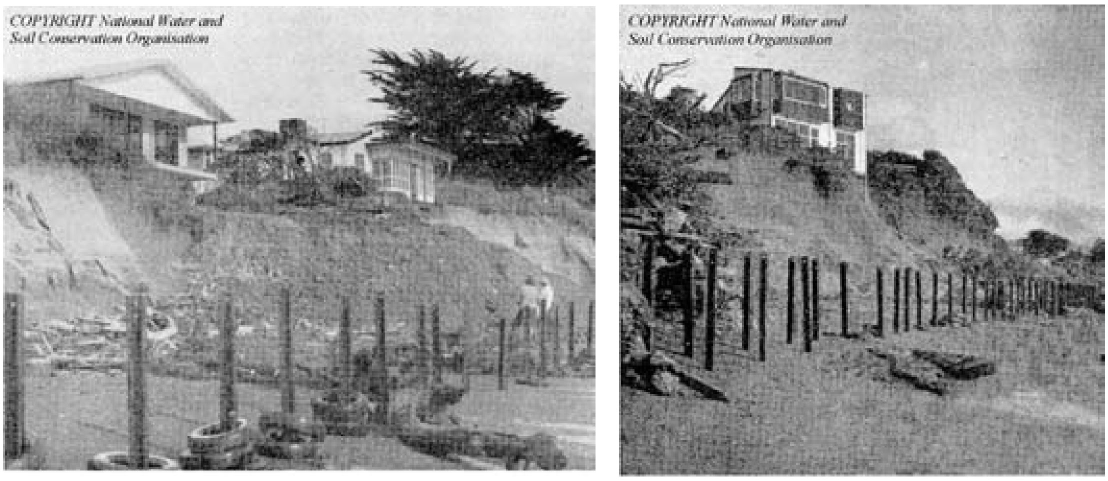

Figure 5.7: Images of coastal erosion at Raumati Beach after the 12–13 September 1976 storm surge. At this location, 15 m of foredune were removed during the 3-day event, almost reaching the houses. Note on the left image, the loose fill of clay and rotten-rock being pushed onto the beach by bulldozer on the day after the storm. (From Gibb 1977).

The term "coastal erosion" needs careful definition, as it is a matter of timescale. Natural coastal processes often produce periodic cycles of shoreline cut-back followed by a dune-building phase that builds the shoreline seawards. These cycles can operate at storm-event, seasonal, 2–5 year El Niño–Southern Oscillation and 20–30 year Interdecadal Pacific Oscillation timescales. "Coastal erosion" is often reserved for the long-term trend of a coastline to retreat over several decades, even though short-term fluctuations may see a shoreline build seawards for a period. However, coastal property owners are only too aware of shoreline cut-back during short time scales from storm events up to a few years, and refer to this as erosion.

Normally coastal erosion is not a major problem where there is no habitation, such as large stretches of the Wairarapa coast. But pressures to build and live close to the sea have lead to increasing "coastal squeeze", where the natural cut-back and dune building cycles become constrained. The risk of damage also rises as beachfront property values soar on the back of a strong demand.

Gibb (1978b) produced the most consistent regional and national comparison of coastal erosion and accretion rates around New Zealand's coastline. A summary diagram of open-coast rates of either erosion or accretion for the North Island from the data of Gibb (1978b) is shown in Figure 5.8. Three main areas vulnerable to coastal erosion identified by Gibb for the Wellington region were:

- Kapiti coast (south of the cuspate foreland at Paraparaumu);
- eastern Palliser Bay;
- the entire Wairarapa coast.

This type of regional and national synthesis of long-term rates of erosion and accretion desperately needs updating as two decades have past, and erosion patterns have changed somewhat. Nevertheless it still provides the most consistent picture of coastal erosion in the Wellington region over several decades.

The other known potential erosion hazards in sheltered waters are:

- Pauatahanui Inlet (Porirua Harbour) — rock seawalls are being placed by Transit NZ to protect SH 58 from coastal erosion caused by wave and tide action;
- Eastbourne coastal road — the shoreline is in another recession phase after building out over the last few decades from a pulse of sediment from the south;
- Perched pocket beaches within Wellington Harbour e.g., Oriental and Balaena bays, which gradually erode because of no natural sand supply, given the hardened adjacent catchments (Lewis *et al*., 1981; Carter and Gibb, 1985; Carter and Mitchell, 1985). Renourishment may be required from time to time to keep the sand stock maintained;
- Lake Ferry, near the mouth of Lake Onoke.

Historical storms that have caused damage to, or threatened, coastal dwellings were described in the previous section on coastal flooding (e.g., Gibb,1978a; Donnelley, 1959). In other cases, erosion has steadily undermined dwellings, particularly on the Wairarapa and Kapiti coasts e.g., a house fell into the sea at Te Kopi (South

Wairarapa) at the end of the 1996 winter, after being perched on the edge of a cliff for months. Another recent example is the retreat of the coastline at northern Paraparaumu Beach since 1995, in contrast to accretion in past decades (Figure 5.8) while the apex of the cuspate foreland a short distance away continues to accrete (J. Gibb, pers. comm.).

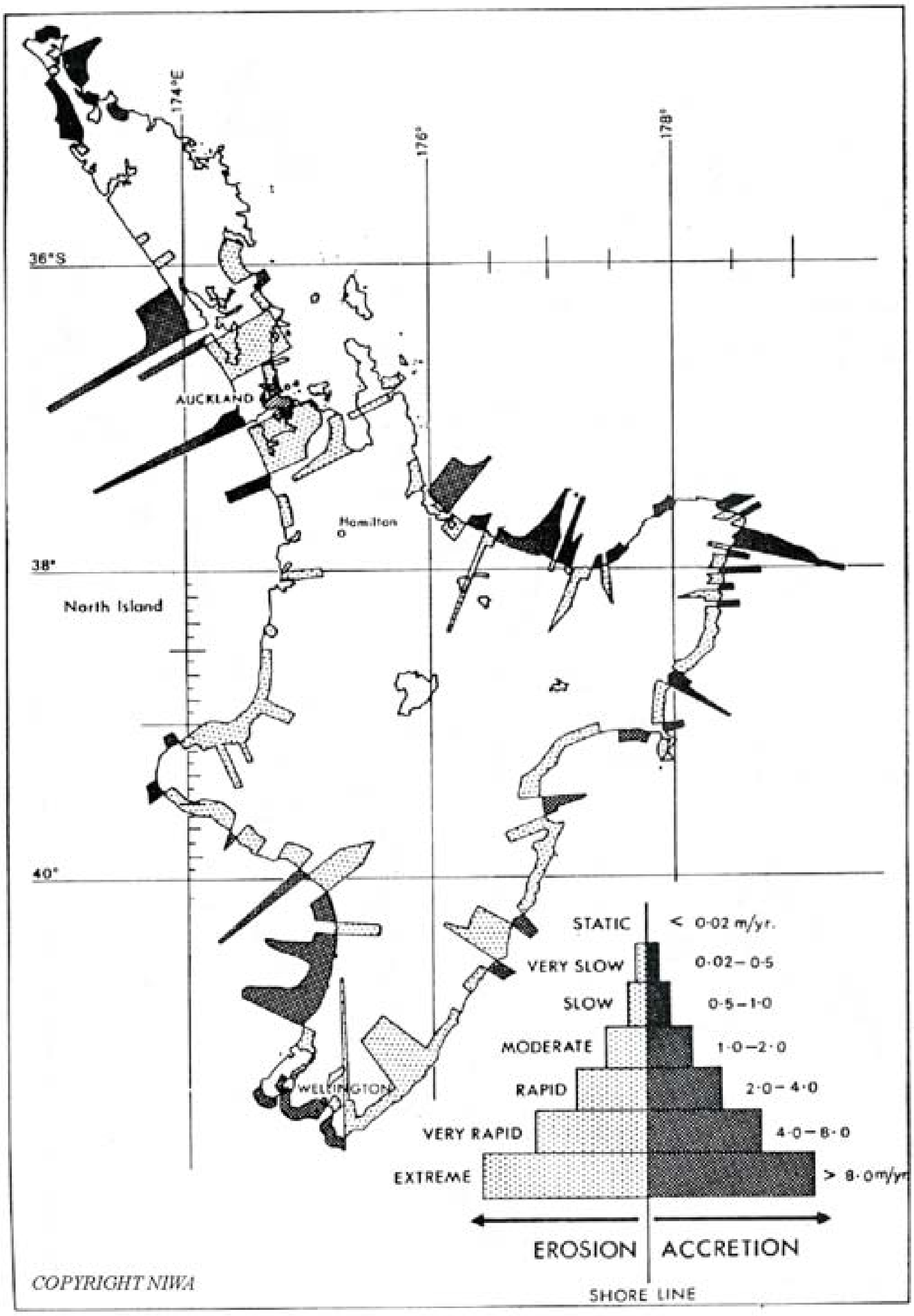

Figure 5.8: Historic long-term rates of open-coast erosion and accretion around the North Island coast based on data from Gibb (1978b).

5.2.1 Risk of Coastal Erosion

The risk of coastal erosion is difficult to predict without regular measurements of shoreline position and beach/dune volumes and monitoring data on the various "drivers" that cause erosion, such as waves, winds, storm surge, tides, and local sediment supply to the coast. Knowledge of offshore sediment supplies, availability and mobility are also crucial. In this respect, several studies have mapped and studied sediment processes along the south Wellington coastline e.g., Pickrill (1979), Matthews (1980a,b), and Carter and Lewis (1995).

Antecedent conditions or the "health" of both the beach and dune sediment deposit prior to any major storm event are also very important factors in determining the risk. In this regard, it is likely that beaches respond to interdecadal fluctuations like the 20–30 year IPO cycle, or to a lesser extent, the 2–5 year El Niño–Southern Oscillation cycle, which means the conventional "return-period" approach to the erosion risk may be inappropriate. Some decades may have a much higher risk of coastal retreat than other decades or years, where shoreline advance occurs.

5.3 Knowledge Gaps

Updated analysis of the Queens Wharf record is needed for storm tides and long-period cycles in sea level including sea-level rise to check comparison with Auckland. Vertical GPS measurements and regular survey control will enable relative sea-level rise to be determined.

Given the large changes in tidal range around the Wellington region, the level of Mean High Water Perigean-Springs and the Highest Astronomical Tide around the coastline need to be determined. This is a useful starting point for engineering/house design (including building floor levels) and an assessment of storm-tide heights.

Joint-probability methods for determining the risk of storm tides along vulnerable coastlines from tides, winds, atmospheric pressure and wave set-up need to be applied.

There are several sources of wave data or observations for the Cook Strait area, but no single document that presents a consistent risk analysis of wave conditions. Much of the data or information is buried in various reports, which should be collated and updated with data from the present buoy off Baring Head.

Consistent in-depth risk assessment is needed for both coastal erosion and coastal flooding hazard hotspots across the region, linked in with more detailed topography of low-lying areas (the LINZ 1:50,000 database only has contours at either 10 m or 20 m above WVD-53, which is too coarse for defining the extent of hazard prone areas for varying probabilities of occurrence).

Evacuation street maps (derived from inundation maps) for populated coastal areas or roads that have a pre-defined level of risk associated with coastal flooding from storms or tsunami, or from coastal erosion need to be prepared.

Wave and wind modelling of Wellington Harbour to determine the effect of wind set-up and wave set-up/run-up at vulnerable areas is needed.

Basic knowledge of coastal sediment processes and sand budgets off Kapiti Coast and Wairarapa beaches is needed.

5.4 Vulnerable Areas

- Coastal erosion
  Waikanae Beach, north Paraparaumu Beach, Raumati to Paekakariki, Eastbourne (Wellington Harbour), perched pocket beaches within Wellington Harbour (e.g., Oriental and Balaena Bays), Lake Ferry (Lake Onoke), and the entire Wairarapa coastline (including Riversdale Beach and Castlepoint).

- Coastal flooding
  Known areas at potential risk of coastal flooding are SH1 between Paekakariki and Pukerua Bay; Plimmerton; Porirua Harbour margins, Populated bays along the south coast of Wellington city (Owhiro Bay, Island Bay, Lyall Bay, Breaker Bay); Wellngton Harbour margins, especially the CBD area around Te Papa and Lambton Quay, the Hutt-Eastbourne roads, Petone and near the Hutt River mouth; Lake Ferry (Lake Onoke) and Castlepoint.

5.5 Amelioration Methods

Continued rigid adherence to planning mechanisms under the NZ Coastal Policy Statement, the Regional Coastal Plan, and District Plans to ensure sufficient coastal buffers to absorb most of the consequences of coastal erosion and coastal flooding is required. A prime example of what can be done in relatively "undeveloped" erosion-prone areas is Queen Elizabeth Park, south of Raumati (Boffa Miskell, 2001).

Combating coastal erosion in developed areas that threaten to undermine dwellings is a major issue, which has no easy answers. For example, seawalls have been tried at Raumati with limited success, but their long-term viability will be threatened by extreme storms and future sea-level rise. Long-term managed retreat of dwellings is another option, but will encounter concerted opposition, along with the debate about compensation. The "do-nothing" approach is a further option, but it still requires a deliberate decision by the community and coastal managers, centred on liability issues. Finally, beach renourishment is a "soft engineering" option to stabilising the shoreline (e.g., Coddington, 1972), but is expensive to sustain in the long term, other than for small perched beaches with a high amenity value such as Oriental Bay.

For areas vulnerable to coastal flooding, a simple storm-surge/wave warning system could be set up based around wave and sea-level monitoring systems, which along with evacuation street maps based on extreme storm tide and wave run-up, would provide a faster response to an event and ease the risk of damage and injury.

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6. Severe Winds

6.1 Weather situations causing high winds

Winds in the Wellington region are influenced by several meteorological factors. The western part of the region is subject to frequent high winds associated with Cook Strait. Northerly winds occur for more than half the time and high winds from this direction are common, particularly in the spring and summer. Although the surface direction is typically from the north, above the ground the flow is from the northwest. An example of a synoptic situation associated with a high wind occurrence is in Figure 6.1. On this day there was a peak gust at Wellington Airport of 126 km/hr. A key feature is the front to the west, this has the effect of producing windy, wet conditions. Northerly winds typically affect the Wellington coast and hill suburbs. The Wairarapa coast and the zone from the south coast along the foot of the Rimutaka range are also often affected.

Southerly winds flow onto the Wellington region parallel to the main ridge systems so that the high winds are felt more generally. An example of a particularly severe event, the Wahine storm, is described elsewhere in this report. More commonly, southerlies occur with less intense storms. Gusts are usually not as high as in northerly winds but mean wind speeds are higher. An example of a southerly situation is in Figure 6.2. A strong cold airstream affected the region. The maximum gust at Wellington Airport was 112 km/hr on the 2 May 1982.

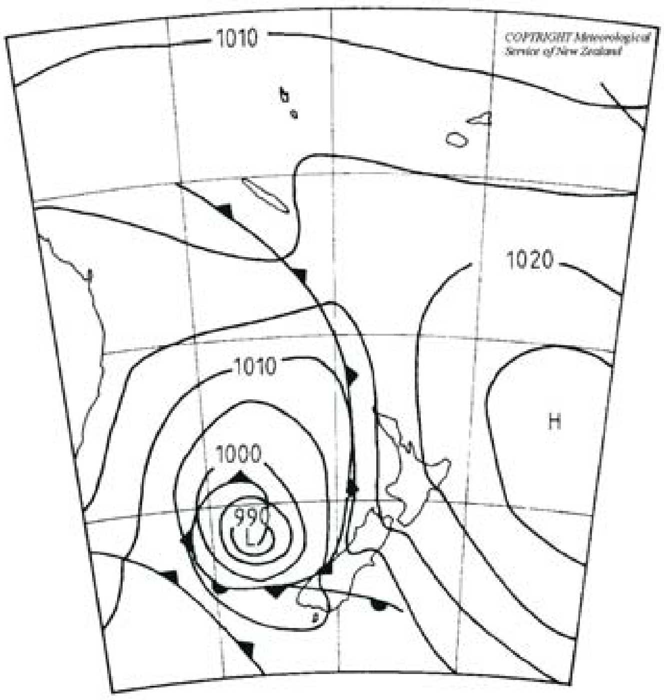

Figure 6.1: The synoptic situation at 0000 hours NZST on 8 October 1983 causing strong northerlies in Wellington.

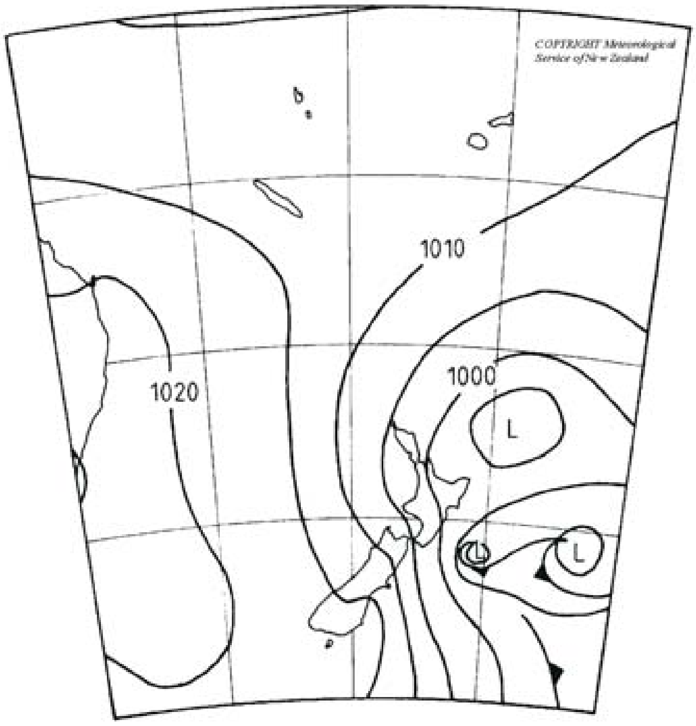

Figure 6.2: The synoptic situation at 0000 hours NZST on 2 May 1982 causing strong southerlies in Wellington.

The Tararua Range, separating the Wairarapa from the Manawatu, is a high wind region. Winds affecting any part of the Wellington region are usually augmented about the Tararua ridges to some degree and very high speeds are likely. In north or northwesterly airstreams, the mountains have a role in generating waves that can produce very high winds at the ground to the east of the ranges (Porteous *et al*., 1999). These are sometimes called downslope winds. This is thought to be the mechanism causing the high winds occurring in the Wairarapa.

6.2 Maps of extreme winds

Maps of extreme winds in the Wairarapa have been previously produced (Porteous *et al*., 1999). These were intended to be indicative of extreme wind speeds. In the present report, the data in the maps have been extended to cover the rest of the regional council area using wind observations in the Wellington and Manawatu areas. Variations over the region are again indicative because the effects of the hills and valleys on the flow are not completely understood. There has been no consideration of the possible effects of climate change on the extreme winds.

In the ten-year period, 1990 – 2000, gust speeds exceeded 144 km/hr four times at Wellington Airport. In the same period, they exceeded 126 km/hr four times at Paraparaumu Airport and were above 169 km/hr three times at Castlepoint. The data are only comparable when they are adjusted to the same height above ground and the effects of hills are removed from the data. When these adjustments are done, the gusts speeds at a 142-year return period are 176 km/hr at Wellington Airport, 166 km/hr at Paraparaumu Airport and 198 km/hr at Castlepoint. The extrapolation to high return periods is subject to large errors and is best carried out using groupings of stations on the basis that combined station data represents an ensemble of approximations to the same distribution. Speeds at a 472-year return period are taken to be about 10% higher than speeds at a 142-year return period.

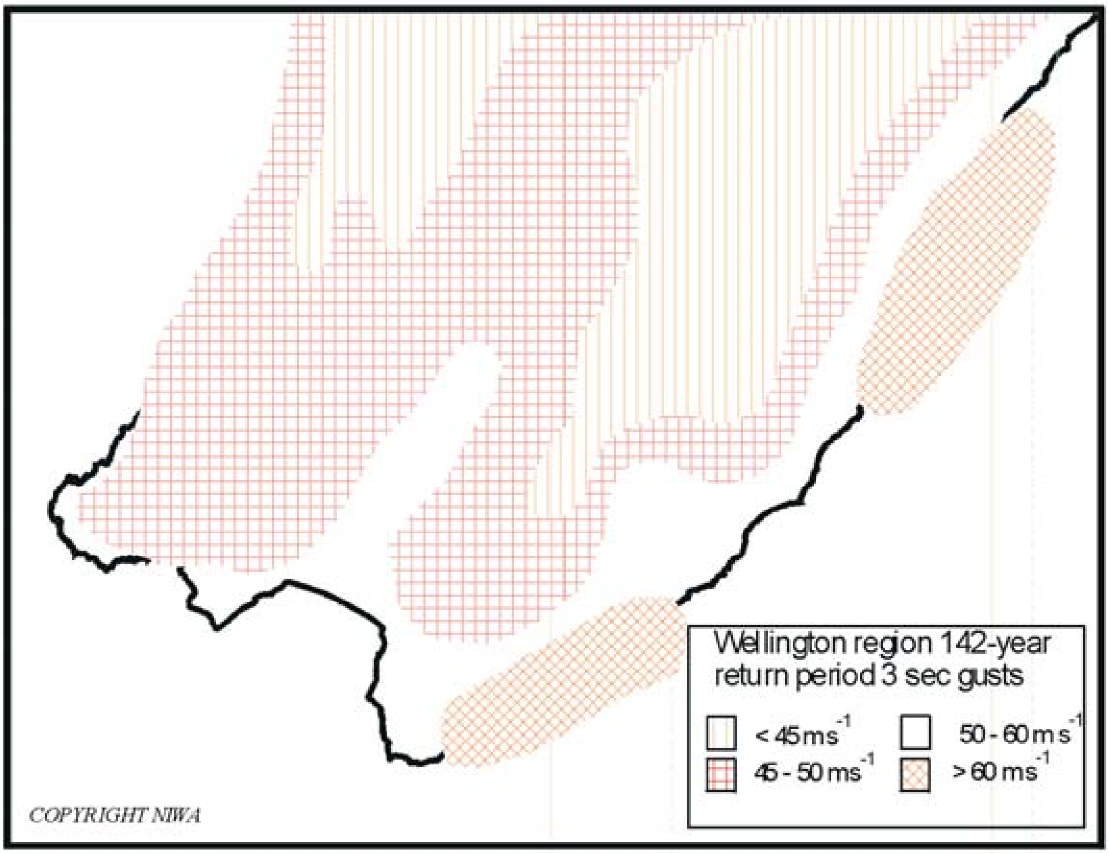

Figure 6.3: Contours of maximum 3-second gust speed (ms^{-1}) expected to be equaled or exceeded at average intervals of 142 years (multiply by 3.6 to convert to km/hr). The data is for 10 m above the ground but for hill and mountain sites, changes of land height produce large variations on a scale that is too small to be represented. The speed-up and elevation effects need to be allowed for separately (see text).

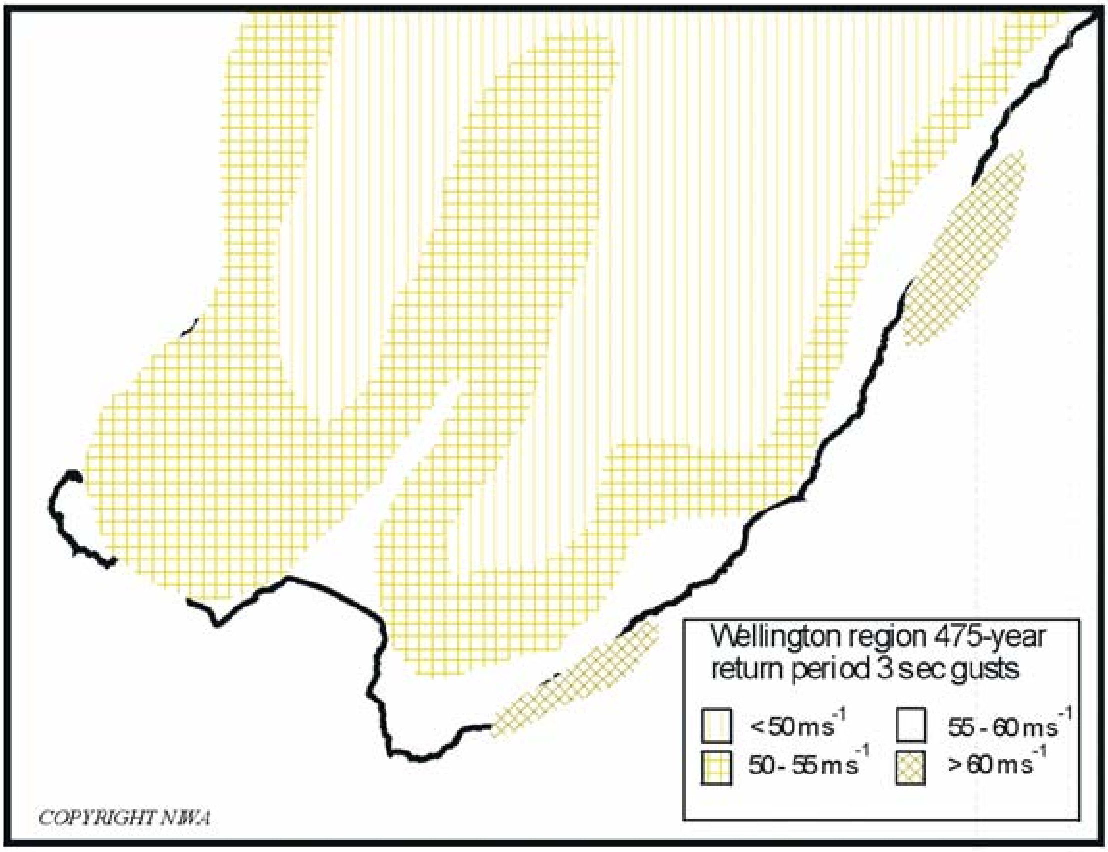

Figure 6.4: Contours of maximum 3-second gust speed (ms^{-1}) expected to be equaled or exceeded at average intervals of 475 years(multiply by 3.6 to convert to km/hr). The data is for 10 m above the ground but at hill and mountain sites, changes of land height produce large variations on a scale that is too small to be represented. The speed-up and elevation effects need to be allowed for separately (see text).

Maps of 3-second gust speed (ms^{-1}) expected to be equaled or exceeded at average intervals of 475 years and 142 years are shown in Figures 6.3 and 6.4. The data is for 10 m above the ground and to get data for hill and mountain sites, speed-up and elevation effects need to be allowed for separately. The speed-up effects are summarized in Table 6.1 and the effects of land elevation can be estimated by multiplying the low-land gust speed by the factor F given by the equation,

$F = 1 + 0.00015\ E$,

where E is the site elevation in metres.

Table 6.1: Factors to be applied to flat-land gust speeds to obtain gust speeds on hilltops. Copyright NIWA.

Upwind slope gradient	Escarpments	Hills and ridges
0.05	1.04	1.09
0.10	1.08	1.18
0.20	1.16	1.36
0.30 and greater	1.24	1.54

6.3 Extreme Winds Knowledge Gaps

The major knowledge gaps for extreme winds occur because the conditions are rare, and there is limited experience on how the relative distributions of severe speeds may differ from more normal winds. Experiences during the Wahine storm suggest that strong winds occurred in some places that are not normally much affected by southerlies. Questions arise about the effects of northerlies that exceed all previous recorded speeds by a large amount in Wellington city. Knowledge of the spatial variation of extreme wind speeds due to terrain are very important and is an area where progress is possible due to improved numerical models.

Expectations on the recurrence of extreme winds need to be based on very long periods of reliable records; in the absence of such records large scale computer models are needed to simulate the type of weather systems that may occur in rare scenarios. Changes of wind-measuring instrumentation and siting in recent years have produced measurable changes in wind data and have almost certainly affected the data on extremes. Knowledge of instrumentation characteristics is important and recording of instrument characteristics and siting could be improved. Changes of extreme wind associated with natural and human induced climatic variations are also important but are difficult to determine with much certainty.

6.4 High Risk Areas

The areas subject to high winds have a higher risk of damage. They are generally sparsely populated and provided any structures that are constructed are properly engineered, costs of wind damage should not be proportionately any higher than elsewhere in the region.

6.5 Amelioration Methods

Wind damage can be ameliorated, as noted above, by design of structures for their particular locations. Much progress has been made in recent years by recognising that design is not just a question of geographical location but that design against winds requires micro-zoning so that crests of ridges lying across the winds and local areas with channelling are identified. Further research is needed so that balance between risks in zones with different wind intensification factors is not lost. The identification of hazards due to trees is potentially important and mitigation and interception of flying debris in extreme-wind situations needs consideration.

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7. Snow and Frost

Snowfall (a period when snow is reported as falling, even if it melts upon reaching the ground) is a relatively uncommon event at sea level in the Wellington region, although falls are reported most years. Snow lying on the ground, i.e. snow which does not melt immediately, is a much rarer event. At the Kelburn meteorological station, snow is reported as lying on the ground on average once in every five years. In the hill country and mountains, snowfalls and snow lying on the ground are more common, typically occurring during winter and early spring. Frosts are more common than snowfalls in the Wellington region, particularly in non-coastal areas like the Hutt Valley. As hazards, snow and frost have a significant impact on transport systems, particularly roads, with slippery roads often causing major traffic problems.

7.1 Map of Mean Annual Snowdays

Snowfall observations have been recorded at only a few sites in the region, and for the most part these sites are located in the plains or lower hill country where snowfalls are relatively rare. Hence it is difficult to make a comprehensive assessment of the risk of snowfalls in all parts of the Wellington region.

A simple but quite useful method of obtaining estimates of the number of snowfalls per year, at least at various heights above sea level, is to calculate the relationship between snowfall observations and the altitude of the observing station. This relationship may then be interpolated to give approximate snowfall risk for a range of land height intervals. The method has been adopted in a study of meteorological hazards impacting the Timaru District (Tait *et al*., 2001) and an assessment of snowfall probability in the Gisborne–Tuai area (Tait and Bromley, 2002). We have adopted this method here, and the result is displayed in Figure 7.1.

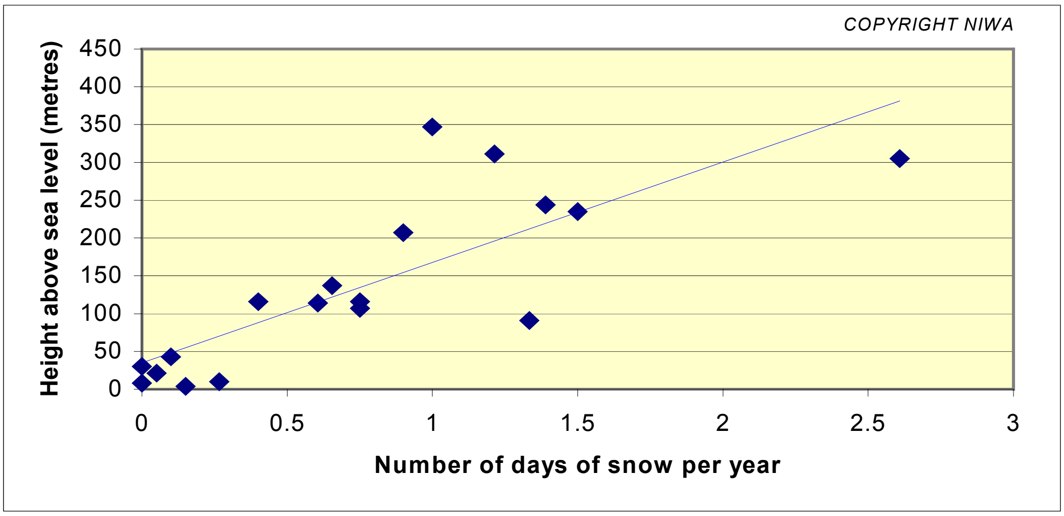

Figure 7.1: Average number of days of snowfall per year reported at meteorological observing sites in the Wellington region versus height above sea level. Note, this figure refers to observations of snow *falling*, not snow lying on the ground.

The data suggest that below about 200 metres, snowfalls occur about once in 2–5 years. At about 200 metres above mean sea level and above, on average at least one fall of snow is likely each year. An extrapolation of these data, and data from Hawke's Bay which is not included here, suggest that at around 600 metres there are an average of 5 snowfalls a year. Above 800 metres, an average of about 22 days of snowfall have been reported at Makahu Saddle and Ngamatea, in the ranges to the north of Wairarapa.

The average number of snowfalls per year, based on the relationship between altitude and snowfall reports, is shown in Figure 7.2.

7.2 Knowledge Gaps

While snowdays are a standard meteorological variable, snow depth is not measured at New Zealand climate stations. Hence, there is no way of knowing from the records whether 1 cm or 20 cm of snow fell on a particular snowday. This has obvious implications for hazards analyses, as snow becomes more hazardous (affecting transportation, communications, damaging power lines and roofs due to snow loading) the more of it that falls and settles on the ground.

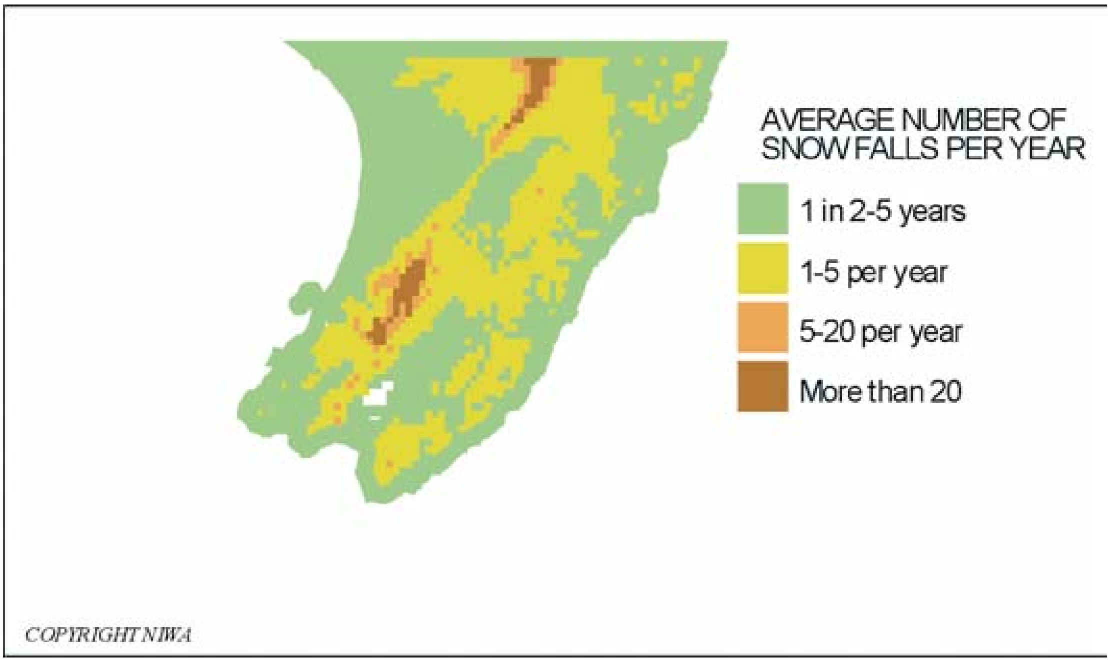

Figure 7.2: Average number of snowfalls per year in the lower North Island, based on the relationship between snowfall reports and height above sea level in the Wairarapa and southern Hawke's Bay. Reported snow observations suggest: 0-200 m snow falls are rare (one in 2-5 years); 200-600 m, 1-5 falls per year; 500-800 m, 5-20 falls; above 800 m, more than 20 snow falls per year.

Table 7.1: Minimum air temperature on July 4, 2001 and the long-term mean number of ground and screen frosts at climate stations throughout the lower North Island. Copyright NIWA.

Station Name	Latitude (°S)	Longitude (°E)	Minimum Air Temperature (°C)	Mean number of ground & screen frosts per year	
Pahiatua	-40.450	175.817	-2.7	*	34
Masterton Intermediate School	-40.958	175.670	-4.0	*	25
Masterton, Te Ore Ore	-40.957	175.707	-3.5	88	41
Kopua	-40.083	176.283	-3.3	55	17
Dannevirke	-40.217	176.117	-4.5	56	20
Waione EWS	-40.453	176.308	-3.9	*	13
Castlepoint Station	-40.898	176.220	+2.0	2	0
Castlepoint AWS	-40.905	176.212	+2.6	*	0
East Taratahi AWS	-41.017	175.617	-5.0	*	38
Martinborough EWS	-41.253	175.389	-3.0	64	18
Palliser,Ngawihi AWS	-41.583	175.233	+2.5	*	*
Paraparaumu Aero	-40.900	174.983	-2.1	46	10
Paraparaumu Aero AWS	-40.900	174.983	-1.6	*	10
Palmerston North AWS	-40.317	175.600	-5.1	*	18
Palmerston North EWS	-40.383	175.617	-3.6	51	13
Levin AWS	-40.622	175.257	-3.7	*	11
Mana Island	-41.083	174.783	+2.2	20	*
Wellington, Kelburn	-41.283	174.767	+1.8	14	0
Wellington Aero	-41.333	174.817	+1.4	17	1
Wallaceville	-41.135	175.052	-5.7	67	30
Wallaceville EWS	-41.135	175.052	-5.4	*	*

* No data available

7.3 Example of a Severe Frost

On July 4^{th}, 2001 a minimum air temperature of –5.7 °C was observed at Wallaceville, Upper Hutt. This was the second coldest minimum air temperature at the site since records began in 1924 (the coldest was –5.9 °C on June 28^{th}, 1975). Hence, the July 4^{th} frost was a 1-in-40 year event. Table 7.1 lists the minimum air temperature on the same night at other lower North Island locations. It can be seen that while places like the Hutt Valley, Palmerston North, Levin and east of the Tararuas received very cold temperatures, Wellington, Mana Island and Castle Point did not fall below freezing. Table 7.1 also lists the mean number of days of ground and screen frosts at each station where frost occurrence data are recorded.

7.4 High Risk Areas

From Table 7.1 it can be seen that the high frost risk lowland areas are the Hutt Valley, particularly Upper Hutt, east of the Tararuas along State Highway 1 between Paraparaumu and Palmerston North, and west of the Tararuas between Masterton and Dannevirke. All high elevation areas such as the Rimutaka and Tararua Ranges are also high frost risk areas. Section 12.2.6 of this report discusses potential changes in the number of days of frost given certain climate change scenarios. With respect to snowfall, the highest risk areas are the areas above 500 m in elevation, as shown in Figure 7.2.

7.5 Amelioration Methods

Extreme cold temperatures, such as those experienced in the first 10 days of July 2001, can cause serious health problems. Several international studies have shown that mortality during cold spells is significantly higher than during normal weather conditions (Kunst *et al*., 1993; Alberdi *et al*., 1998; Eng and Mercer, 1998; Huynen *et al*., 2001). Damage to vegetation from frosts can be severe, as was seen in Upper Hutt after the July 2001 frosts when many of the native Punga trees were badly frost-burned. Also, driving on frosty and/or snow-covered roads is extremely dangerous.

The Meteorological Service of New Zealand issues frost and snowfall warnings, which are very useful. To reduce the hazardous impacts of frost and snowfall, residents should be advised to stay indoors, monitor those at high risk (particularly the elderly), cover sensitive plants and drive with extreme caution. Also, the application of salt and/or grit to roads speeds up the melting process and hence reduces the potential for accidents.

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8. Excessive Temperature

The climate of the Wellington region is relatively mild and excessive temperatures are generally rare and short-lived compared with continental locations. Nevertheless, extreme temperatures can still pose a hazard in the region, as the health of residents, particularly the elderly, can be detrimentally affected by significantly above average temperatures.

8.1 Mean Annual Extreme Maximum Temperature

Figure 8.1 is a map of the mean annual extreme maximum temperature at 5 km resolution derived from the data presented in the sixth column in Table 8.1, which shows the mean annual extreme maximum temperatures at several locations throughout the Wellington region (these are temperatures measured 1.3 m above the ground in a standard meteorological screen). It can be seen from Figure 8.1 that the mean annual extreme maximum temperatures are typically around 31–32 °C on the Wairarapa Plains in the vicinity of Masterston and Greytown. The east coast typically receives extreme temperatures up to around 30 °C, while west of the Rimutakas and Tararuas maximum temperatures rarely exceed 27 °C.

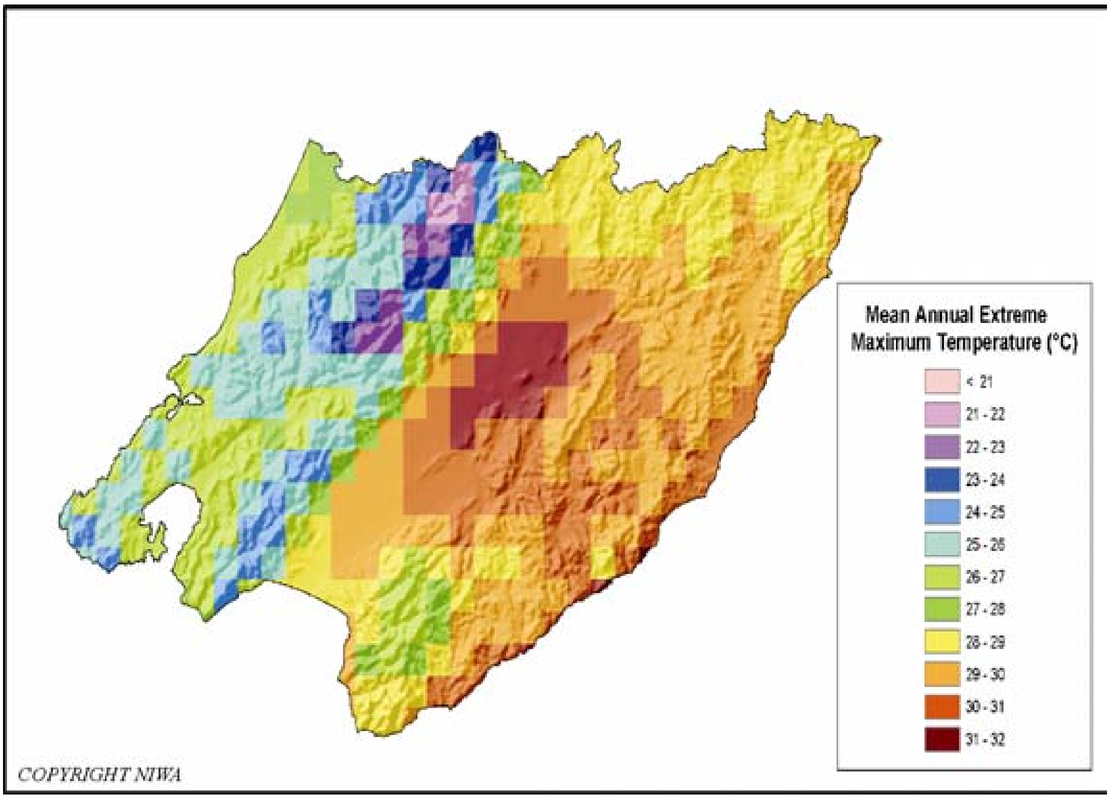

Figure 8.1: Map of mean annual extreme maximum temperature for the Wellington region.

Table 8.1: Mean annual extreme maximum temperature (°C), extreme maximum temperature ever recorded (°C), and the mean annual extreme maximum minus mean summer temperature (°C) at several locations. Copyright NIWA.

Location	Latitude (°S)	Longitude (°E)	Height (m)	Length of Record (Years)	Mean Annual Extreme Maximum Temperature (°C)	Maximum Temperature ever recorded (°C)	Difference from Mean Summer Temperature (°C)
Pahiatua	-40.450	175.817	116	51	28.6	29.6	12.1
Masterson	-40.867	175.767	171	33	29.2	32.6	12.4
Waingawa	-40.983	175.617	114	74	31.5	35.1	14.6
Kopua	-40.083	176.283	311	34	28.8	32.3	12.5
Dannevirke	-40.217	176.117	207	45	28.9	33.1	12.2
Castlepoint Lighthouse	-40.900	176.217	4	12	28.7	31.0	11.0
East Taratahi	-41.017	175.617	91	5	31.3	33.8	14.4
Ngaumu Forest	-41.033	175.883	244	31	30.0	34.4	14.0
Waiorongomai	-41.267	175.150	21	22	28.8	32.6	12.1
Martinborough	-41.200	175.467	30	12	31.2	34.2	13.5
Cape Palliser	-41.617	175.300	10	11	30.2	31.5	12.1
Kapiti Island	-40.850	174.933	16	43	25.9	30.3	9.0
Paraparaumu Aero	-40.900	174.983	5	49	26.4	29.4	9.5
Marton	-40.083	175.417	141	17	27.5	30.1	11.3
Bulls	-40.233	175.267	9	31	28.1	30.4	11.2
Ohakea Aero	-40.200	175.383	48	50	28.4	31.1	11.1
Palmerston North	-40.383	175.617	34	77	28.5	33.0	11.4
Levin	-40.650	175.267	46	60	27.5	28.4	11.0
Porirua	-41.150	174.850	94	7	27.0	29.0	10.6
Titahi Bay	-41.117	174.833	31	5	26.7	29.6	9.5
Lower Hutt, Taita	-41.183	174.967	65	24	27.3	31.4	10.8
Wellington, Kelburn	-41.283	174.767	125	132	26.5	31.1	10.3
Wainuiomata	-41.283	174.950	82	21	27.1	30.1	10.9
Wellington Aero	-41.333	174.817	43	35	26.9	30.6	9.6
Kaitoke	-41.083	175.183	223	23	27.3	30.4	12.0
Wallaceville	-41.135	175.052	56	55	27.7	31.0	11.4

The second-to-last column in Table 8.1 shows the highest temperature ever recorded at these locations. This shows that it is possible, although very rare, to get temperatures as high as 35.1 °C on the Wairarapa Plains, as high as 31.5 °C on the east coast, and as high as 33.0 °C west of the mountains.

8.2 High Risk Areas

From Figure 8.1, it can be seen that the area of highest risk of extremely high air temperatures is the Wairarapa Plains. However, the health dangers associated with extremely high temperatures (e.g., heat stroke) are not limited to the highest temperature regions, rather it is the relative difference between average and extreme temperatures which is important. Rooney *et al.* (1998) show that mortality in England and Wales rose dramatically by an estimated 619 deaths during a two-month heatwave in 1995 when Central England temperatures did not exceed 25 °C, yet were on average 3 °C warmer over the whole summer compared with the previous year.

The last column in Table 8.1 shows the difference between the mean annual extreme maximum temperature and the mean summer (December–February) temperature. These data are included to provide a relative extreme temperature index (i.e. extreme temperature relative to normal). Figure 8.2 is a map derived from these values.

Figure 8.2 shows that the highest health risk area, with respect to extreme heat, is eastern Wairarapa in the hills around Gladstone extending northwest to include Masterton.

As mentioned in the drought section (section 3), excessive temperatures can also cause buckling of railroad tracks. This is most likely to be a problem in the Wairarapa, where the mean annual extreme maximum temperatures are above 30 °C. Section 12.2.6 of this report discusses the possible impacts of climate change on excessive temperatures for the Wellington region.

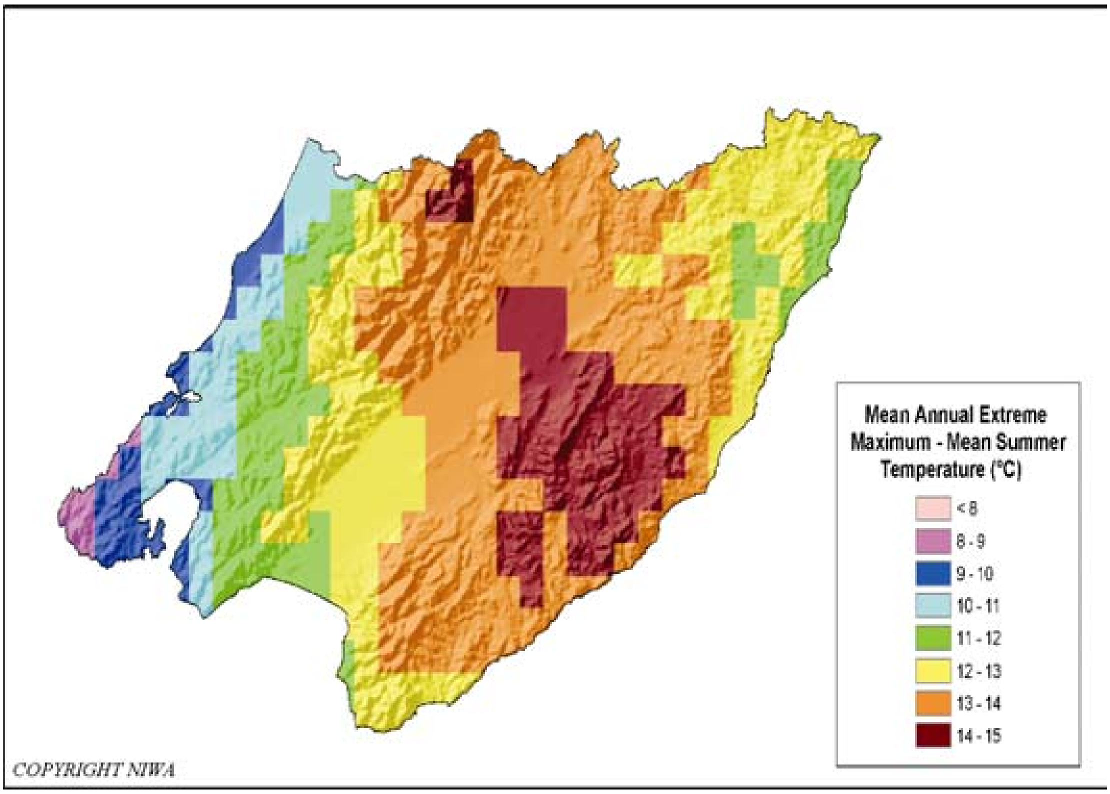

Figure 8.2: Map of mean annual extreme maximum minus mean summer temperature for the Wellington region.

8.3 Amelioration Methods

New Zealanders have a tendency to bask in the heat and may not understand the dangers of excessively hot temperatures. As was shown in the England heatwave study, health problems are significantly correlated with sustained above normal temperatures, even if the actual daily temperatures are only in the 20–30 °C range. An awareness campaign, particularly directed at residents in the Wairarapa, may alleviate many unnecessary health risks.

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9. Lightning and Hail

Lightning and hail are weather elements associated with severe convective storms. They cause damage directly as well as being associated with the other damage caused by such storms through for example severe wind and rain. This direct damage can include, for lightning, the destruction of electrical and electronic installations providing power and communications, and for hail the destruction of crops and damage to infrastructure.

The rate of energy release involved in a severe convective storms associated with lightning and hail is enormous and can exceed 1400 GW, some fifty times the energy production in NZ at any time from all sources (oil, hydro, gas). It is perhaps not surprising that these storms have impressive outcomes, such as hailstones (measured in studies of overseas hailstorms) over 10 cm diameter and with a fall speed of over 170 kmh^{-1}.

Hail forms when some of the microscopic water droplets forming a cloud freeze (because the temperature high in a cloud can be well below 0 ºC) and then collect some of the other, liquid, droplets that then also freeze around the first. This heavier particle starts to fall, sweeping out yet more droplets and growing rapidly. If there is upward airflow in the cloud (an updraft) this embryo-hailstone may stay suspended as it grows while the cloud flows up around and into it. In a severe storm the hail grows large enough to cause damage when it falls. Figure 9.1 gives a cross-sectional view through a typical severe storm producing damaging hail.

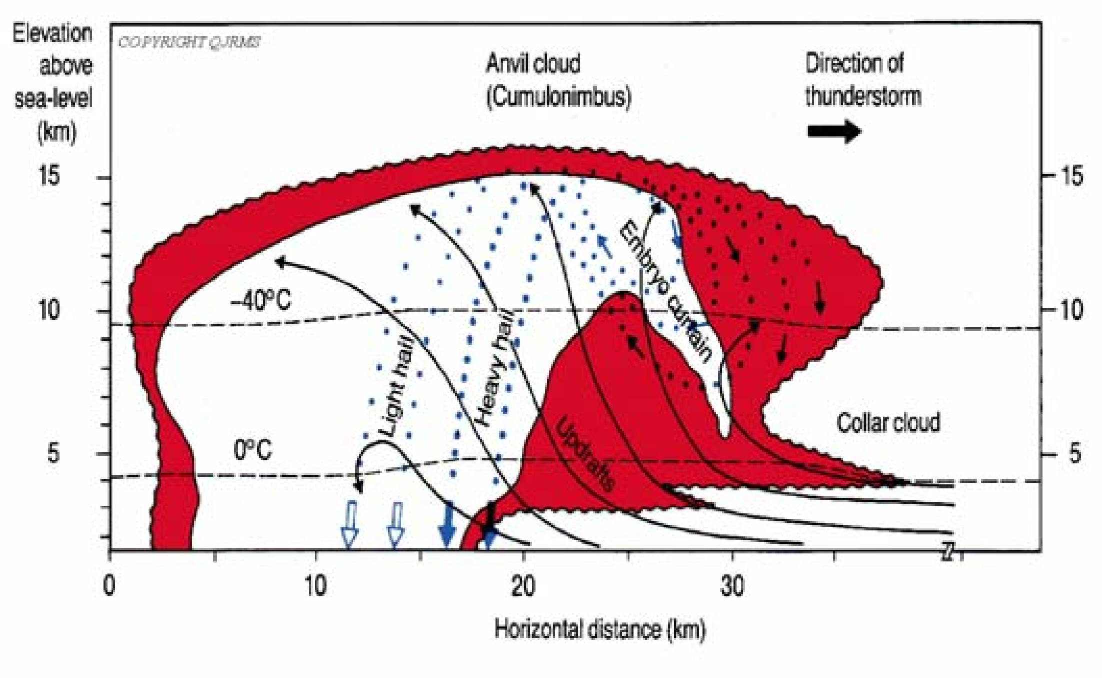

Figure 9.1: A cross-sectional view through a typical severe storm producing damaging hail (after Browning and Foote, 1976).

In such storms air from near the ground is swept up in the updraft at high speed into the core of the storm and may rise to 30,000ft (10,000m) or more. The clouds are identified by this deep vertical extent, a limited horizontal extent and, as the storm matures, the development of an 'anvil' spreading out horizontally from the top of the cloud. Growing hail may be swept up in the updraft, tossed out of it, fall into it again, several times as it grows, before finally falling as large hail to the surface.

The same storms also generate lightning. Electrical charges are separated, in ways that are not yet understood, apparently during the collisions between growing hailstones and smaller ice crystals. The conditions for lightning generation are apparently that in the cloud there should be growing hail, many cloud droplets, and vigorous updrafts and these conditions characterise severe convective storms.

In less severe storms such as small showers or widespread frontal rain, the updrafts are less vigorous, lightning is not produced and hail cannot be supported once it has grown beyond a limited size. In fact most of Wellington's rain and hail originates in this way, as hail high in the cloud, but the hail melts as it falls and is usually fully melted before it reaches the ground. In cold outbreaks the sub-cloud air may not be warm enough for this melting to occur, but the hail, though not melted, is still too small to cause much damage.

9.1 Mean Annual Number of Lightning Strikes

The risk of lightning flashes to the ground is usually expressed in terms of the 'ground flash density', or N_g, the number of such ground flashes per km^2 per year as estimated from historical records. In preparing this report this parameter has been estimated from observer reports from manned stations and from electronic Lightning Flash Counters (LFC) at automatic weather stations. There are large discrepancies between the data sets that we have not been able to resolve in this scoping study. A map of ground flash density for the Wellington region derived from the historical observer data is shown in Figure 9.2.

The data in Figure 9.2 are derived from station observer records of the number of days of each year on which thunder was heard (T_d). The Ground Flash Density (N_g) has been estimated from these records using the techniques described by Mackerras (1984), by Anderson (1984) and by Schneider (1999). All give similar results; Figure 9.2 shows those obtained using a modified version of the simple Schneider technique we have used elsewhere in New Zealand,

$$N_g = T_d / 13$$

Values of N_g derived from the LFCs on the other hand are quite different. The LFCs detect the radio signals originating from the lightning and N_g is derived after making assumptions about the range of detection of the instruments. The values of N_g obtained from the three stations in the Wellington region differ from those shown in Figure 9.2 by factors as large as 10 and the geographic distribution is also quite different. We are inclined to the view that there are potentially errors in these LFC data which make them less reliable than the observer data, but acknowledge that there are likely to be errors in the observer data also. The data are tabulated in Table 9.1. Note that further data is becoming commercially available from a new lightning detection system which could assist this analysis (see section 9.4).

The values of N_g found in the Wellington region are comparable with those found in much of Europe. They are less than those found in Mid and Eastern USA and considerably less than those found in the tropical regions of South-East Asia, Africa and Central America.

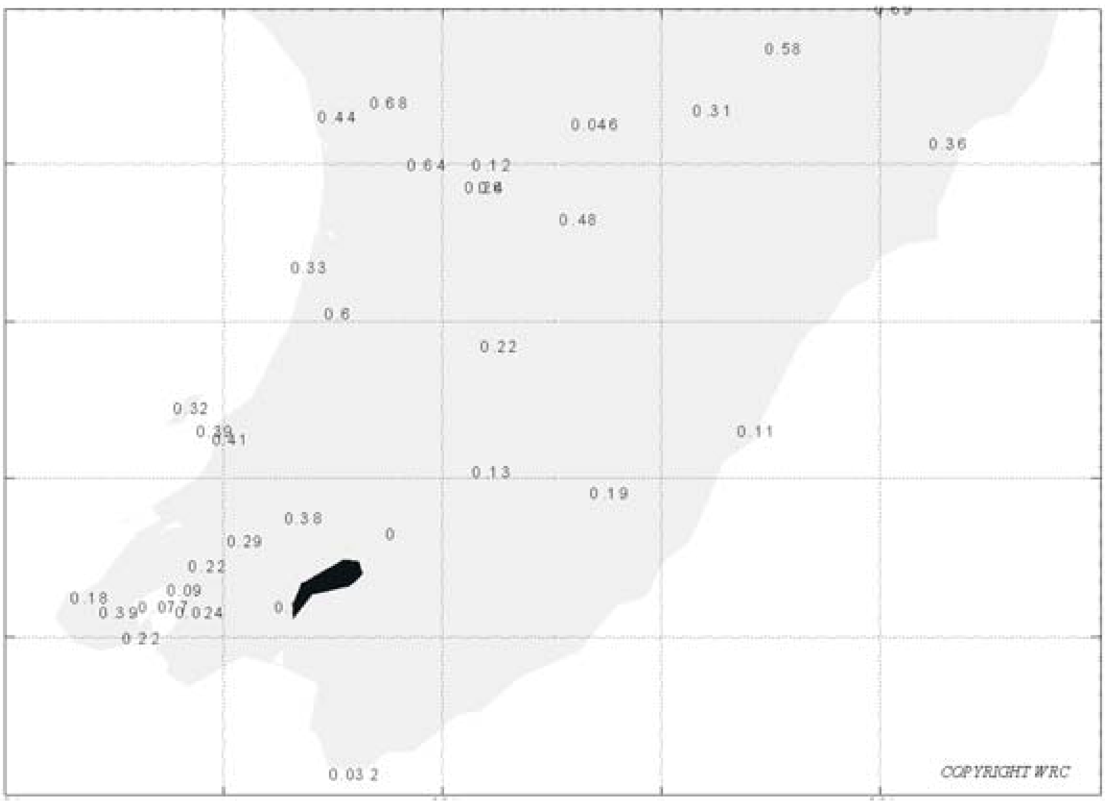

Figure 9.2: Lightning Ground Flash Density (N_g, in flashes/km^2/year) for the Wellington region, from observer records.

Table 9.1: Lightning Ground Flash Density at recording sites in the Wellington region. Also shown is the number of years of data available from each site and the standard deviation in the ground flash density at each site over that period. Copyright NIWA.

Latitude	Longitude	Station	N_g average (observer)	Number of years of data	Std Dev in Td	Ng average (LFC)
-40.00	176.53	Waipukurau Aero	0.69	25	0.39	
-40.08	176.28	Kopua	0.58	29	0.32	
-40.20	175.38	Ohakea Aero	0.68	37	0.32	
-40.22	176.12	Dannevirke	0.31	41	0.24	
-40.23	175.27	Bulls,Flockhouse	0.44	13	0.35	
-40.25	175.85	Wharite Peak	0.05	15	0.05	
-40.28	176.66	Porangahau	0.36	11	0.21	
-40.33	175.62	Palmerston N Aero	0.12	28	0.17	
-40.32	175.60	Palmerston N Aero LFC				0.63
-40.33	175.47	Palmerston N Kairanga	0.64	13	0.28	
-40.38	175.62	Palmerston N	0.40	28	0.27	
-40.45	175.82	Pahiatua,Mangamutu	0.48	53	0.26	
-40.55	175.20	Waitarere Forest	0.33	27	0.18	
-40.65	175.27	Levin M.A.F.	0.60	36	0.27	
-40.72	175.63	Mt Bruce Res	0.22	23	0.30	
-40.85	174.93	Kapiti Island	0.32	27	0.26	
-40.90	176.22	Castlepoint Light	0.11	15	0.12	
-40.90	174.98	Paraparaumu Aero	0.39	45	0.23	
-40.90	174.98	Paraparaumu Aero LFC				0.18
-40.92	175.02	Paraparaumu,Wairere	0.41	11	0.18	
-40.98	175.62	Waingawa	0.13	25	0.14	
-41.02	175.62	East Taratahi LFC				0.25
-41.03	175.88	Ngaumu Forest	0.19	16	0.22	
-41.08	175.18	Kaitoke	0.38	18	0.29	
-41.12	175.38	Tauherenikau	0.00	21	0.00	
-41.14	175.05	Wallaceville	0.29	42	0.24	
-41.18	174.97	Lower Hutt,Taita	0.22	24	0.20	
-41.25	174.70	Makara	0.18	18	0.14	
-41.27	175.15	Waiorongomai	0.20	34	0.22	
-41.27	174.87	Somes Is	0.08	11	0.11	
-41.28	174.95	Wainuiomata Coast Rd	0.02	16	0.08	
-41.28	174.77	Wellington,Kelburn	0.39	73	0.22	
-41.33	174.82	Wellington Aero	0.22	32	0.12	
-41.62	175.30	Cape Palliser	0.03	31	0.07	

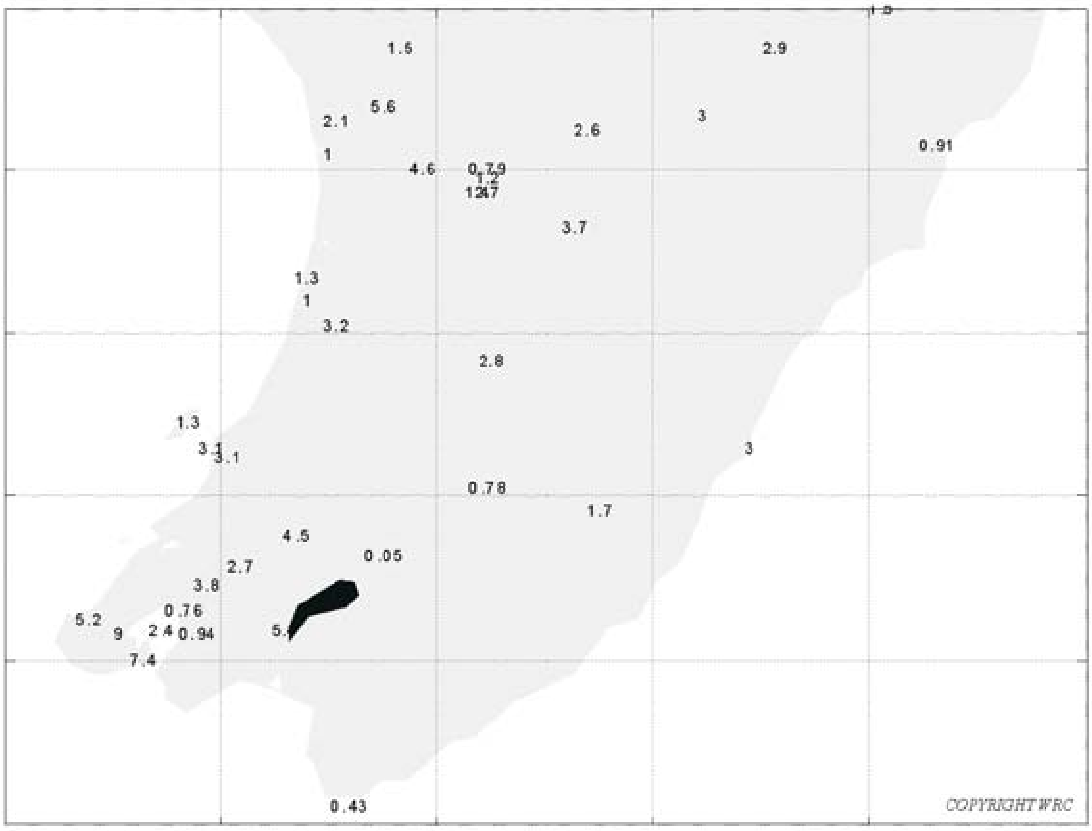

Figure 9.3: A map of the Mean Annual Days of Hail for the Wellington region, based on historical records.

9.2 Mean Annual Days of Hail

The risk of hail occurring at a particular location is estimated from historical records of hail observed at climate stations. Note that these data relate to all hail, not just larger damaging hail. The data are reasonably reliable and consistent from station to station, but must be interpolated to give full spatial coverage.The resulting map (Figure 9.3) gives the general features of hail distribution over the region. There will be local variations (which may be significant) on a small scale caused by local topography and other surface features. Also, because the data are based on observer records some hail events, particularly at night, may be missed and the map should be interpreted as a lower bound for the true distribution. The data on which this map is based are presented in Table 9.2.

Table 9.2: Mean annual days of hail at recording sites in the Wellington region. Also shown is the number of years of data available from each site and the standard deviation in the annual days of hail at each site over that period. Copyright NIWA.

Latitude	Longitude	Station Name	Av Number Hail Days	No. Years in Sample	Std Dev Hail Days/Yr
-40.00	176.53	Waipukurau Aero	1.50	26	1.48
-40.08	175.42	Marton,M.A.F.	1.47	19	1.50
-40.08	176.28	Kopua	2.90	29	2.43
-40.20	175.38	Ohakea Aero	5.56	52	3.17
-40.22	176.12	Dannevirke	3.02	41	2.22
-40.23	175.27	Bulls,Flockhouse	2.09	35	2.50
-40.25	175.85	Wharite Peak	2.63	19	1.71
-40.28	176.66	Porangahau	0.91	11	1.22
-40.30	175.25	Tangimoana	1.00	20	1.49
-40.33	175.47	Palmerston N Kairanga	4.63	16	3.65
-40.33	175.62	Palmerston N Aero	0.79	28	1.10
-40.35	175.62	Palmerston Nth B.H.S.	1.16	19	2.24
-40.38	175.60	Massey University	1.44	9	1.13
-40.38	175.62	Palmerston N	2.66	68	2.97
-40.45	175.82	Pahiatua,Mangamutu	3.68	53	3.02
-40.55	175.20	Waitarere Forest	1.30	27	1.27
-40.60	175.20	Hokio Beach School	1.00	11	1.10
-40.65	175.27	Levin M.A.F.	3.23	26	2.42
-40.72	175.63	Mt Bruce Res	2.78	23	2.73
-40.85	174.93	Kapiti Island	1.27	49	1.45
-40.90	174.98	Paraparaumu Aero	3.13	47	1.95
-40.90	176.22	Castlepoint Light	3.00	15	3.18
-40.92	175.02	Paraparaumu,Wairere	3.09	11	1.58
-40.98	175.62	Waingawa	0.78	37	1.00
-41.03	175.88	Ngaumu Forest	1.71	17	1.21
-41.08	175.18	Kaitoke	4.45	22	2.94
-41.12	175.38	Tauherenikau	0.05	21	0.22
-41.14	175.05	Wallaceville	2.72	57	2.17
-41.18	174.97	Lower Hutt,Taita	3.79	24	3.26
-41.23	174.92	Lower Hutt,Gracefield	0.76	17	1.39
-41.25	174.70	Makara	5.22	18	3.06
-41.27	174.87	Somes Is	2.36	11	2.73
-41.27	175.15	Waiorongomai	5.38	21	3.35
-41.28	174.77	Wellington,Kelburn	9.00	73	5.02
-41.28	174.95	Wainuiomata Coast Rd	0.94	17	1.03
-41.33	174.82	Wellington Aero	7.44	32	3.75
-41.62	175.30	Cape Palliser	0.43	14	0.51

9.3 The Masterton Hailstorm of 7 January 2001

A violent hailstorm with hailstones the size of golf balls struck Masterton late in the afternoon of 7 January, 2001. This storm lasted only a short time but caused significant damage in its 10-20 minute rampage across Masterton. Balloon soundings showed that there was little wind through much of the atmosphere, resulting in a short-lived multicell storm. Radar images showed that the storm complex which passed over Masterton was but one of three or four that occurred during that afternoon. This complex consisted of two major cells, which together passed across Masterton in a curve, moving from the southeast veering northwest and finally moving away southwestward (Figure 9.4).

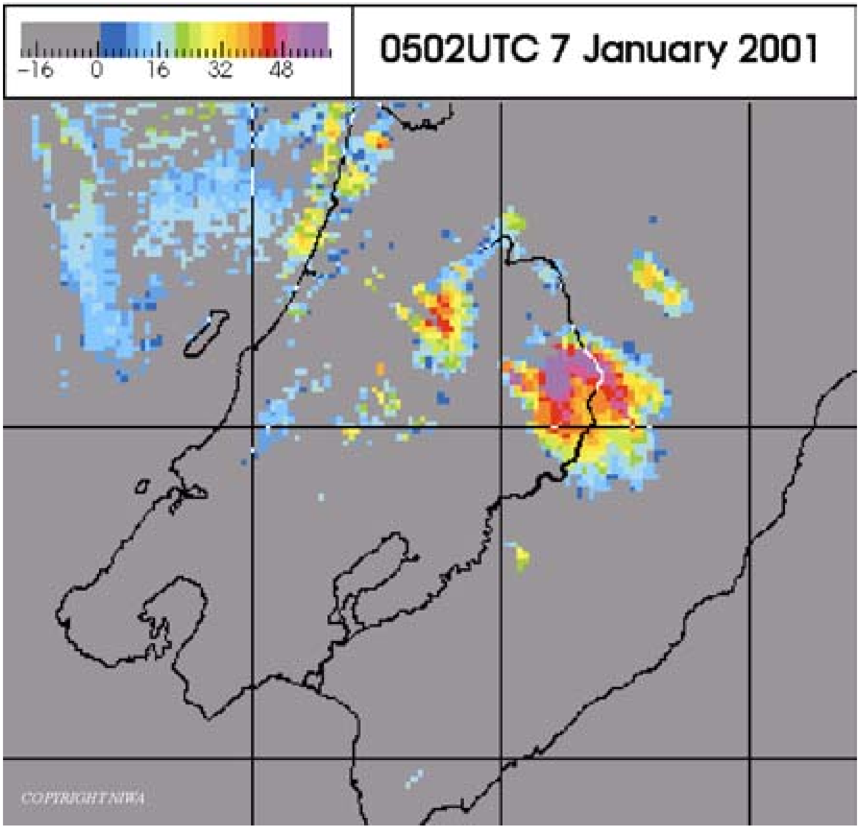

Figure 9.4: A radar map of the Masterton hailstorm of 7 January 2001, as it appeared at 18.02 local time (0502UTC). The 'map' shows instantaneous precipitation intensity from light (blue) through heavy (red) to intense/hail (purple) as measured by the radar above the surface, at a height of approximately 700 m (2000 ft). Data source: MetService.

The system developed as a result of cold air moving over a sun-warmed surface. The resulting instability could well have been released by lifting resulting from the arrival of the East Coast sea breeze (Figure 9.5).

Much damage resulted from the hail, or from the inundation into buildings of rainwater failing to flow down hail-filled gutters. Orchards and vineyards had plants damaged, some losing the whole season's crop. Plastic roofing, skylights and guttering were holed, car bodies dented and windscreens broken. Birds were knocked senseless from trees, some being killed outright. Hail drifts were so large that, even fourteen hours after the storm, some were still piled one metre high.

This type of storm, with its multicell structure, while being one of the larger hazardous events, may not represent the biggest severe convective storm that could affect our region. Storms that develop in a more strongly sheared environment can become significantly more intense, and can develop into what have been described as "supercell" storms. These storms would result in a significantly larger swath of devastation. Still greater in magnitude would be a mesoscale convective complex. These systems, though mainly seen over continental areas, would represent by far the most significant hazard from severe convection. One storm developed near Munich caused $500m worth of damage.

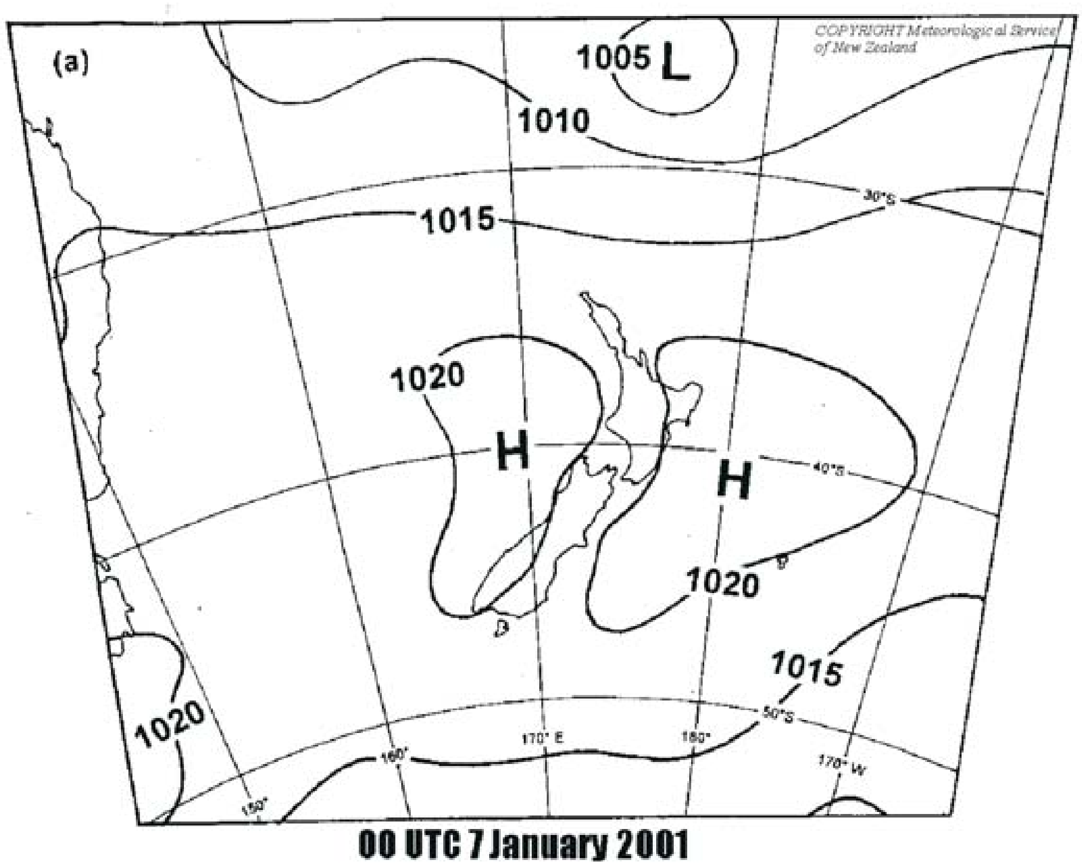

Figure 9.5: A synoptic weather map of conditions near the time of the Masterton hailstorm of 7 January 2001.

While the Masterton event occurred over a plain and away from the metropolitan area, strong convective systems have affected Wellington City (May 1976, June 1998, January 2002). Such storms can cause much disruption, as seen during those examples.

9.4 Knowledge Gaps

There is substantial uncertainty in our knowledge of the frequency and distribution of lightning. To resolve the discrepancies in the data will involve a more detailed study than has been possible here. As noted above, further data is becoming commercially available from a new lightning detection system which could assist this analysis, at some cost. The system (owned by TransPower) is automated and detects the radio signals from the flash, so it has the advantages offered by the LFCs, but is expected to avoid most of the potential errors that those instruments have. At this time (mid-2002) the system has been operating only a little over 12 months and insufficient data is available to construct reliable statistics from this system alone (at least 10 years data is needed). However it may be possible to use a much shorter period of data, obtained in parallel with data from the manned stations and the LFCs, to obtain an estimate of the reliability of the two existing data sets. Resolution of this issue of discrepancies in the data sets, to give reliable estimates of Ground Flash Density, is important in the planning of new communications and power infrastructure.

There is also some uncertainty about the detailed distribution of hail, which would be relevant in the planning of sensitive structures and crops. It has been found elsewhere that severe hail often occurs repeatedly along ‘corridors’ a few hundred metres wide and several kilometres long, related to particular topographic features upstream which have enhanced the probability of hailstorm development. These ‘corridors’ would not generally be resolved by the current observing network.In some areas with good low-level weather radar coverage they potentially could be identified from analysis of the radar data archive. In other areas they could only be identified by the installation of a very high spatial resolution climate station network with reliable hail detectors, which is not a very practical solution. The use of insurance industry data could help to identify high risk areas but the data require complex interpretation involving crop type and insurance coverage, outside the scope of this preliminary report.

Of some significance are the knowledge gaps associated with climate change. Climate change is likely to change the risks of both hail and lightning (see section 12.2.7). A warmer atmosphere will carry more moisture so that convective storms are likely to be more vigorous, with stronger updrafts able to support more and larger hailstones and generate more electrical energy. While an increased risk of hail and lightning over the region is therefore most likely, current knowledge is not sufficient to be certain of this. Because of the unknown effects of climate change on the numbers and characteristics of the small aerosol particles which trigger the first freezing of cloud droplets to hailstones, and on the (also unknown) processes by which electric charge is separated, it has not been possible to model hail and lightning production in a changed climate. It is even possible that there may be other unsuspected processes which act either to counter any increase or to further increase hail and lightning.

9.5 Risks and Risk Amelioration Methods

9.5.1 Current risks

There are no areas within the Wellington region that currently have a particularly high risk of either damaging hail or lightning, when compared with the risk of other meteorological hazards such as wind and flood. The risk is primarily an issue for sensitive structures and crops. Thus hail is obviously a risk to vinyards, glasshouse developments, car storage lots and the like, and lightning to communications towers, power and telephone cables. These risks are generally appreciated and taken into account by developers. There are no practical techniques for reducing the frequency of occurrence of either hail or lightning, so that risk amelioration requires, for hail, the avoidence of 'hail corridors' (currently unidentified) by sensitive horticulure developments and, for lightning, the building of appropriately robust installations.

Because many of the control services for infrastructure are increasingly electronic and sensitive to damage from lightning induced transients (not just direct strikes to the equipment) these services should be robust and not be routed near high-risk areas (see below). The danger is that although the damage directly caused by lightning is typically small compared with that from other meteorological hazards the loss of control and monitoring services and/or communications during an event such as a major flood, as has happened overseas, may significantly worsen the outcome.

9.5.2 Future risks

As noted above climate change is likely to change the risks of hail and lightning, most probably increasing the risk of each (IPCC 2001), because of an increase in convective activity (White and Elkin, 1997). One overseas study has suggested that an increase of 1ºC in average wet-bulb temperature may be accompanied in mid-latitudes by a 40% increase in lightning (Reeve and Toumi, 1999).

9.6 Areas of High Risk

The frequency of occurrence of both hail and lightning is relatively low in southern Wairarapa and correspondingly higher to the north and near the Kapiti Coast. We can anticipate that the frequency will be higher still over the Tararua ranges, although the data does not show it because of the lack of observing sites. Lightning is attracted to high structures, including mountain tops, and peaks in the Tararuas will have the highest frequency of lightning occurrence in the region. Hail will also be relatively more frequent at high elevations because the colder temperatures will lead to less melting of hail that, over lower areas, would reach the ground as rain.

However the frequency of occurrence of hail is not a good measure of risk. Small hail generally causes little damage (an exception may be if it blocks stormwater systems) and a measure of hailstone size is required. There are no data kept on hail size in New Zealand. It can be expected that hail size will be closely related to storm updraft velocities and in turn to atmospheric instability. For this reason we anticipate that the largest and most damaging hail will occur over the Wairarapa plains.

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10. Ex-Tropical Cyclones

Tropical cyclones are one of nature's most extreme phenomena. They develop over the warm tropical waters where the resulting convection can get organized into intense storms, leading to heavy rain, storm surge, and wind speeds in excess of 130 km/h. Tropical cyclones have a distinctive structure, with warm rising air at the core (IRI, 2001 gives a good description of Tropical Cyclone development). This structure leads to a tight core of damaging weather conditions, often only 60 km in radius. However, as these cyclones leave the tropics they often undergo a transition, with an injection of cold air, which can result in a re-intensification, and an expansion of the areas of extreme weather. These ex-tropical cyclones are often the source of New Zealand's most extreme weather, leading to extensive flooding and wind damage. This damage (and also the naming of the storms) leads to them being well-remembered by the public. Most people will have heard of Cyclone Bola. Cyclone Gisele has become known as the Wahine storm.

This section of the report takes a look at ex-tropical cyclone Gisele, and uses this example to put into context the risks from these weather systems.

10.1 An Historical Ex-Tropical Cyclone Event: Gisele — The Wahine storm

The path taken by ex-tropical cyclone Gisele across the North Island to lie east of Cape Palliser resulted in one on New Zealand's greatest maritime disasters, yet this ex-tropical cyclone was not, in itself, an extreme event. The Southwest Pacific mid-latitudes have seen more intense and even more damaging ex-tropical systems. The depression that redeveloped from the remnants of tropical cyclone Bola is one example, with wind and flooding damaging causing devastation across much of the North Island. However, Gisele's path close to Cook Strait resulted in record wind speeds that, in turn, led to mountainous seas. These waves, in conjunction with intense rainfall, triggered a series of events that ultimately led to the stranding of the Wahine.

At noon on Sunday April 7, tropical cyclone Gisele lay just northwest of New Caledonia with observed winds of about 75 km/h. As tropical cyclones go it was relatively weak. Over the next 2 days it moved southeast to lie about 500 km northwest of Kaitaia by noon on Tuesday. By this stage it had lost its tropical cyclone structure but now came under the influence of a very intense upper (~10 km) level trough in the midlatitude westerlies. Re-intensification took place and by 6 p.m. on April 9 winds of 165 km/h and a central pressure of 974 hPa were being recorded at Kaitaia. By midnight the system had crossed over Tauranga giving easterlies of 110 km/h.

By 6 a.m. on the morning of April 10 the centre of the storm (967 hPa) lay between Castle Point and Hastings, but the strongest winds were now 110 km/h (gusting to 150) at the entrance to Wellington Harbour where the inter-island ferry Wahine was making its arrival. The winds at Wellington airport had been rising steadily from 75 km/h over the preceding 2 hours and by 9 a.m. were 144 km/h (10 minute average) gusting up to 187 km/h. The highest wind gust in the region was 1268 km/h on a cliff top at Oterahanga bay. The combination of high winds and a following sea with heights well over 10 m and short horizontal wavelength was too much for the ship to handle and it ran aground on Barret reef. During the following 6 hours winds remained over 110 km/h dragging the ship into the harbour. At 3 p.m. the winds dropped back to a northwesterly of 22 km/h, but the damage had been done. The ship sank and 51 people lost their lives. Figure 10.1 shows the synoptic pressure map at 9 p.m. NZST on April 10, 1968.

The cost of damage from this storm (including the loss of the Wahine) is estimated at being around $150m in today's dollars (NIWA, 2000). It is worth remembering that such systems, because of their size, can lead to widespread direct damage both from the intense rainfall and strong winds, and consequent damage from flooding and landslides. Indeed, cyclone Bola affected most regions in the North Island. Consideration should be given to the fact that, during such events, help from other regions may not be forthcoming because of the problems they are also experiencing (see also Metservice 2002, NIWA 2000b).

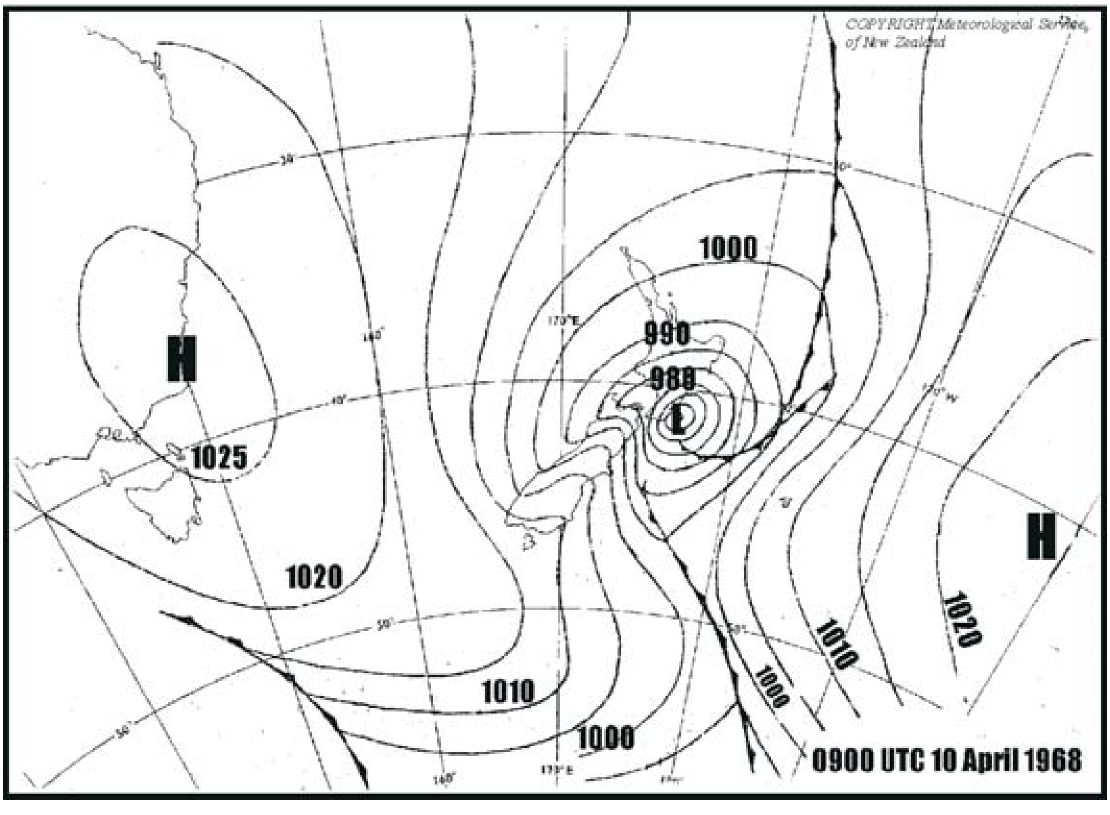

Figure 10.1: Synoptic map at 9pm NZST, 10th April 1968 (Wahine Storm).

10.2 Wahine Storm Return Period

Estimating the return period for this storm is difficult. Tropical cyclone track data would suggest that central New Zealand, including the Wellington region could be affected by cyclones of tropical origin once every three to six years. Initial work on the recurrence of ex-tropical cyclones suggests that Gisele was a more extreme and rarer event than this. However, the preliminary work is limited by the resolution of the input data, and may not well-represent such storms.

The maximum wind speed measured at Wellington was 192 km/h, and remains the record for that site. However, it was the combination of wind and waves that caused the Wahine difficulty, and an assessment of the frequency of this combination is the subject of significant further research currently being undertaken within the Coastal Hazards group at NIWA.

10.3 Knowledge Gaps

As the IPCC has stated, global climate change will probably not increase the number of tropical cyclones generated in the tropics to any great extent (see section 12). Further, with the possibility of increased El Niño events as the climate warms, the number of ex-tropical cyclones reaching New Zealand and the Wellington region is not yet certain. Scenario type research to investigate how climate warming could affect ex-tropical cyclones reaching New Zealand will allow for a greater degree of planning to ameliorate the risks.

10.4 High Risk Areas

Ex-tropical cyclones pose a risk in that they bring both intense rainfall and wind, which as detailed previously in this report, can cause major damage. Far from being confined to wind damage, flooding, landslides and erosion, there is also the potential for storm surges and waves to exacerbate the situation.

A flood event brought about by heavy rain during an ex-tropical cyclone will cause greater damage in low-lying coastal areas if a storm surge or high waves develop and prevent rivers draining to the sea. A severe flood therefore has the potential to cover a greater area than previously thought and more lifelines would be exposed to failure.

Areas of risk from ex-tropical cyclones in the Wellington region are those detailed in sections 2–Rain, 5–Coastal Flooding, and 6–Severe Wind. It is worth mentioning again that these weather systems will come with both damaging wind and heavy rain, and the combination of these factors will exacerbate the situation.

10.5 Amelioration Methods

Ex-tropical cyclones can generally be forecast reliably, usually allowing for a number of days warning before they reach New Zealand. Amelioration measures for these cyclones are the same as for intense rainfall and floods (section 2), coastal flooding (section 5), and severe winds (section 6).

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11. Wildfire

Typically, the Wellington region experiences at least one wildfire each year, with the highest risk months being January and February. In some years, such as 2001, there can be several fires, which can be attributed to drier than normal conditions and an abundance of combustible material. Lower than normal rainfall in summer is the main proponent leading to a higher than normal wildfire season. Hence information on droughts in the region (section 3 of this report) can be directly related to wildfires.

11.1 An Historical Wildfire Example: Silverstream, January 2001

In January 2001 there were four significant wildfires in the Wellington region, three of which were the result of arson. The four fires were in Porirua, Plimmerton and two in Silverstream. Each of these fires resulted in the burning of large areas of bush and forest and the consumption of hundreds of thousands of dollars worth of man-hours and fire-fighting equipment usage.

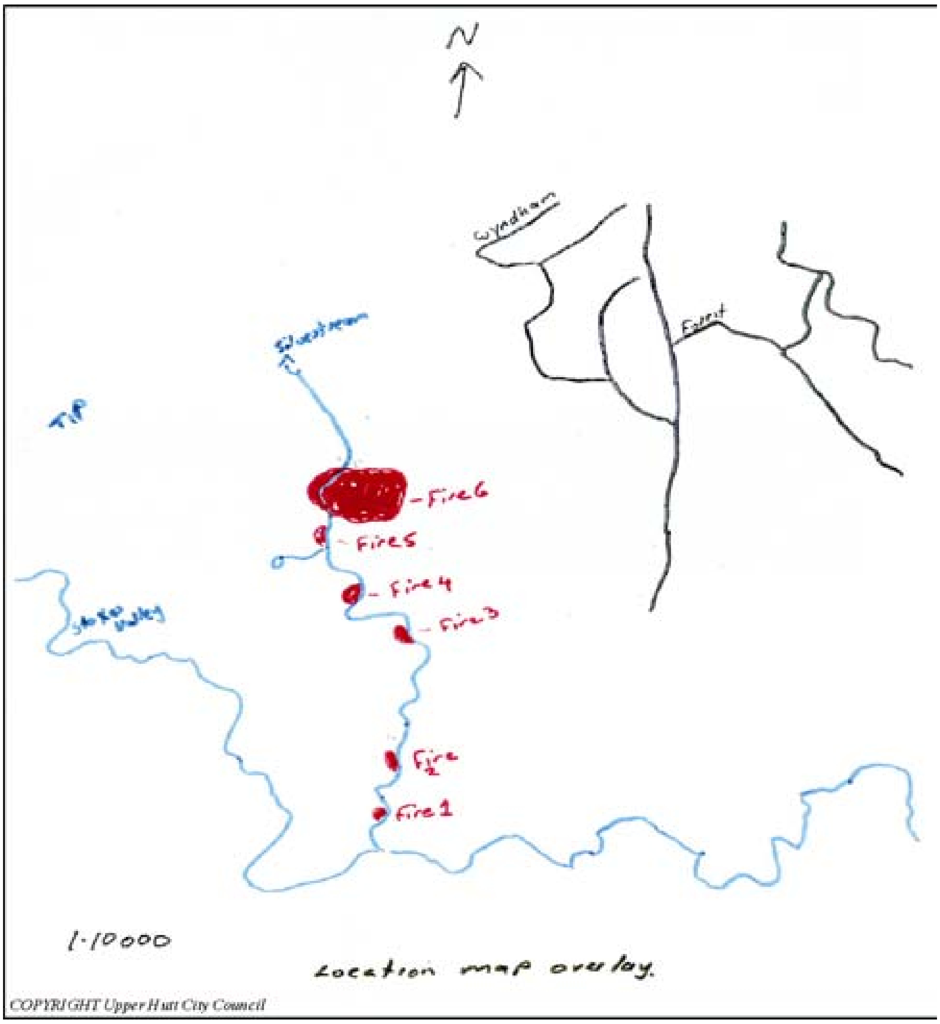

Figure 11.1: Location and extent of Avro Road fires, Silverstream, 15 January 2001. The fires were lit along a logging track. Map courtesy of David Etchells, Upper Hutt City Council Principal Rural Fire Officer.

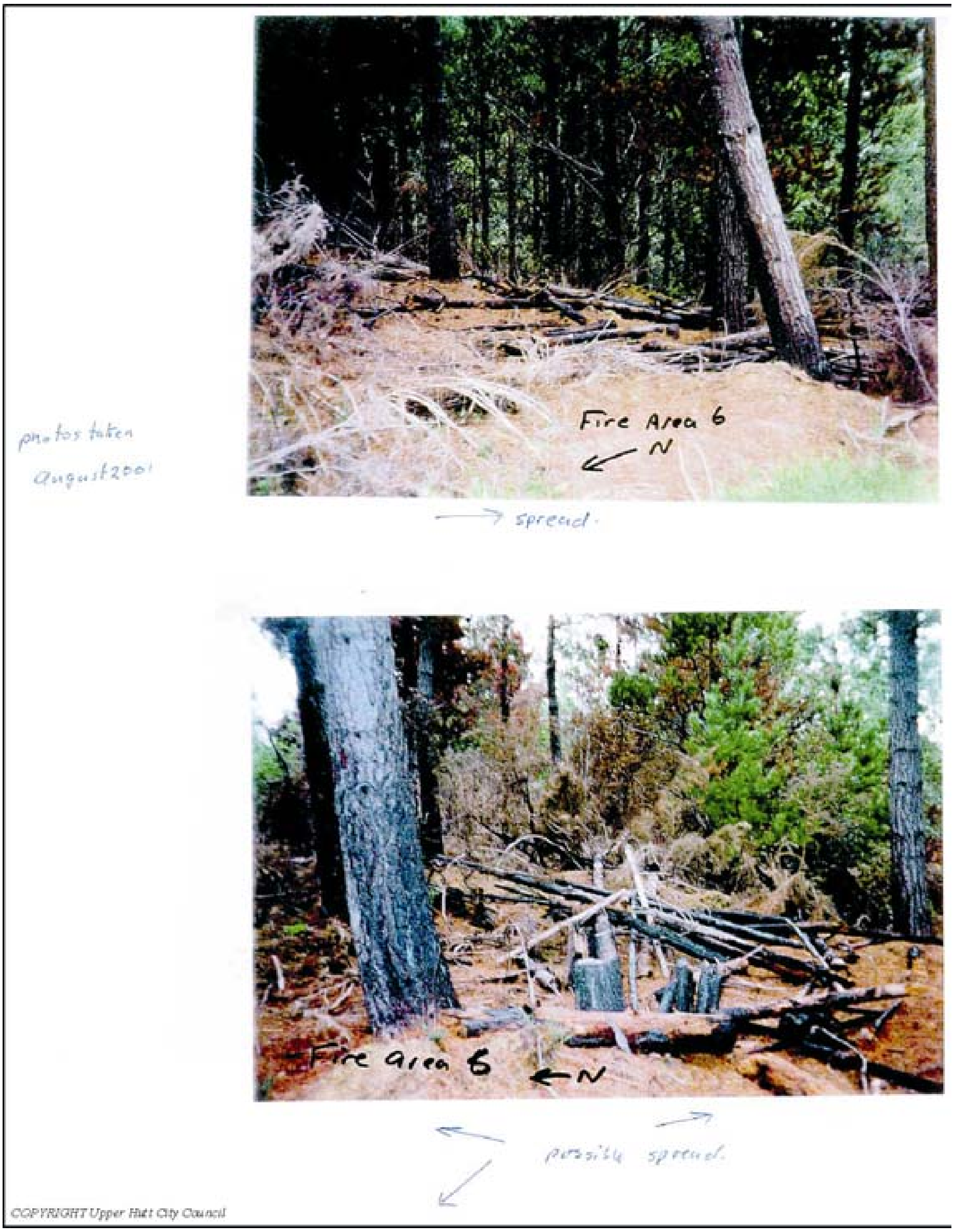

Figure 11.2: Photos showing damage to trees and undergrowth from the Avro Road fires, Silverstream, 15 January 2001. Photos courtesy of David Etchells, Upper Hutt City Council Principal Rural Fire Officer.

Figure 11.1 shows the pattern and extent of fires deliberately lit near Avro Road, Silverstream, on 15 January, 2001. Fire 6 damaged around 2 ha of pine forest and scrub (Figure 11.2). Luckily, the fire did not "crown" (fire spread into tree tops), and was limited to the forest. Otherwise, there would have been significant risk to approximately 20 properties in Avro Road, a few properties in Wyndham Road, and high-tension power lines running along the crest of the hill behind the fire.

Wildfires the size of the Avro Road fires are not uncommon in the Wellington region. However, while the occurrence of four fires at the same time was an extremely rare event, according to David Etchells, Upper Hutt City Council Principal Rural Fire Officer, the chances of similar fire seasons in the future are more likely due to easier access into forested areas, taller trees (more fuel) and a more blurred rural-urban interface.

11.2 Knowledge Gaps

The Wellington Regional Council, City Councils throughout the region, the National Rural Fire Authority, Forest Research and the National Institute of Water and Atmospheric Research Ltd have achieved much already towards understanding the wildfire hazard risk in the Wellington region. Several documents have been produced and published on the NRFA website (http://nrfa.fire.org.nz/) on the identification and prediction of "fire weather", tracking fire severity, and modelling fire risk (see Bibliography).

An accurate meteorological forecast is vital for real-time analyses of the probable spread of the fire and its heat intensity, according to David Etchells. These estimates help determine the best method of fire fighting, whether it be hoses, bulldozers, helicopters or some combination of these.

Grant Pearce, a Fire Research Scientist working for Forest Research, identifies the current knowledge gaps as: a lack of high quality statistics on wildfire occurrence and a lack of appropriate models for fire behaviour in New Zealand vegetation types.

11.3 High Risk Areas

Figure 11.3 shows the estimated fire hazard risk for the Wellington region. The derivation of this map is described in WRC (1997, 1998). The greatest fire risk areas are characterised by gorse and scrub type vegetation, on steep slopes, with relatively low rainfall, and close to areas frequented by people. Approximately 20% (165,500 ha) of land in the Wellington region is at 'high', 'very high' or 'extreme' risk from wildfire.

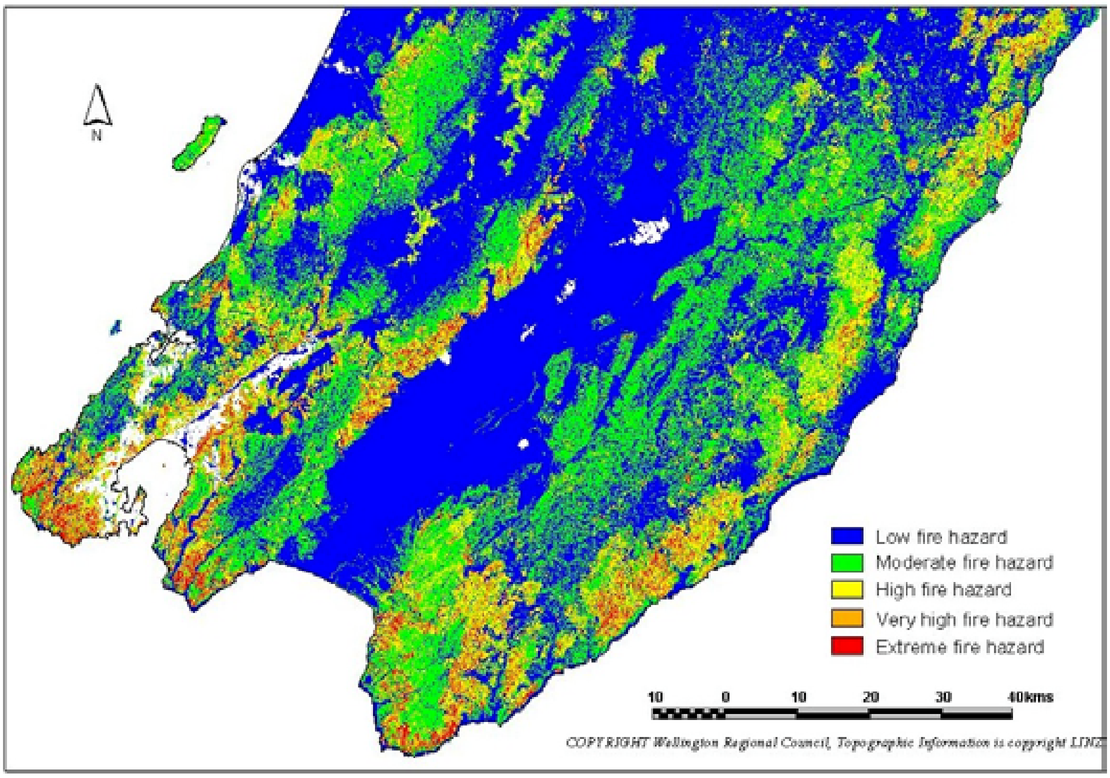

Figure 11.3: Fire hazard map, reproduced from WRC (1998).

11.4 Amelioration Methods

Mitigation measures, according to WRC (1997, 1998) include: increasing the size and maintaining defensible space around buildings; replacing flammable vegetation with less flammable species; managing vegetation to speed floral succession at the boundaries of defensible space; use of fire resistant building materials and structures such as stone walls to reduce flammability of buildings; matching of building design, siting, and materials to perceived hazard; and land use planning for new subdivision development.

11.5 Bibliography

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12. Climate Change and Decadal Variability

Concentrations of greenhouse gases in the atmosphere will continue to grow through the 21st century, leading to changes in global, regional and local climate. The rates of anthropogenic greenhouse gas and aerosol emissions that influence climate will vary according to changes in population and economic growth, technology, energy availability and national and international policies. Even if these emissions could be predicted precisely throughout the century, there would still be scientific uncertainties in estimating the resulting greenhouse gas concentrations and global, regional and local climate changes.

The usual approach for providing predictions in an uncertain world is the use of scenarios, in which a number of greenhouse gas emission pathways are constructed for the future, based on a range of plausible social, economic and technological developments. For each of these scenarios, predictions are then made for greenhouse gas concentrations and the resulting climate changes, based on scientific understanding and incorporating science-based uncertainty ranges. The result is a set of several different climate "projections", spanning likely future emissions pathways.

Complex global climate models (GCMs) are required to convert a global greenhouse gas concentration into detailed estimates of feedbacks and regional features of climate change. Even with the fastest computers of today, these GCMs can only sample a subset of the various concentration scenarios. In the most recent simulation results prepared for the Inter-Governmental Panel on Climate Change (IPCC) Third Assessment, models generally predict that mean temperatures will increase somewhat slower for New Zealand than for the globe. They also predict that precipitation will increase in the west and decrease in the east of the country, and that the prevailing westerly winds will intensify across New Zealand. However there is considerable variation between models.

These anthropogenic projections should be viewed within the context of natural decadal variability in circulation, which periodically could either augment or weaken the west-east rainfall gradient across New Zealand. The Interdecadal Pacific Oscillation (IPO) has been shown to be associated with decadal climate variability over parts of the Pacific Basin, and to modulate interannual El Niño-Southern Oscillation (ENSO) climate variability over Australia (Power *et al.,* 1999) and New Zealand (Salinger *et al*., 2001). Three phases of the IPO have been identified during the 20th century: a positive phase (1922–1944), a negative phase (1946–1977) and another positive phase (1978–1998). Analysis of the latest sea temperature data suggests that we have entered another negative IPO phase, under which more La Niña (and less El Niño) activity might be expected, together with a period of higher temperatures for New Zealand. Weaker westerlies are also likely, along with an implied weakening in the west-east rainfall gradient across the country.

12.1 Downscaled Climate Change Scenarios for the Wellington Region

The downscaled scenarios presented here draw on the work of Mullan *et al.* (2002), which focused on the most common "1% greenhouse gas plus sulphate" emissions scenario. In these GCM experiments, the atmospheric concentration of sulphate was specified, and the carbon dioxide concentration followed historical observations up to 1989, and was thereafter compounded at 1% annually. This imposition of a 1% per annum growth in future greenhouse gas concentrations corresponds quite closely to the SRES A1 scenario developed for the IPCC Third Assessment (Nakicenovic and Swart, 2000).

The GCMs used here do not span the full IPCC Third Assessment range, which suggests a global warming of between 1.4 and 5.8 °C over the period 1990 to 2100. Linearly extrapolating the 50-year warming rate from these six models would give a global warming by 2100 in the range 2.4 to 3.4 °C. Thus, changes outside the bands described below could occur under more extreme emission scenarios (i.e. changes between 40% smaller and 70% larger, although many scientists do not consider the extreme IPCC emissions to be very likely).

Regional downscaling from GCM projections to predict how climate will vary across the Wellington region adds further uncertainties. The IPCC has identified the reliability of local and regional detail in projections of climate change, especially climate extremes, as a key uncertainty (see Table SPM-3 of the Summary for Policymakers in "Climate Change 2001: Synthesis Report"). This report represents our best judgement on what may happen to the climate of the Wellington region over the coming century, but we cannot guarantee that all changes will lie within our range of projections.

The statistical downscaling technique used involves developing regression relationships between circulation and climate variations from observed data, and then applying these to the projected GCM changes. The method is a simple and robust way of adding the signal of New Zealand's orography onto a large-scale background field. The GCMs cannot account explicitly for the orography because of the coarse model resolution of several degrees latitude grid spacing. The downscaling relations describe how the station climate differs from the large-scale "background" climate at the same latitude in the presence of west-east and south-north windflow variations. Equations were derived for 58 temperature stations and 92 precipitation stations nationwide (Mullan *et al.*, 2002).

Figure 12.1a,b shows scenarios as downscaled from six GCMs, using the nationwide set of stations noted above. These national scenarios are replotted for just the lower North Island, and show annual-average changes in mean temperature and precipitation, from the 1980s to 2030s. The centre panels in each row give the 6-model average. Thus, predicted 50-year trends in annual mean temperature in the Wellington region lie in the narrow range 0.75–0.80 °C (compared to a model-average Southern Hemisphere temperature increase of 1.0 °C). Trends are smaller than this in summer (0.65–0.75 °C, not shown) and larger in winter (about 0.95 °C). The predicted annual precipitation trend from the six model average ranges from a 2–3%

increase in the northwest of the Wellington region to a 4–6% decrease in the Wairarapa. Seasonally, this change in west-east rainfall gradient is weakened in summer (+2% in west to –4% in east), and enhanced in winter (+8% to –4%) with increased rainfall in the western part of the region.

Figure 12.1a: Fifty-year trend in annual mean temperature (ie, projected increase between 1980s and 2030s, in °C) over the lower North Island, as averaged over downscaled patterns from six global climate models. The three panels show the "second lowest" changes (left), average changes (centre), and "second highest" changes (right). See text for further explanation.

Figure 12.1b: As 12.1a, but for annual mean precipitation trend (ie, projected percentage change in rainfall between 1980s and 2030s).

The side panels in Figure 12.1 show the "second lowest" (left) and "second highest" (right) patterns of change. The patterns were derived by ranking the changes of the six models from lowest to highest at each station, dropping out the extreme values, and contouring the resulting lower and upper values across the country. The GCM responsible for the projected change will vary across the map, in general. The "second lowest" and "second highest" maps can be used to determine ranges of warming or precipitation change, where the possibly unrealistic outlier values have been eliminated. The annual mean range of changes can therefore be summarised as follows: for temperature, a 50-year trend of 0.55–0.90 °C, with the greater warming occurring in the northern Wairarapa. Rainfall trends show increasing precipitation in the west (0–6% increase over 50 years), and drier conditions in the east (2–10% decrease).

12.2 Effects of Human Induced Climate Changes and of Natural Decadal Variability on Specific Climatic Hazards

When it comes to considering the effect of climate change on extremes, there is very little information available directly from the models at the New Zealand scale. The global models have much too coarse a resolution to provide a reliable spot value for, say, an extreme daily rainfall or temperature. There are three possible approaches by which we might infer local effects:

- Use of a high resolution regional model "nested" within a GCM. Only one such data set has been produced for New Zealand (Renwick *et al*., 1999), based on an older Australian "equilibrium" model, where present greenhouse-gas concentrations (1xCO_2) are compared to a doubled-carbon dioxide (2xCO_2) situation.
- Use of statistical models such as "weather generators", which can simulate daily weather sequences at individual sites; or Markov models of breakpoint rainfall data (Sansom and Thompson, 2002) which can simulate high resolution rainfall records. These models are tuned to current data, but their parameters can be adjusted to take account of expected climate changes, as has been done in the CLIMPACTS programme (Thompson and Mullan, 2001, 2002).
- Generalisation of extreme changes analysed for other parts of the globe, along with the use of physical reasoning, to argue on at least the direction of expected changes if not the magnitude.

All three approaches are applied in the following sections.

In considering the effect of decadal natural climate variability on climatic extremes, we must rely on past observations. In particular, we can compare what happened in the most recent negative phase (1946-1977) and positive phase (1978-1998) of the IPO (Figure 12.2). In doing so, however, we must be aware of the possibility that underlying trends associated with global warming could influence observed local differences across this 50-year period. Salinger and Griffiths (2001) calculated trends in New Zealand daily temperature and rainfall extremes over the period 1951-1998. Some of their computed changes (e.g. decrease in frost frequency) were in agreement with global climate model projections, but most of the observed past changes had marked regional patterns and could be related qualitatively to decadal circulation changes.

Figure 12.2 shows a time series of the IPO, illustrating three major phases of last century and the change to the negative phase in 1999. The switch in 1977/78 was accompanied by an increase in mean westerlies across New Zealand, and changes in mean annual rainfall shown in Figure 12.3. Eastern parts of the WRC region became drier by between 4 and 8%, with relatively little change in the west. Accompanying changes in extreme rainfall are described below.

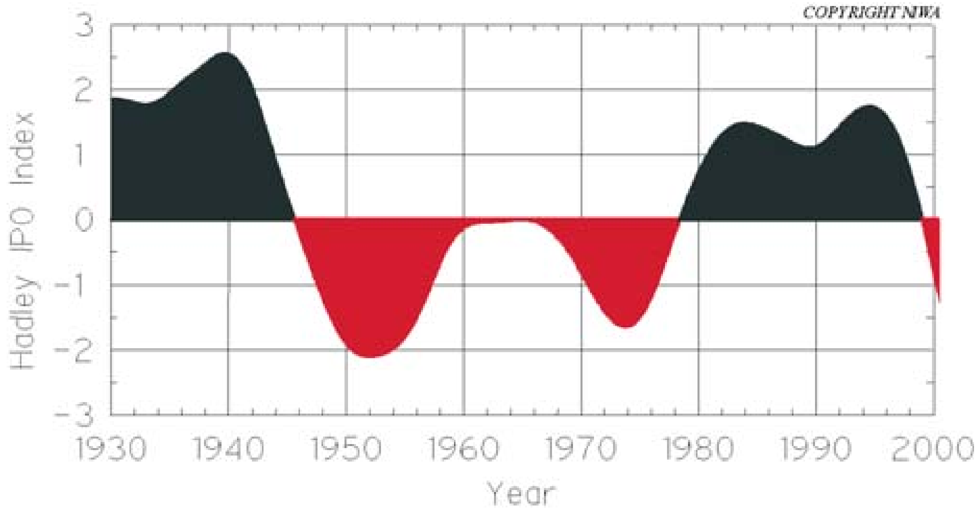


Figure 12.2: Time series of Interdecadal Pacific Oscillation (IPO), derived from eigenanalysis of Pacific-wide sea surface temperatures.

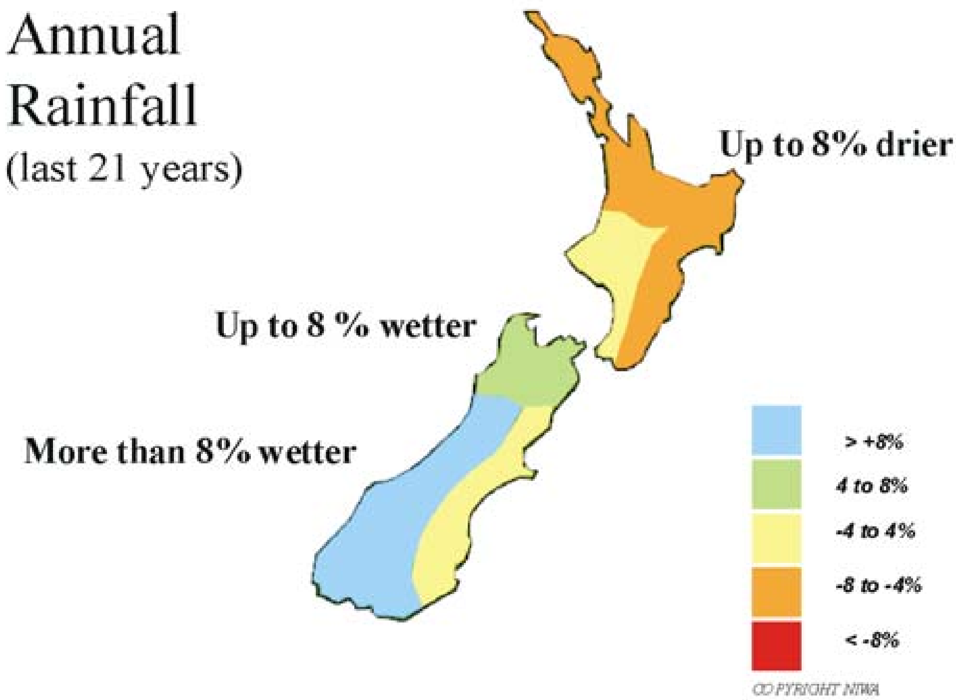


Figure 12.3: Annual rainfall changes (in %) between 1957-1977 and 1978-1998 for six regions of New Zealand. Source: 1999 NIWA publicity on "climate shift".

12.2.1 The high rain/flood risk

The IPCC Third Assessment, relying on both observational and modelling studies, declared that more intense precipitation events are "very likely, over many areas" (Table 1 in Summary for Policymakers, IPCC, 2001). This does not necessarily apply to an area as small as that of the Wellington region. However, a warmer atmosphere can hold more moisture (about 8% more for every 1°C increase in air temperature), and so the potential for heavier extreme rainfalls is present.

An alternative way of viewing these systematic increases in average rainfall intensity is to say that a reduction in the return period of heavy rainfall events is expected. The only estimate of projected changes in return periods for Australasia is that provided by Whetton *et al*. (1996), who suggested that: by 2030, there would be "no change through to a halving of the return period of heavy rainfall events", and by 2070, "no change through to a fourfold reduction of the return period".

Some direct model evidence of increases in rainfall intensity for New Zealand is provided by Figure 12.4, which is derived from the daily rainfall data archived from the high resolution regional model simulations of Renwick *et al*. (1999). The figure is a scatterplot of the percentage contribution of the heaviest precipitation to the annual total at each of the 782 New Zealand land points, comparing $1xCO_2$ and $2xCO_2$ simulations. For the "present" climate ($1xCO_2$), all raindays at a gridpoint are ranked to identify the daily accumulation corresponding to the 90-percentile. The total accumulated rainfall in the top 10-percentile is then expressed as a percentage of the annual rainfall, and plotted along the horizontal axis. Thus, under the current New Zealand climate, the model suggests that about 30–40% of the annual rainfall total is contributed by the wettest 10% of raindays. Under doubled-CO_2, the contribution to the annual total from days wetter than this *same* ($1xCO_2$) 90 percentile amount can be substantially greater (i.e., scatter much greater along the vertical axis).

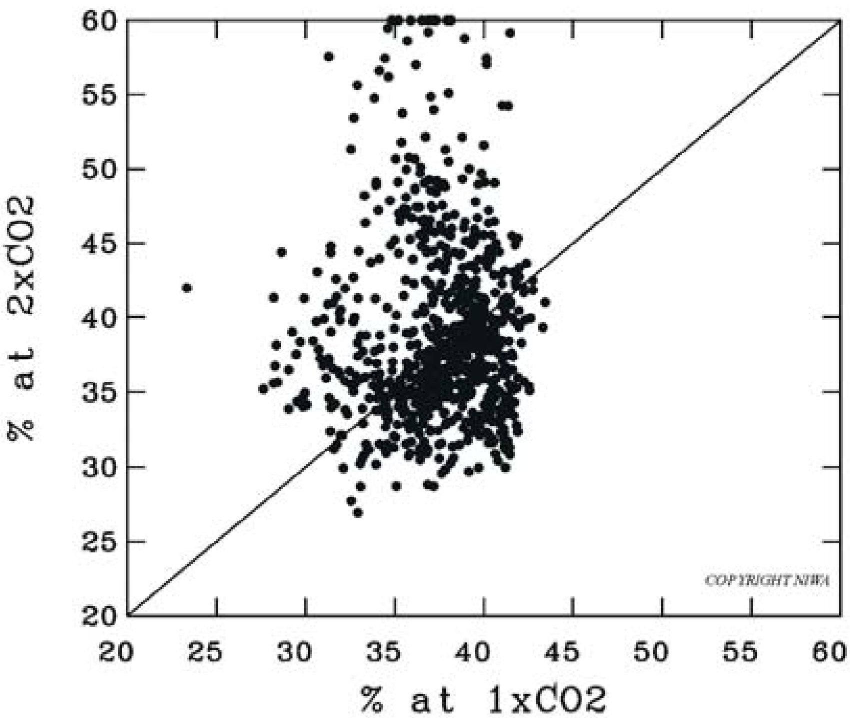
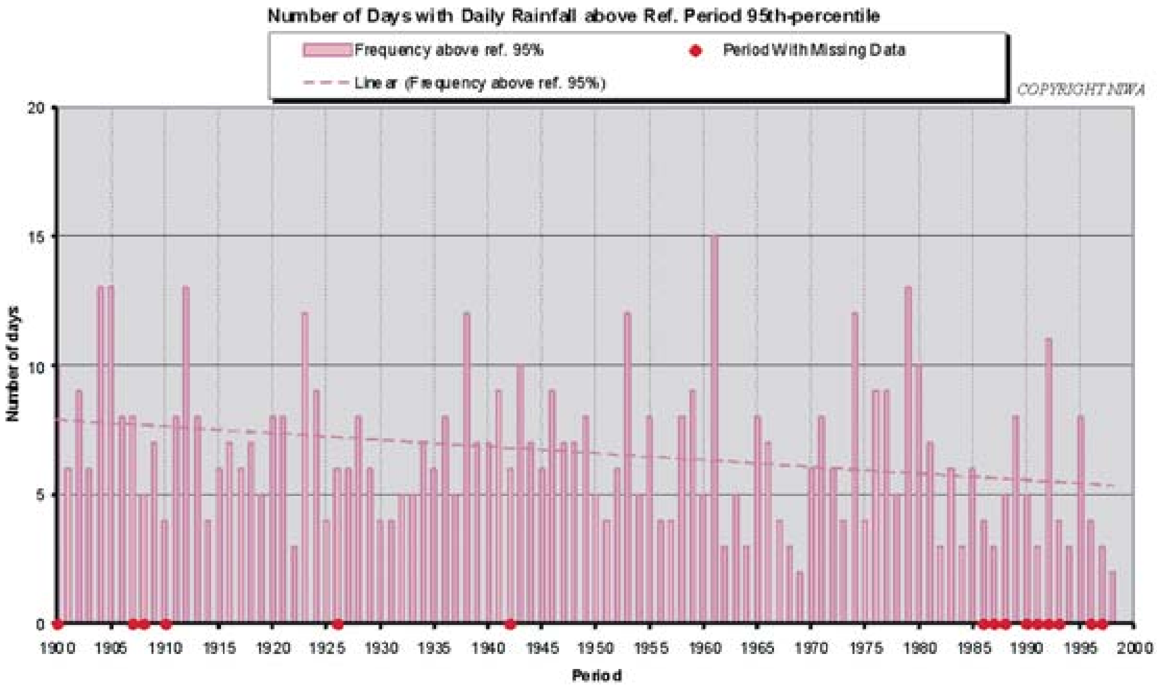


Figure 12.4: Percentage contribution of the heaviest precipitation to the annual total at each of the 782 New Zealand land points, comparing $1xCO_2$ and $2xCO_2$ simulations. See text for further explanation.



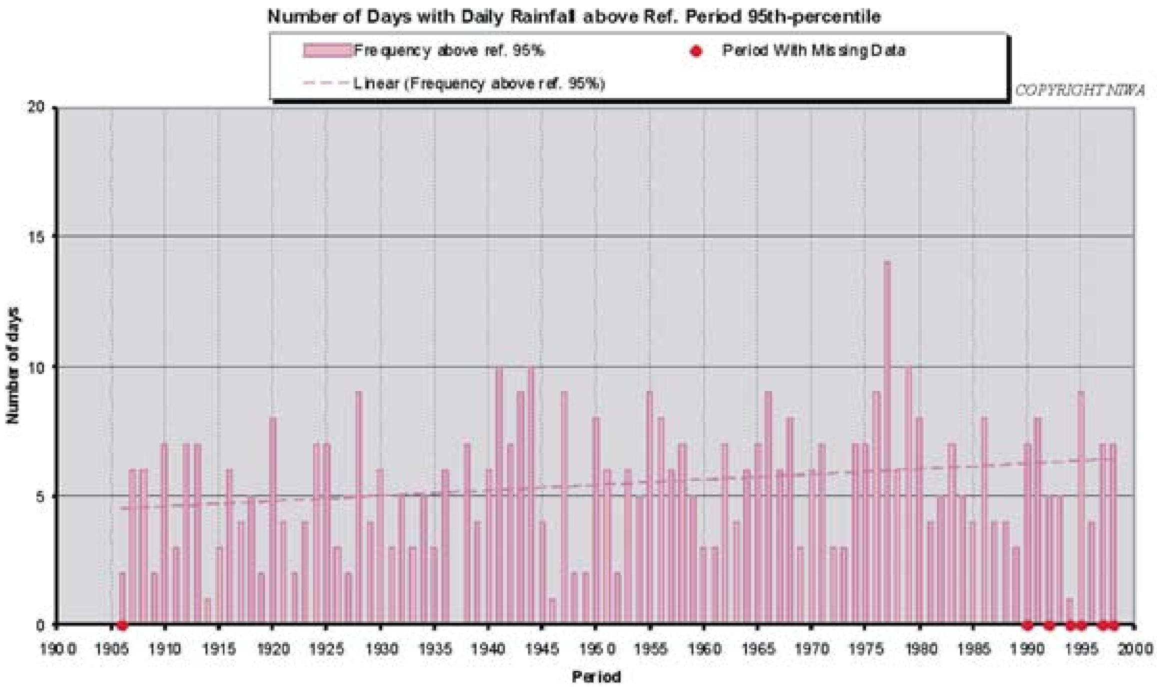


Figure 12.5: Number of raindays per year with daily rainfall greater than the 1961–1990 95-percentile, for Masterton (above), and Wellington (below).

Historical changes in New Zealand extreme rainfall have been documented by Salinger and Griffiths (2001). Figure 12.5 shows the number of days per year, at Masterton (top figure) and Wellington (bottom figure), with daily rainfall greater than the 1961–1990 95-percentile. The trend lines suggest an increase in heavy rainfall in the west of the WRC region (Wellington) and a decrease in the east (Masterton). Interestingly, there is no indication of a decrease at Masterton in the number of "very wet" years with, say, at least 10 days above the 95-percentile. These variations do not seem to coincide with the IPO shift around 1978, which generally is most marked in the South Island, on both the West Coast and in central Otago. Hence, the observed data do not suggest any marked decadal variations in rainfall extremes with the IPO in the lower North Island. Since this statement probably applies to many other climate elements as well, the following sections concentrate mainly on risks associated with global warming rather than decadal variability.

In summary, the rainfall rate during periods of heavy rainfall might increase by up to 10%, and the return period between severe flooding episodes might decrease by up to a factor of 2, over the next 50 years. However these figures are still quite uncertain, and little or no change in extreme rainfall and flood return period cannot be entirely ruled out. It is hoped that new NIWA research using regional models will lead to improved guidance on this matter within the next 2-3 years.

12.2.2 The drought risk

Increased drought risk is related to a combination of both increased evapotranspiration and reduced precipitation. Factors influencing evapotranspiration are complex: radiation is the most important, followed by vapour pressure deficit. Wind speed can also be a factor. Systematic changes in all these drivers cannot readily be deduced from model simulations at this point.

Historical changes in rainfall extremes have been assessed by Salinger and Griffiths (2001). As Chapter 3 of this report notes, there are different ways of defining a drought. An index computed by Salinger and Griffiths (2001) relevant to low rainfalls is the maximum number of consecutive dry days in a year. Over the last 50 years, this index shows a trend in Wellington region for an increase in Wellington and a decrease in Masterton.

Griffiths (1990) estimated changes in runoff for a scenario with rainfall changes ranging from about a 5% increase on the Kapiti coast to a 5% decrease in the Wairarapa – not too dissimilar to the 50-year changes suggested in Figure 12.1b. He found runoff percentage changes of approximately twice the projected precipitation changes, implying increased drought frequency in the eastern part of Wellington region. However, this analysis was based on the dubious assumption of no change in evapotranspiration – a condition applied largely because of uncertainty in how to treat this factor.

Mullan *et al.* (2001c) assessed future river flow changes using the latest scenarios of temperature and precipitation change (as in Figures 12.1a,b), coupled to a detailed hydrological model of a river catchment. None of these catchments was in Wellington region, but again the reduction in river flow could be twice as large in percentage terms as the rainfall reduction. River flow could also decrease for small (5% or less) increases in precipitation. However it is important to take into account the whole catchment of a river in considering climate change effects. For example, some of the rivers which flow through areas of the Wairarapa which are expected to have less rain under future climate change scenarios have headwaters in the Tararuas where rainfall may increase.

Analyses using the regional version of the CLIMPACTS model (Kenny *et al*., 2001; Kenny, 2001) also suggest a significant risk that eastern regions of New Zealand (such as Wairarapa) could experience more frequent, and potentially more severe, droughts.

In summary, it is likely that the east of Wellington region could experience increased drought risk through a combination of higher temperatures, reduced mean rainfall, a changed rainfall distribution (possibly fewer raindays but more rain per rainday), and more westerlies.

12.2.3 The coastal erosion risk

Generic descriptions of possible global-warming effects on shoreline stability for different types of coastal morphology are given by Bell *et al.* (2001). Based solely on sea-level rise, present beaches which are in dynamic equilibrium or eroding are likely to experience increased rates of erosion. Accreting coasts are likely to continue to build seawards, but at a slower pace. Gravel beaches will continue to roll back, but build higher berms. However, sea-level rise is only part of the story.

Coastal shoreline stability is governed by a complex mix of various drivers, such as tides, storms, waves, winds, sediment supply, coastal currents, besides sea-level rise. Further, global warming is likely to modify many of these drivers (apart from tides), some towards a more erosive beach state, while other changes may ameliorate the potential erosion from just sea-level rise. The largest changes to drivers of coastline state will probably in sediment supply to the coast (through changes in river sediment exports and cliff erosion), and changes in wave climate (direction and height). Cliff erosion is unlikely to accelerate directly as a result of sea-level rise, because the process is largely one of erosion at the toe de-stabilising the entire cliff face. However, changes in storminess or waves due to global warming may speed up the process of toe erosion.

Subtle changes in wave climate at decadal timescales are thought to be part of the reason for the onset of erosion along parts of the cuspate foreland centred on Paraparaumu in the wave shadow of Kapiti Island (Gibb, 1978; pers. comm.).

Detailed research by NIWA on beaches on the northeast coast of the North Island suggests a strong connection between the 20 to 30 year IPO cycles and shoreline erosion. Beaches were generally in a healthy state since the late 1970's, following the change to the positive phase of the IPO (Figure 12.2) accompanied by more frequent and persistent El Niño events. However, since 1998 when the IPO switched to a negative phase, beaches on the northeast coast of the North Island have cut back substantially. Hints of similar behaviour are seen in the beach along the coastal road south of Eastbourne. After a period of several years accretion, following the placement of protection works along parts of the road, the beach has now eroded back to the protection works in the last year or so (A. Bannatyne, pers. comm.).

Further work is needed to establish the extent of an IPO pattern on coastal erosion around the Wellington region's shoreline, before the fluctuating inter-decadal risk can be quantified. Some decades are more likely to have a higher risk of erosion, than in other decades, when climatic cycles are more favourable for beach building. There is also likely to be substantial differences between the response of east coast versus west coast shorelines in terms of erosion and any connection with the IPO cycle. If coastal erosion does operate at 20-30 year cycles aligned somewhat with the IPO, then the risk may well be heightened over the next few decades for the east and south coast (but we are unsure about the west coast).

The direct effect of sea-level rise on coastal erosion is not expected to feature prominently for 40 to 50 years, when sea level is projected to be around 0.14–0.18 m higher (*Bell et al*., 2001). In the meantime, the combination of 2 to 5 year El Niño-Southern Oscillation and inter-decadal cycles in climate are likely to be the backdrop that will exacerbate coastal erosion hazards around the Wellington region over particular periods of years to decades.

12.2.4 The variability of sea-level

Sea level is rising around New Zealand, starting around the early to mid part of the 1800's. In Wellington, the historic rate of rise has been around 1.7 mm/yr or approximately 0.2 m over the past 100 years up to 1988 (Hannah, 1990). 1.7 mm/yr is the average across New Zealand based on Hannah's analysis of tide-gauge data from the four main ports. This value also lies mid-way in the range of estimated global sea-level rise of between 1 and 2.5 mm/yr since the early 1800's.

When it comes to the risks associated with sea-level rise, the quantity of primary interest is the sea-level rise *relative* to the landmass that the tide gauge sits on. In particular, if the landmass is subsiding, then the relative sea-level rise is higher than the absolute sea-level rise. It is unclear, as yet, what the relative sea level rise is at Wellington (i.e. relative to the landmass). A research monitoring project is underway to determine the variation and change in the vertical position of the land at a number of ports with fixed GPS sensors and more determined efforts to tie gauge benchmarks back to a solid landmass rather than reclaimed land or a wharf, such as in Wellington (K. Berryman, GNS, pers. comm.).

There is no sign yet of any definitive acceleration in the rise of sea level from any New Zealand sea-level gauges. However, the Third Assessment Report of the IPCC is predicting a slowly increasing acceleration over the next 50 years and beyond.

The 20 to 30 year IPO cycle changed in 1998 to a negative phase. This will bring more balance between El Niño and La Niña episodes and exhibit a quicker rate of sea-level rise than that experienced over the previous positive phase of IPO from 1976 to 1998. This pattern of a quicker sea-level rise during negative phases of the IPO has been demonstrated from the Port of Auckland tide-gauge record (Figure 12.6). A similar analysis should be undertaken for the Queens Wharf tide-gauge record from Wellington Harbour. It is possible that a similar trend is occurring around the southern North Island, in which case the next 20 to 30 years should see a faster rise in sea level than the mean long-term trend of 1.7 mm/yr.

Global projections of sea-level rise by the latest 2001 IPCC Third Assessment Report are likely to be similar to the rise of relative sea level around New Zealand, given on historic similarities between the New Zealand average compared to the global average of around 1.8 mm/yr.

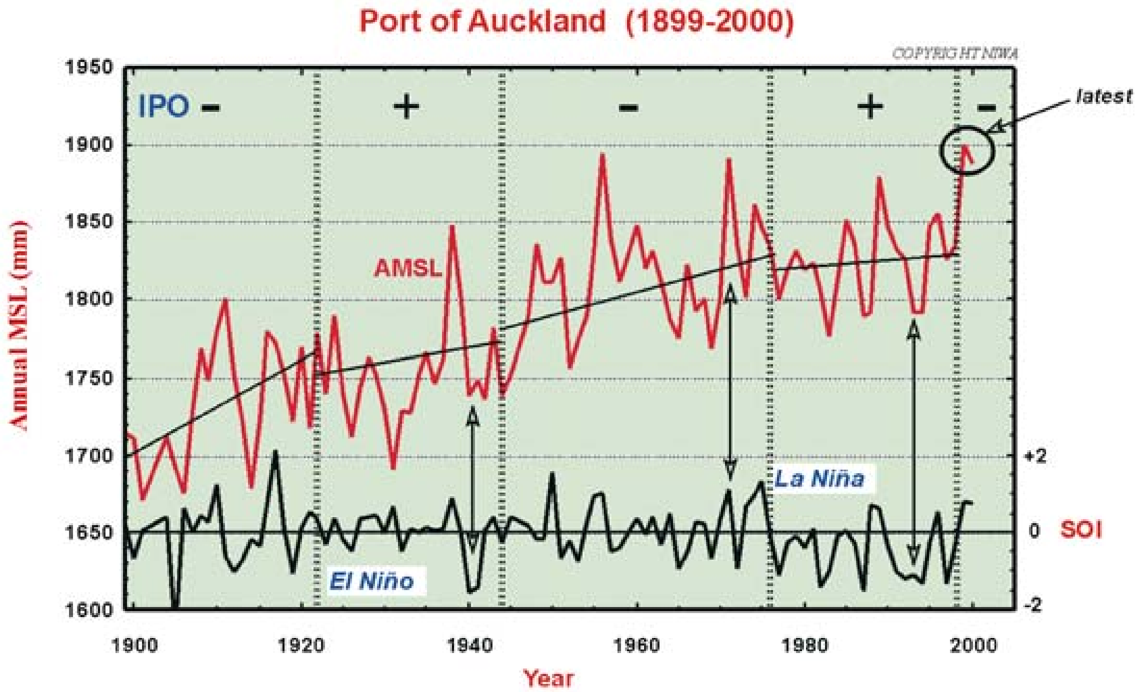


Figure 12.6: Annual mean sea level from the Port of Auckland since 1899 up to 2001, compared with the annual mean Southern Oscillation Index. Vertical bars indicate the switch in phase of the Interdecadal Pacific Oscillation (IPO). The mean trend overall in sea level at Auckland has been 1.4 mm/yr, while in Wellington it has been slightly higher at 1.7 mm/yr. *Data sources:* Ports of Auckland Ltd., Prof J. Hannah (Otago), NIWA.

Table 12.1: Most-likely sea-level rise projections for the Wellington region based on IPCC projections and converted to Wellington Vertical Datum–1953. Copyright NIWA.

Year	Sea-level rise above 1990 levels (m)	Projected mean level of the sea (m WVD-53)
Present (up to 1990)	–	0.12
2050	0.14–0.18	0.26–0.30
2100	0.3–0.5	0.42–0.62

The mean level of the sea (MLOS) over the past two decades at Queens Wharf has been 1.03 m above the tide gauge zero or 0.12 m above Wellington Vertical Datum 1953 (WVD-53). A "most likely" estimate for sea-level rise around the Wellington region by 2050 and 2100 is summarised in Table 12.1. These values are based on mid-range IPCC projections (see Table 1 of Bell *et al*., 2001), and assume no ongoing trend in vertical movement of the landmass. There is a small chance that sea level might rise by up to 0.88 m in the year 2100, which would reach 1.00 m above WVD-53.

In terms of monitoring in the Wellington region, NIWA operates two open-coast sea-level gauges at Kapiti Island on the west coast (commenced in July 1997) and Riversdale on the east coast (commenced in August 1997). These gauges will provide complementary data to the Queens Wharf tide gauge operated by the Wellington Regional Council. These three gauges could provide strategically important sea-level data to monitor local and regional changes in relative sea-level rise, provided accurate survey control is implemented at each site.

Sea-level rise will not be a "temporary" aberration, but will continue for several centuries even if greenhouse-gas emissions are curtailed somewhat.

12.2.5 The severe wind risk

Under global warming the mean westerly wind component across New Zealand is expected to increase by approximately 10% of its current value in the next 50 years (Mullan *et al*., 2001b). This "mean westerly" is composed of individual days where the actual wind is sometimes westerly and sometimes easterly. Thus, as with other climatic elements, changes in the mean do not translate easily into changes in extremes.

Strong winds are associated with intense convection (expected to increase in a warmer climate) and with intense low pressure systems which might also become more common (see extra-tropical cyclones below). Thus an increase in severe wind risk could occur. Indeed, Knippertz *et al.* (2000) identified an increasing number of strong wind events over the North Atlantic in their climate model simulation, which they relate to the increasing number of intense cyclones.

In summary, while an increase in severe wind risk may occur over the Wellington region during the coming century, this is by no means certain, and it is not yet possible to quantify the likely change in risk. This is an area requiring further research.

12.2.6 The extreme temperature risk

Higher mean temperatures obviously increase the probability of extreme warm days and decrease the probability of extreme cold days. The IPCC also notes that climate models forecast a decrease in diurnal temperature range at many locations (Cubasch *et* *al*., 2001); that is, the night-time minimum increases faster than the day-time maximum. Salinger and Griffiths (2001) show clear evidence of decreasing numbers of frost days in the past record at many New Zealand sites. The evidence for increasing numbers of very warm days is less clear, with regionally varying patterns that can be related to circulation fluctuations.

Changes in New Zealand extreme temperatures have been examined by Mullan *et al*. (2001a) using the CLIMPACTS framework. In this approach, a number of global emission scenarios are linked to a number of downscaled GCM patterns of New Zealand change. At individual sites, a weather generator (that simulates daily sequences of maximum and minimum temperature and rainfall) is run for ranges of future climates. Figures 12.7a,b show projected changes in high and low temperature extremes, respectively, taken from Mullan *et al.* (2001a). The emissions scenario used here is the SRES A1 scenario, with an assumed mid-value for the global climate sensitivity to greenhouse gases (i.e. 2.5 °C equilibrium global temperature increase per doubling of carbon dioxide). Mullan *et al.* (2001a) give further results for scenarios that are more extreme and less extreme than the one reproduced in this report.

Figure 12.7a indicates large increases in the number of warm days in the lower North Island, with bigger increases in the Wairarapa than in the west of the Wellington region. The exact value depends on the climate model used. As a benchmark, Masterton currently experiences about 37 days per year (December through March) with daily maximum temperatures above 25 °C. Figure 12.7a suggests at least a 50% increase in the number of such warm days by 2100.

Figure 12.7b shows corresponding changes in days below 0°C. The contoured values are negative, meaning fewer frost days everywhere. Both climate models are in good agreement here, indicating about 10 fewer frost days per year by 2100 in the Wellington region, for the mid-range scenario. For comparison, Masterton currently experiences about 26 days per year with daily minimum temperatures below freezing. Note also that these figures were produced by contouring output from the CLIMPACTS weather generator at specific sites. There is a general tendency for a bigger reduction in frost days at the colder (South Island) sites, even though the projected mean warming is less here. Reductions of more than 10 days per year in frost occurrence would also be expected at colder, higher altitude sites (e.g. Tararuas) in the Wellington district, which were not part of the CLIMPACTS dataset.

Increasing temperatures have implications for human comfort and effects on agriculture and the economy of the Wellington region. On hot summer days, human comfort is affected by the amount of moisture in the air as well as the temperature. These two factors are taken account of in the "heat index", which can increase more than the temperature alone (Delworth *et al*., 2000). Changes in heating and cooling degree days are another extreme temperature-related effect of global warming.

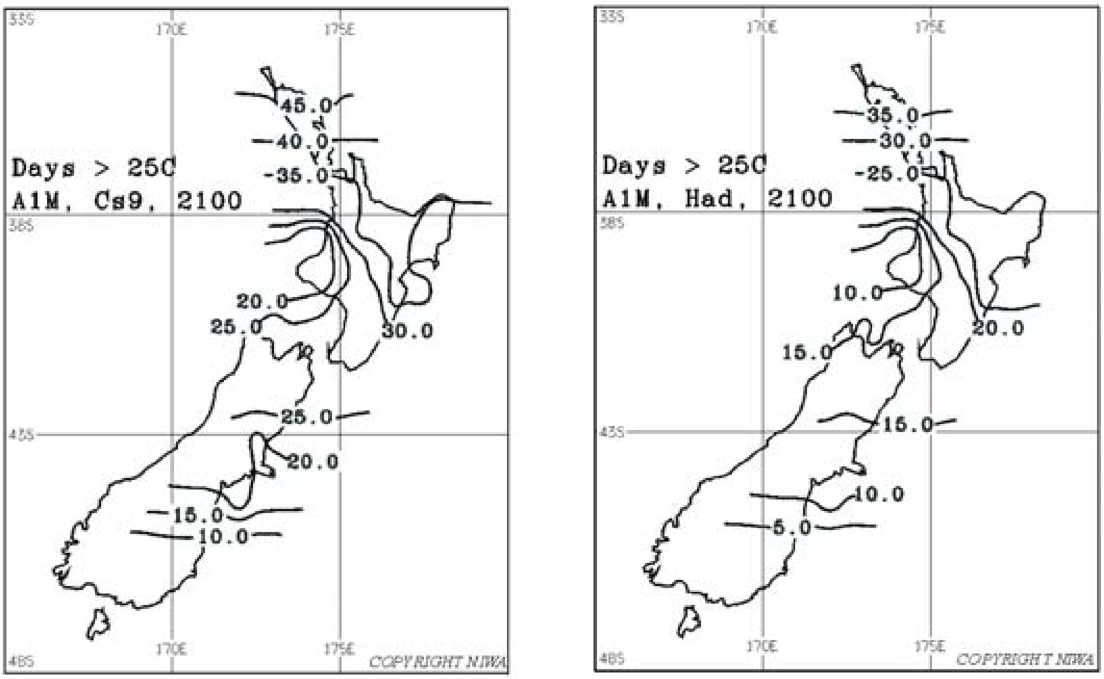


Figure 12.7a: Change between 1990 and 2100 in the number of days per year above 25°C, for the SRES A1 mid-sensitivity emission scenario, and for the HadCM2 (left) and CSIRO9 (right) global climate models. Contours are at 5-day intervals. Source: Mullan *et al.* (2001a).

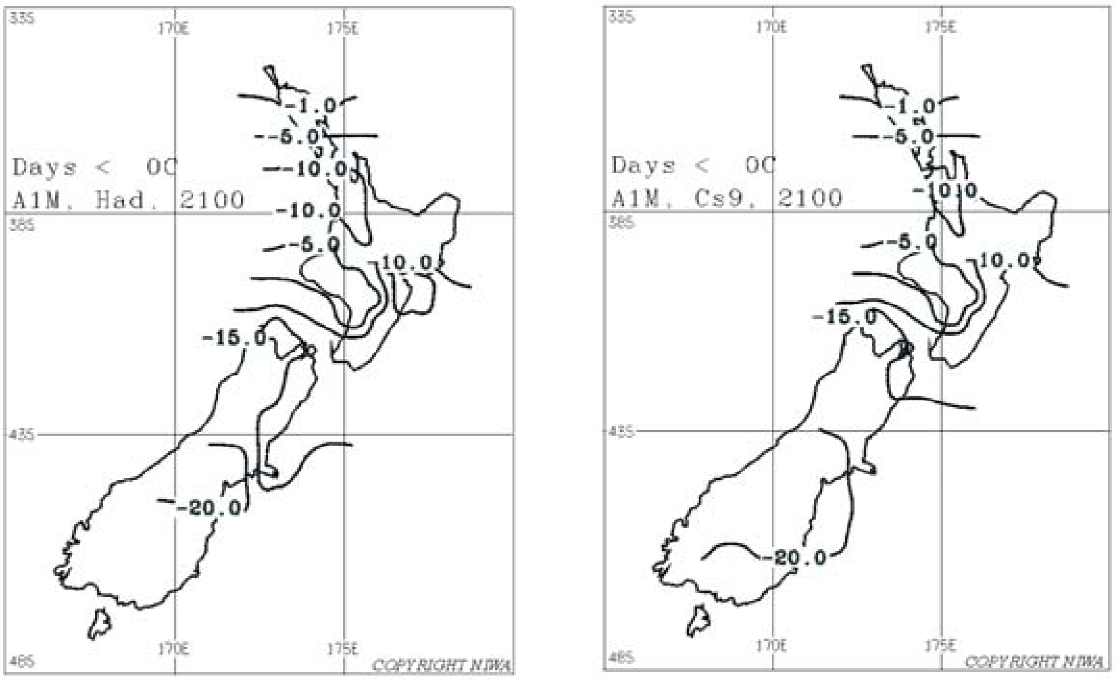


Figure 12.7b: As for Figure 12.7a, but for change in number of days per year below 0°C. Contours shown for –1 day, and then at 5-day intervals from –5 days.

12.2.7 The lightning/hail risk

Lightning and hail are small-scale phenomena, very sporadic in time and space, and it will be difficult to establish statistically significant changes in their frequency. However, both lightning and hail are associated with intense convection, which is generally expected to become more frequent in a warmer and moister atmosphere because of increased latent heating (although the climate models do not simulate these features directly).

The IPCC Working Group I Third Assessment report (in section 9.3.3.6) points to some studies from the 1990s which suggest an increase in lightning and hail occurrence is likely with global warming. The Working Group II report (section 8.2.3) notes a study suggesting a 1°C increase in average wet bulb temperature could be accompanied in mid-latitudes by a 40% increase in lightning. Nevertheless, Working Group I of IPCC concludes that definitive conclusions cannot yet be drawn concerning possible future changes in hail and lightning.

12.2.8 The ex- and extra-tropical cyclone risk

The IPCC Third Assessment indicates that by the end of the 21st century, it is likely that in some regions the peak wind intensities in tropical cyclones will increase by 5-10% and peak rainfall intensities by 20-30%. Of course, tropical cyclones have changed their characteristics by the time they reach New Zealand, and very few of those affect the Wellington region (see section 10). We also know that during El Niño periods, tropical cyclones tend to track further east in the South Pacific with fewer of them travelling towards New Zealand. Many climate models show an El Niño-like change in the mean state of the tropical Pacific over the next 50 years. However, whether or not this decreases the likelihood of ex-tropical cyclones reaching central New Zealand is not yet clear. There are no research results yet which draw implications from this regarding the wind and rain intensities in ex-tropical cyclones that reach New Zealand's latitudes. However, consideration should be given to the consequences of living in an environment of more severe weather.

Mid-latitude storms (also known as *extra*-tropical cyclones) derive their energy from two sources: the large-scale meridional temperature gradient and the condensation of moisture. Global warming therefore has the potential to alter the intensity or frequency, or both, of extra-tropical cyclones. However, relatively few analyses of model simulations have been done, and there is no general agreement on future change in mid-latitude storms. Carnell and Senior (1998), in a study over the Northern Hemisphere, found a reduced total number of cyclones but a greater number of very intense lows. They attributed these two apparently contradictory changes to a reduced equator-North Pole temperature difference (reducing total numbers), but increased latent heating in a moister atmosphere (more intense convection).

In the Southern Hemisphere, both the energy sources (meridional temperature gradient and latent heating) are predicted to increase under global warming. It would therefore be reasonable to infer that "more storminess" was likely. Unfortunately, the only analysis of Southern Hemisphere changes in GCMs that is available (Sinclair and Watterson, 1999) was done for the previous generation of equilibrium climate models where the meridional temperature gradient (and westerlies) weakened. These results are therefore not relevant anymore, because the latest transient, or coupled ocean-atmosphere, models indicate an increase in the mean westerly flow associated with an increase in the temperature gradient between equator and high southern latitudes.

While it therefore appears likely that "storminess" will increase in the Southern Hemisphere this century, we cannot yet say whether this would mean more intense storms, or a higher frequency of passing cold fronts, or some combination of these. Moreover, a general increase in storminess across the Southern Hemisphere as a whole does not necessarily imply an increase locally in the small sector of the hemisphere that New Zealand occupies. The regional changes would be sensitive to changes in prevailing wind strength and direction, which vary considerably between models. Such an analysis requires processing large quantities of daily data from climate model runs, and is a topic identified by NIWA for future research.

There is probably some decadal variability in extra-tropical cyclone frequency over New Zealand, although existing studies do not cover a long enough data period to establish this. Sinclair *et al*. (1997) analysed daily pressure fields over the period 1980-1994, and showed that during El Niño events, a reduced number of low-pressure systems pass across the North Island.

12.2.9 The wildfire risk

Wildfire risk is clearly related to drought risk, and additionally can be aggravated by strong winds and lightning occurrence. Thus, it is possible that wildfire risk might increase over the next 50 years, particularly in the drier eastern parts of the Wellington region. Because of the uncertainties already referred to regarding strong winds, lightning, and drought we cannot yet quantify the likely future change in forest fire risk.

12.3 Impacts and Consequent Changes

12.3.1 Wellington Regional Council activities

- Civil Defence and Emergency Management
  Under the Civil Defence and Emergency management legislation currently before Parliament, the Wellington Regional Council will be the administering authority for a CDEM (Civil Defence and Emergency Management) Group which will involve constituent local authorities, the NZ Police, the NZ Fire Service and District Health Boards. A key task for this group will be developing a CDEM plan which will state and provide for (amongst other things) the hazards and risks to be managed by the Group, and the civil defence emergency management necessary to manage these hazards and risks.

This plan is likely to focus mainly on current risk levels, including the risks from the main climate-related hazards identified in earlier chapters of this report. However in developing this plan the CDEM Group should also take cognisance of the expected future increase in the frequency or magnitude of some of these hazards, due to climate change. This applies particularly to the high rain / flood risk, the associated erosion risk, and the ex- and extra-tropical cyclone risk. Background on the formation of CDEM groups and development of CDEM plans is provided in the two Ministry of Civil Defence and Emergency Management reports listed in the bibliography for this chapter. More comments on the development of a CDEM plan are provided in Chapter 13.

- Water Supply and Regulation

  Monitoring undertaken by the WRC suggests that generally there is enough water available to meet the full range of community needs. There are, however, occasional shortages due to natural climate variations and these shortages highlight the need for the community to be prepared for water shortages. The possibility of lower rainfall, induced by climate change, in some areas of the region could increase the frequency and duration of these water shortages in the next 50 years and therefore competition among water users.

  The WRC has undertaken work to develop drought-forecasting techniques and to implement water conservation initiatives to help the region be prepared for water shortages. WRC takes a very regulatory approach to the management of groundwater. This is necessary because adverse effects on groundwater can be long lasting, even irreversible. Climate change could result in rising sea levels making groundwater aquifers near the coastline vulnerable to saltwater intrusion, and also give a reduction in recharge due to possible lower rainfall in some areas. The most vulnerable areas, and the timescale for changes, still need to be assessed.

- Flood Protection

  Tolerance for the effects of climate change are built into design specifications for flood protection works based on the existing knowledge of climate change impacts e.g. the actual rise of sea level, and the projected life of the protection works. Most flood protection structures are designed to withstand a 1 in 100-year flood event. At the design stage a 'freeboard' of between 600 and 900 mm is added to floor levels and stop bank height to allow for uncertainties. Such uncertainties may include larger floods, rapid bed level aggradation, flow modelling inaccuracies, and sea level changes.

  Throughout the life of flood protection works, a maintenance programme of gravel extraction and asset management is undertaken. Hydrological data is collected from rain and river flow gauges to refine hydrographic models of major rivers every ten years or after a major flood event. A survey of bed levels is undertaken every five years to monitor gravel extraction requirements and update flow models. After each damaging flood event flood protection structures are repaired to the designed level. Expected climate change with an increase in the magnitude and frequency of high intensity rainfall events could increase the number of significant flood events in the next 50 years, which would in turn require increased maintenance to ensure the integrity of protection works is retained.

- Pest Control
  The WRC is responsible for controlling a number of plant and animal pests in the region and has management strategies in place. Changes in temperature and rainfall regimes brought about by climate change may cause problems for these eradication programmes. New species may enter the region, or those currently localised to small areas may spread to a wider coverage. A change in vegetation, or increased vegetation fruiting, may lead to population explosions of pest animals.

- Sustainable Land Management
  The WRC promotes soil conservation and sustainable land use throughout the region in an effort to manage the physical loss of soil through erosion. Approximately 184,000 ha of land have been classified as being in need of soil conservation measures in the Wellington region. Green (1999) estimates that a worst case scenario of a 20% increase in rainfall across the entire region could qualify an additional 32,000 ha of land for soil conservation measures, as they would be subject to even more severe slippage or erosion than experienced under current rainfall regimes. However, a blanket increase in rainfall such as this is not predicted – there are expected to be decreases in some eastern areas and increases in some western areas. Further work is needed to identify land that could become susceptible to failure and erosion under the areas of increasing rainfall, and likewise for land that may move out of the susceptible category given a decrease in rainfall.

  In areas where an increase in rainfall is predicted, it is likely that erosion would increase with resulting reductions in water quality and productive pasture base, increases in damage to roads and other utilities, and increased sedimentation in rivers on adjacent land.

12.3.2 Lifeline utilities and services

Based on the possible increase in frequency and intensity of extreme weather events, the biggest threat to lifelines and services is likely to come from heavy rainfall and associated floods and erosion. Increased peak flows in urban catchments will put pressure on stormwater and wastewater infrastructure. Lifelines and services that are currently near riverbanks are also likely to become more prone to floods. Structures such as bridges may need to accommodate higher flood peaks in their design.

Lifeline utilities and infrastructure throughout the region will be exposed to a higher risk of landslides than currently if the frequency and intensity of heavy rainfall episodes increase. As described earlier in this report, landslides in the Wellington region can occur when due to short duration intense rainfall and also due to a longer period of above average rainfall.

Potential increases in heavy rainfall could cause more erosion above and below road cuttings and lead to more frequent repair work. However, a road such as the Rimutaka Hill road could incur less winter maintenance costs due to less snowfall.

Areas near the coast may become increasingly prone to erosion due to rising sea levels. There is potential for considerable damage to the region's low lying coastal settlements and infrastructure where population, tourism, and capital investment are large and predicted to expand. Infrastructure such as roads, bridges, water mains, stormwater and sewerage systems needs to be assessed to determine its suitability, with respect to location and future operating potential. Rising sea levels will increase the risk of storm surges leading to breaches of sea defences and coastal flooding.

An increase in drought conditions may result in increased competition for water uses between agricultural irrigation, domestic and industrial use. Water supply to the four territorial authorities of Upper Hutt, Lower Hutt, Porirua and Wellington cities is collected and distributed by WRC. WRC has put much work into predicting future water use to guarantee supply for the years to come. Problems have arisen on the Kapiti Coast during recent droughts when demand has exceeded what can be supplied from current sources.

The Wellington and Wairarapa Engineering Lifelines Associations, comprising local territorial authorities and utility organisations, have been set up to collect information on all hazards impacting engineering lifelines in the region. These groups assess the relative risk of different hazards (including meteorological as well as other hazards), determine the potential level of damage and disruption, and draw up plans to optimally manage the impact of the hazard.

12.3.3 Biodiversity and indigenous ecosystems

In the future, the biota in the Wellington region may face a greater rate of long-term climate change than has occurred throughout New Zealand's history of human habitation. Eecosystem response would occur in a landscape that is already highly altered and fragmented by non-climatic pressures from human settlement. Most of the major transformations of vegetation cover in the past few hundred years have resulted from either the indigenous vegetation being cleared through logging or fire, or from the spread of introduced weeds and herbivores such as possums (McGlone, 2001). As the climate continues to warm these disruptive influences will become even more severe as natural protection mechanisms of ecosystems are progressively affected by changing climatic conditions.

Changes in soil characteristics, water and nutrient cycling, plant productivity, species interactions (competition, predation, parasitism etc), and the composition and function of ecosystems are highly likely responses to increases in atmospheric CO_2 concentration and temperature, and shifts in rainfall regimes. These changes would be exacerbated by any increases in fire occurrence and insect and weed outbreaks. Aquatic systems will be affected by disproportionately large responses in runoff, river flow and associated nutrients, wastes, and sediments that are likely from changes in rainfall and rainfall intensity, and also by sea level rise in estuaries and other low lying coastal areas.

More frequent fruiting of beech trees and tussock after a warmer than average summer could provide a more reliable food source for mice and rats, which in turn could boost the numbers of stoats and cats with detrimental flow-on effects on endangered bird populations (McGlone, 2001).

Many of the potential changes in aquatic ecosystems under climate change start with the effects on surrounding vegetation and altered amounts of runoff to streams and rivers. Freshwater ecosystems will be impacted by higher temperatures which will affect lake mixing and associated eutrophication processes, decrease the available habitat for native species, and increase the habitat and growth of undesirable exotic species. Climate change is also expected to bring about changes in the magnitude and seasonality of river flows, which will reduce the habitat for native species and increase nutrient loading, and the further loss of the region's wetlands and associated wildfowl populations.

The complexity of ecosystem dynamics makes the prediction of climate change impacts very difficult. Although the region's biota and ecosystems are well adapted to New Zealand's high climatic variability, it is unclear whether this will provide any natural adaptation advantage. Response of natural ecosystems is difficult to predict unless a species by species basis is adopted. Adaptability to climate changes is the factor that will determine the success of individual species. A great deal is known of the tolerance limits of many species in the Wellington region, but not all, and it is the interactions between these species that will determine an ecosystem's response to climate change as a whole.

Climate change will add to existing problems such as soil erosion and sedimentation under higher rainfall regimes and drought under lower rainfall (Pittock and Wratt, 2001). Increased temperature will increase the resources required to manage the expansion of tropical weed infestations and pest animals. Land use management techniques (e.g. modification of animal stocking rates, control of pests and weeds, changed forestry practices, plantings along waterways, and control of development in coastal areas) may be the best way managing this change.

Knowledge of climate change impacts on aquatic and marine ecosystems is relatively limited. The initial expansion of coastal wetlands may provide habitats for many plants, animals and wading birds although saltwater intrusion into dominantly freshwater areas may initiate habitat loss. The extent to which this will occur and to which humans modify land close to the sea will determine the extent to which wetlands adapt to sea level rise and is one example of how research, monitoring, and both climatic and ecological prediction will be necessary for management of ecosystems under a changing climate.

12.3.4 Agriculture, horticulture, and forestry

The agricultural sector has substantial opportunities for productivity gains and diversification under climate change, but also faces some long-term risks (MfE, 2001).

The most significant risks are associated with the potential increases in the number of extreme events (Kenny, 2001) such as droughts and floods, causing more damage and reducing recovery time for farmers. The generally drier conditions projected for the Wairarapa mean that water could become a more limited resource in some areas, and competition between agriculture and other water users could increase.

Changes in temperature and rainfall regimes that affect the suitability of districts for particular crops, changes in crop and pasture performance, changes in soil fertility, stock health issues, and problems with weeds, pests, and diseases are likely to be the most significant effects on agriculture and horticulture of climate change. Impacts will vary widely between districts, crops, and decades, as the change in climate becomes more pronounced.

Any changes in global production, and therefore international food commodity prices, would have major impacts on locally grown produce.

An increase in temperature combined with changes in the amount and distribution of rainfall could affect the timing of agricultural activities, the production of a farm unit, or even its land use. In the future fewer frosts may mean that a particular area is no longer suitable for growing a particular fruit crop, or may increase opportunities for growing other crops.

Any increase in temperature could lead to lower stocking rates on beef and sheep farms with a corresponding drop in production (Green, 1999). As this trend continues, beef will be favoured over sheep as they are more suited to higher temperatures.

Changes in climate will affect the performance, and therefore suitability, of a particular crop for a given piece of land. If agriculturists and horticulturists operate within the sustainable parameters of their current land use they will be better placed to deal with the effects of climate change.

Farmers and horticulturists need to be aware of changes in climate, as well as the state of the market, to enable them to make quality decisions on stocking rates and herd compositions, and crop choice respectively.

Indigenous forests cover approximately 20% of the land area of the Wellington region, with exotic forest covering another 5%. Changes in rate of tree growth, forest biomass, geographical range and species composition, exposure to pests and disease, and changes in fire frequency are all effects that forest may experience under changing climate.

A number of benefits have been suggested for production forestry due to an increase in temperature and CO_2 concentrations such as an increase in growth rate and wood density. However, higher temperatures may also increase the occurrence of damaging conditions such as upper mid-crown yellowing under dry conditions and fungal diseases in warmer winters.

A negative impact of climate change on plantation growth rates could lie in changes in rainfall patterns (MfE, 2001). Radiata pine requires about 1500 mm of annual rainfall for optimal growth, and drier areas in the Wairarapa could experience growth reductions under projected decreases in total rainfall. However, this reduction could be offset by increased water efficiency of trees under increased levels of CO_2.

Under climate warming, most indigenous forests would extend their ranges south and upwards to higher elevations. An increase in temperature and frequency of storm events may lead to an increase in some tree funguses and pests and wind-throw damage to forests. Slowly maturing trees of indigenous forests may suffer dieback and invasion of exotic weed species and therefore be more vulnerable than other plants to long-term climatic change.

12.4 Knowledge Gaps

Scenarios have been developed for changes in *mean* climate, particularly for temperature and precipitation, based on statistical downscaling from the latest coupled ocean-atmosphere climate models. The CLIMPACTS system has been used to assess some changes in extremes, especially as related to temperature. However, there is a need for considerably more work on quantitative estimates of changes in extreme rainfall and other climate elements.

Change in annual runoff, changes in frequency and length of dry periods, and changes in heavy rainfall and return periods, are all topics deserving further investigation. NIWA is planning to address this knowledge gap over the next 2-3 years through regional climate model simulations. Potential changes in other climate elements such as winds and storms will also be examined with high resolution daily simulations over the New Zealand region.

However, all these regional simulations will be predicated on a particular driving *global* climate model, so the results can only be indicative. We already know that the projected circulation and climate changes can differ considerably between models, and this will remain a limitation for many years. Ultimately, one might anticipate a probabilistic forecast of climate change, in the same way that seasonal forecasts are expressed now.

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13. Hazard Assessment and Risk Management

13.1 Comparison of Meteorological Hazards with Other Hazards

Between 1968 and 1997 a total of $1.05b (adjusted to 1997 dollars) was paid out by the insurance industry for claims throughout New Zealand associated with natural hazards. Of these claims, 30% of the total payments were associated with the earthquake at Edgecumbe, Bay of Plenty on March 2nd 1987. The remaining 70% of payouts were due to *weather related natural hazards* (Figure 13.1). Of these, the largest single events were the 1984 Invercargill flood ($94m) and the 1976 Wellington flood ($42m). There were over a hundred other events, most of which caused damage in the order of $5m.

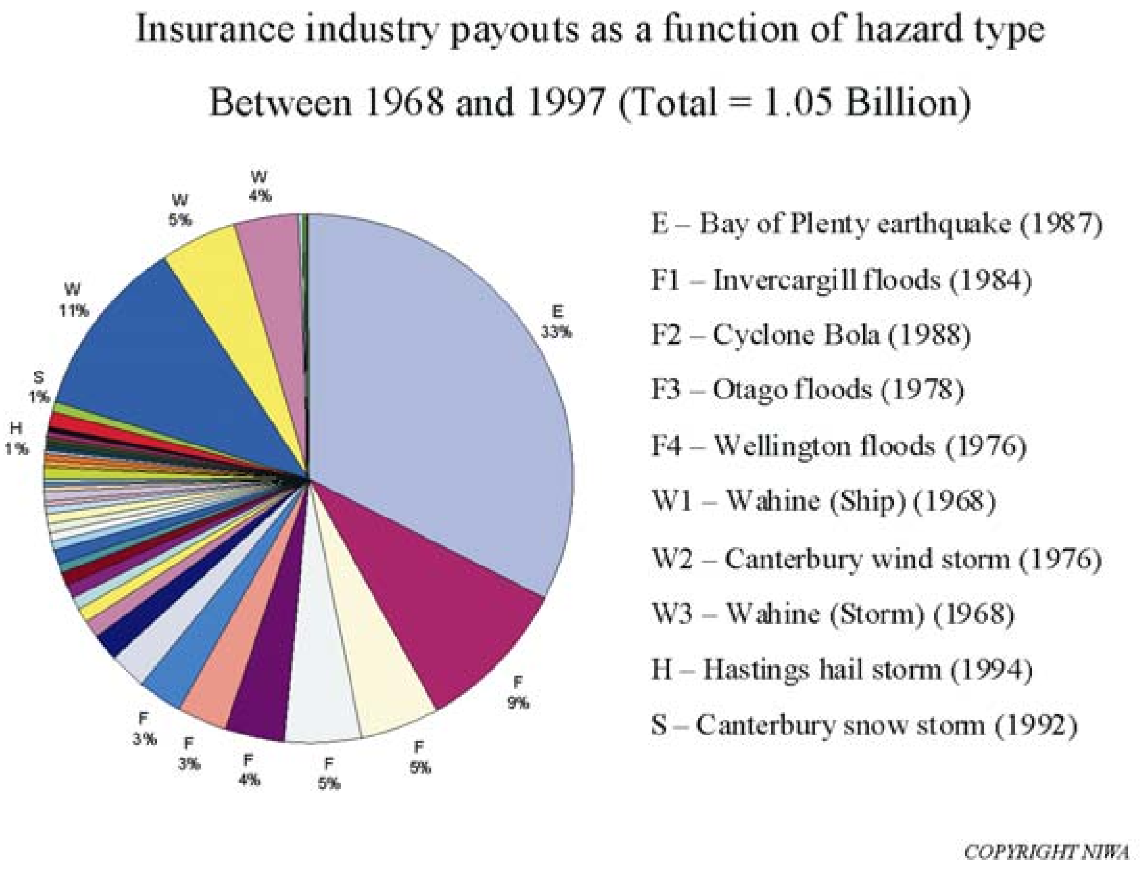

Figure 13.1: Distribution of insurance industry payouts (adjusted to 1997 dollars) between 1968 and 1997. F1 through F6 (i.e. Flood 1 through Flood 6) proceed clockwise around the bottom of the chart. Likewise, W1 through W3 (i.e. Wind Storm 1 through Wind Storm 3) proceed clockwise around the top left of the chart.

The above analysis clearly shows that earthquakes are by far the most costly (and by inference, the most damaging) individual natural hazards in New Zealand. A major flood, by comparison, is about a third to a tenth as damaging. However, the frequency of events must also be considered. In this example, over 50% of all the insurance payouts for this period were due to relatively frequent events like 1-in-5 year floods and wind storms, whereas there was only major earthquake during the period (and none since then).

It is hypothesised that the frequency and magnitude of meteorological hazards is similar to that of technological hazards, such as accidental cuts in the power or gas supply, telecommunication outages due to instrumentation failure or water or sewerage system breakdowns. In general, these hazards can be categorised as occurring relatively frequently and causing small to medium scale damage and inconvenience, with the occasional large impact event once in every twenty-five years or so.

13.2 Civil Defence and Emergency Management

Under the Civil Defence and Emergency Management legislation currently before Parliament, the Wellington Regional Council will become responsible for administering a Civil Defence and Emergency Management (CDEM) Group. This Group will be expected to develop a CDEM plan.

The Ministry of Civil Defence and Emergency Management have produced an information document for local government, outlining the expected structure and content of CDEM plans ((Ministry of Civil Defence and Emergency Management, 2000). Such plans will contain a strategic section, which identifies the hazards and risks for the CDEM Group Area, identifies key issues, and establishes key actions to address risks across the 4 R's (reduction, readiness, response and recovery).

The information provided in this meteorological hazards report will help the MCDEM Group prepare the necessary material on hazards and risks for this strategic section. The Ministry defines *risk* as the chance of something happening that will have an impact on objectives, and says it is measured in terms of *likelihood* and *consequences*. This report, through the information it contains on the magnitude and probability of hazards, provides input on the *likelihood* component. However the CDEM Group will also need assessments of the *consequences* of meteorological and climate-related hazards, a subject outside the scope of the current report. Understanding the likely consequences of a hazard event requires detailed analysis into areas such as the economic, social, cultural and demographic characteristics of at-risk communities.

Once the *consequences* of these climate and weather related hazards have been identified, the Group will be able to *prioritise* the resultant risks alongside those posed by other natural (e.g. earthquake) and technological (e.g. accidental release of hazardous material) hazards. This is a further necessary step in identifying and recording the key hazards within an MCDEM plan.

13.3 Bibliography

Ministry of Civil Defence and Emergency Management, 2000. Civil Defence Emergency Management Plans - Information for Local Government. Available from the Ministry of Civil Defence and Emergency Management website http://www.mcdem.govt.nz.

14. Glossary

Advection–A term referring to the horizontal movement of air. An "advection fog" is one that rolls into an area.

Aerosols–Particles in the atmosphere such as soot and dust.

Anemograph–A recording anemometer for measuring wind speed.

Anomaly maps–These are maps of specific climate variables (like pressure or temperature) after the mean value has been removed. Thus, an anomaly map will show patterns that are different from normal conditions.

Anthropogenic–Caused by humans (e.g. anthropogenic climate change is the result of increased burning of fossil fuels).

Anticyclones–Regions of high atmospheric pressure usually represented by an "H," associated with sinking air and settled weather. Also known as "highs."

Atmospheric waves–Large-scale wind flows often have wave structures. For example, the circular wind belt that flows around the Antarctic continent (called the circumpolar vortex) may have between two and seven pairs of ridges and troughs in it so that the flow alternates between southwesterly and northwesterly rather than consistently from the west.

Autumn–The season consisting of the months March, April and May.

Average recurrence interval–Abbreviated **ARI**. The average length of time expected for a particular size of event to recur. For example, a 50-year flood is that height of floodwaters that is reached *on average* only once in every 50 years.

Catchment–An area of land where all rain that falls within the catchment runs off into the same stream or river.

Convective rainfall–Caused when intensive surface heating forces the air just above the surface to rise and become unstable.

Convergence zone–A zone where two air parcels, potentially of different temperatures and moisture characteristics, converge. This can sometimes be a frontal boundary, and hence is often associated with unstable conditions and unsettled weather.

Cryosphere–Those parts of the world covered by ice or snow.

Cumulonimbus clouds–Tall thunderstorm clouds that can produce very heavy rain or hail. Often have an "anvil" shape to the tops where the wind speed is greater than at the surface.

Defensible Space–Any area between the built and natural environment that will not carry fire, and may include firebreaks, mowed grass, paths or roads.

Depressions–Regions of low atmospheric pressure usually represented by an "L," associated with rising air and unsettled weather. Also called "lows" or "cyclones."

Diurnal–Daily, as in the daily cycle of night following day.

Downscaling–The process of re-scaling of model output to a finer resolution grid.

Drainage wind–Air flowing down a valley (usually cold air during the nighttime) caused by density differences. Associated with katabatic flows.

El Niño–A term given to climatic and oceanic conditions when the SOI is strongly negative (less than –1.0), producing higher than normal pressure over the northeastern region of Australia and more westerly conditions than normal over New Zealand.

Engineering lifelines–Transportation networks, Communication networks, Water supply, Electricity and Gas supply, and Sewerage systems.

ENSO–El Niño Southern Oscillation. An oscillation in the ocean temperatures and surface air pressure between the western and eastern Pacific Ocean.

Eutrophication–The process whereby lakes or ponds become rich in mineral and organic nutrients that promote a proliferation of plant life, especially algae, which reduces the dissolved oxygen content and often causes the extinction of other organisms.

Evapotranspiration–The transfer of water from a plant, through evaporation and transpiration, to the atmosphere.

Ex-Tropical cyclones–Tropical cyclones that have developed in the tropics and have travelled outside the tropics.

Extra-Tropical cyclones–Cyclones that have developed outside the tropics.

Föhn wind–Generally a northwesterly wind that has come down over the mountains. The descending air has lost most of its moisture so is very dry and it also warms up as it descends. Föhn winds can also be called "snow eaters," "chinooks" or just "nor'westers."

GCM–Global Climate Model (also known as General Circulation Model). These are computer models that simulate the current climate and predict future climate. They require super computers to run them.

Greenhouse effect–The re-emission of heat given off by the Earth back toward the Earth's surface by greenhouse gasses in the atmosphere. These gases are mainly carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and water vapour. The greenhouse effect warms up the Earth's lower atmosphere.

Groundwater - Water beneath the earth's surface, often between saturated soil and rock, that supplies wells and springs.

Growing degree days–This is a somewhat confusing term, as the units are not days but rather degrees of temperature. It is an index based on the total number of degrees Celsius above a baseline temperature (e.g. 10 °C) for a year. It is used as an indication of the available heat for growing crops.

Hydrographic models–Computer models which describe the physical conditions, boundaries, flow, and related characteristics of the earth's surface waters.

IPO–Interdecadal Pacific Oscillation. This is a long-term (around 30-year) oscillation in the sea surface temperatures across the tropical Pacific Ocean.

Katabatic flow–Air flow down a slope (usually cold air drainage during the nighttime) caused by density differences (the colder air is denser, so it sinks).

Isobars–Lines of equal air pressure drawn on a map.

Landslide–The downward sliding of a relatively dry mass of earth and rock. Also called a landslip.

La Niña–A term given to climatic and oceanic conditions when the SOI is strongly positive (more than +1.0), producing lower than normal pressure over the northeastern region of Australia and more northeasterly conditions than normal over New Zealand.

Latent heat–The heat released into the atmosphere when water melts or evaporates, or the heat extracted from the atmosphere when water condenses or freezes.

Lee wave–A sinusoidal "wave" of air on the downwind side of a mountain range. The air comes down the mountain, and then rebounds up again.

Lenticular clouds–Lens-shaped clouds that form on the leeward (downwind) side of mountains on the cap of a lee wave.

Mantle–The layer of the earth between the crust and the core.

Meridional temperature gradient–The temperature difference between two locations on the same line of longitude, or meridian.

Meso-scale–100 km to 1000 km. Meso-scale weather phenomena include land and sea breezes and valley drainage winds.

Orographic enhancement–When air is forced to ascend over some hills or a mountain range it becomes unstable and rain and snow can begin or be enhanced.

Orography–The physical geography of mountains and mountain ranges.

Percentile–The 10 percentile value, for example, is the tenth value from the bottom in a ranked list of one hundred data elements (if there are only fifty elements in the list, the 10 percentile value is the fifth from the bottom). A percentile can be directly converted into a probability by using the formula: percentile = 1 in every (100 / percentile). For example, 20 percentile = 1 in every (100/20), or 1 in every 5.

Pressure–A measure of the "weight" of the air above any location, measured in hectaPascals (hPa) which are equal to millibars. The more air in a vertical column above a region the greater the air pressure. Differences in pressure drive the atmospheric circulation as air naturally wants to go from areas of high pressure to areas of low pressure (like the emission of air from a bicycle tyre when the valve is released).

Radiation fog–Forms on cold clear nights when the heat from the Earth (i.e. the radiation) is lost to space and the temperature of the surface rapidly cools. During cloudy nights less heat is lost to space, so radiation fogs are less common.

Return period–See 'Average recurrence interval'.

Ridge of pressure–An area of high pressure.

Seasons–The standard meteorological seasons, based primarily on surface air temperature, are: spring–September, October and November; summer–December, January and February; autumn–March, April and May; and winter–June, July and August.

Snowday–A day when some snow fell. This is the standard snow-related meteorological variable recorded by climate observers in New Zealand. The amount of snowfall is not recorded.

SOI–Southern Oscillation Index. The pressure difference between Tahiti and Darwin. Used as an index of the ENSO.

Soil moisture deficit–The number of days in a growing season when the amount of soil moisture in the root zone is insufficient for plant growth.

Specific heat–The number of thermal units (Joules) required to raise a unit mass (gram) of it through one degree (Celsius).

Spring–The season consisting of the months September, October and November.

Stable air–Conditions when the air is not rising or is sinking. Associated with calm conditions like cold winter nights in inland valleys.

Standard deviation–A statistical term used to show how much variability there is in a data set. If all the values in the data set are close to the mean, then the standard deviation is small. Alternatively, if the values are sometimes much greater than the mean and sometimes much less than the mean, then the standard deviation is large.

Stratiform clouds–These are clouds that cover all or almost all of the sky like a blanket (e.g. stratus). Associated with persistent, but not necessarily heavy rainfall.

Summer–The season consisting of the months December, January and February.

Thermal conductivity–The rate at which heat is transferred through a medium.

Tropopause–The upper limit of the lower atmosphere at around 10 km above sea level. The tropopause is defined by a temperature inversion with a deep isothermal layer above, and effectively caps our weather systems from any further vertical development.

Trough of pressure–An area of low pressure.

Unstable air–Conditions when the air is rising and mixing with the air above. Associated with unsettled weather like fronts and thunderstorms.

Vorticity–Refers to the curvature of an airflow. If an airflow curves clockwise it has cyclonic vorticity, and if it curves anticlockwise it has anticyclonic vorticity.

Weather generator–A computer model which simulates day-to-day weather.

Wind gusts–Extreme values of wind speed measured over three seconds.

Winter–The season consisting of the months June, July and August.