Assessment of the Effects of Large-scale Climate Oscillations on the Flood Risk in the Bay of Plenty

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Executive Summary

This report, prepared for the Bay of Plenty Regional Council, describes the main climate oscillations affecting New Zealand and the Bay of Plenty region and the impacts they have on rainfall, river flow and resulting flood risk.

To set context for this report, the rainfall regime of New Zealand is described, as well as recent trends in the Bay of Plenty rainfall record. Precipitation in the region is highly variable spatially and this should be taken into account when considering longer term planning. Likewise, it is important to look at seasonal data when predicting New Zealand climatic variability instead of only considering annual values to account for temporal variability. As total rainfall is highly correlated with extreme rainfall, any increases in total rainfall associated with a particular phase of a climate regime will be accompanied by the increase in frequency and intensity of extreme rainfall events. Increasing rainfall volumes, frequency and intensity in turn act to enhance the flood risk in the region. Studies have shown a general decrease in rainfall totals and extreme daily rainfall from about the 1970's to the mid-2000's for some locations in the region. It should be emphasised, however, that this pattern in recent climate is not generally representative of the full Bay of Plenty rainfall record.

Four large-scale climate oscillations (Interdecadal Pacific Oscillation (IPO), El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM) and Indian Ocean Dipole (IOD)) are reviewed and their effects on rainfall and river flow in New Zealand and the Bay of Plenty region summarised. Evidence of the positive IPO regime can be seen in reduced Bay of Plenty rainfall totals during the end of the 20th century. These changes are also reflected in decreased flood flows. Similarly, the shorter term ENSO cycle was found to impact Bay of Plenty rainfall and river flow. La Niña conditions are associated with higher rainfall than normal and increased flood peaks consequently increasing the overall flood risk in the Bay of Plenty. Research on past events shows that once El Niño or La Niña events have commenced, their evolution is partly predictable for the coming few months. The SAM and IOD are cited to have a lesser influence on rainfall and river flow in New Zealand, with limited studies encompassing the Bay of Plenty region.

The Bay of Plenty is fortunate that river flows for the larger rivers have been well monitored. In a number of cases these records extend over more than six decades. An update on a study by McKerchar & Henderson (2003) showed partial support for the concept of the IPO phases influencing flood magnitude of some Bay of Plenty rivers. For the lower Rangitaiki River, the Tarawera and the Whakatane Rivers, higher floods have tended to be clustered into the periods from: start of records to 1977; after 2000, and absent for the interval 1978-1999. These periods coincide with intervals when the IPO was in alternate phases. Analysis of extreme rainfall records for the region offers some supporting evidence. However, this effect is not evident in records for other rivers such as the Kaituna, Waioeka and Motu.

A warmer climate due to climate change poses an additional risk of more extreme rainfall events and therefore elevated flood risk in the future. The combination of climate change, interacting natural climate oscillations as well as other variables such as land use change, make longer-term impacts to flood risk difficult to determine. This review of the impacts of climate oscillations on Bay of Plenty

rainfall and river flows provides some supporting evidence for the longer-term climate cycles (ENSO and IPO) likely having an influence on the observed temporal clustering of floods although the relationship is not always clear. Until firmer guidance becomes available, the best course of action for designers estimating design parameters for permanent works such as bridges and stopbanks, and for planners seeking to delineate flood hazard areas and to schedule priorities, is to use all the available records, particularly those extending over two or more phases of the IPO, as a guide for frequency analyses.

At present, we suggest that there is insufficient evidence for delaying infrastructure expenditure based on the timing and effects of the climate cycles analysed in this report. However, we strongly recommend continued collection of river flow, rainfall and other climate data throughout the region, and the re-examination of the relationships between flood flow and climate cycles approximately every 10 years. It is possible that with more data (including, in all likelihood, more flood flow data), the weak relationships identified in this report may be strengthened and therefore be used in future infrastructure investment planning. Also, such continued monitoring will be vital in any future assessment of the potential impacts of climate change.

1   Introduction

New Zealand's climate is complex and highly variable, ranging from warm subtropical in the far north to cool and temperate in the far south. We can get intense storms from the roaring forties of the southern ocean as well as from tropical cyclones from the northwest. Mountain chains extending the length of the country cut across prevailing weather systems, and as a result rainfall patterns in New Zealand are strongly influenced by the interaction between its mountainous terrain and the predominant westerly circulation. This orographic effect means that a west-east gradient dominates the regional rainfall regime, with the greatest amount of precipitation falling along the west coast of the South Island. Regional circulation is also significantly influenced by well-known climate oscillations such as the Interdecadal Pacific Oscillation, the El Niño Southern Oscillation, the Southern Annular Mode and the Indian Ocean Dipole. These large-scale natural climate cycles affect the ocean-dominated climate of New Zealand over monthly to decadal timescales.

The impacts of oscillating climate cycles are far reaching and affect many parts of the natural environment. For river systems and their flood plains, the periodicity of flows over years or decades are subject to changes in rainfall. There may be a period of few storms and low flood activity before intense and large floods occur. The highly variable nature of New Zealand's climate and the resulting river flows can make longer-term changes difficult to determine or perceive.

This report provides a review of four large-scale natural climate oscillations (The Interdecadal Pacific Oscillation, the El Niño Southern Oscillation, the Southern Annular Mode and the Indian Ocean Dipole) and outlines some of the impacts of these cycles on the rainfall and flood flows in New Zealand with a specific focus over the region administered by the Bay of Plenty Regional Council. Furthermore, a previous study carried out by McKerchar & Henderson (2003) on the effect of the Interdecadal Pacific Oscillation on river flows in the Bay of Plenty is updated to include the start of the most recent negative phase.

Although climate change is cited as a potential mechanism of altering these cycles in the future, it is not analysed in depth in this report.

2 General trends in rainfall and flooding

2.1 New Zealand

Most areas of New Zealand receive between 600 and 1600 mm of rainfall, spread throughout the year with more rain falling in winter than in summer. The combination of west to southwesterly prevailing winds and New Zealand's mountainous interior means eastern districts are somewhat sheltered from arriving weather systems. As a result eastern districts tend to have lower rainfall as well as higher variations in rainfall (Figure 1).

Rainfall is the largest climatic variable to influence flood risk. Consequently, it is important to assess the variability of past rainfall when planning future climate sensitive activities. From 1978 to 2000, there have been more persistent westerly winds over New Zealand. Wetter conditions for western and southern areas of the South Island have ensued (about 10% more rainfall), whereas the northeast of New Zealand has been about 10% drier (Salinger and Mullan, 1999). Historical trends in rainfall extremes for the periods 1930-2004 and 1950-2004 were analysed by Griffiths (2006) using indices of extremity from daily station data. As has been shown in previous studies, it was found that extreme rainfall events in New Zealand are highly correlated with the predominant westerly circulation. A seasonal analysis over the period 1958-2004 showed that summer extreme precipitation decreased along the eastern portion of both islands, while increases in extreme rainfall occurred in the winter and spring in the western South Island.
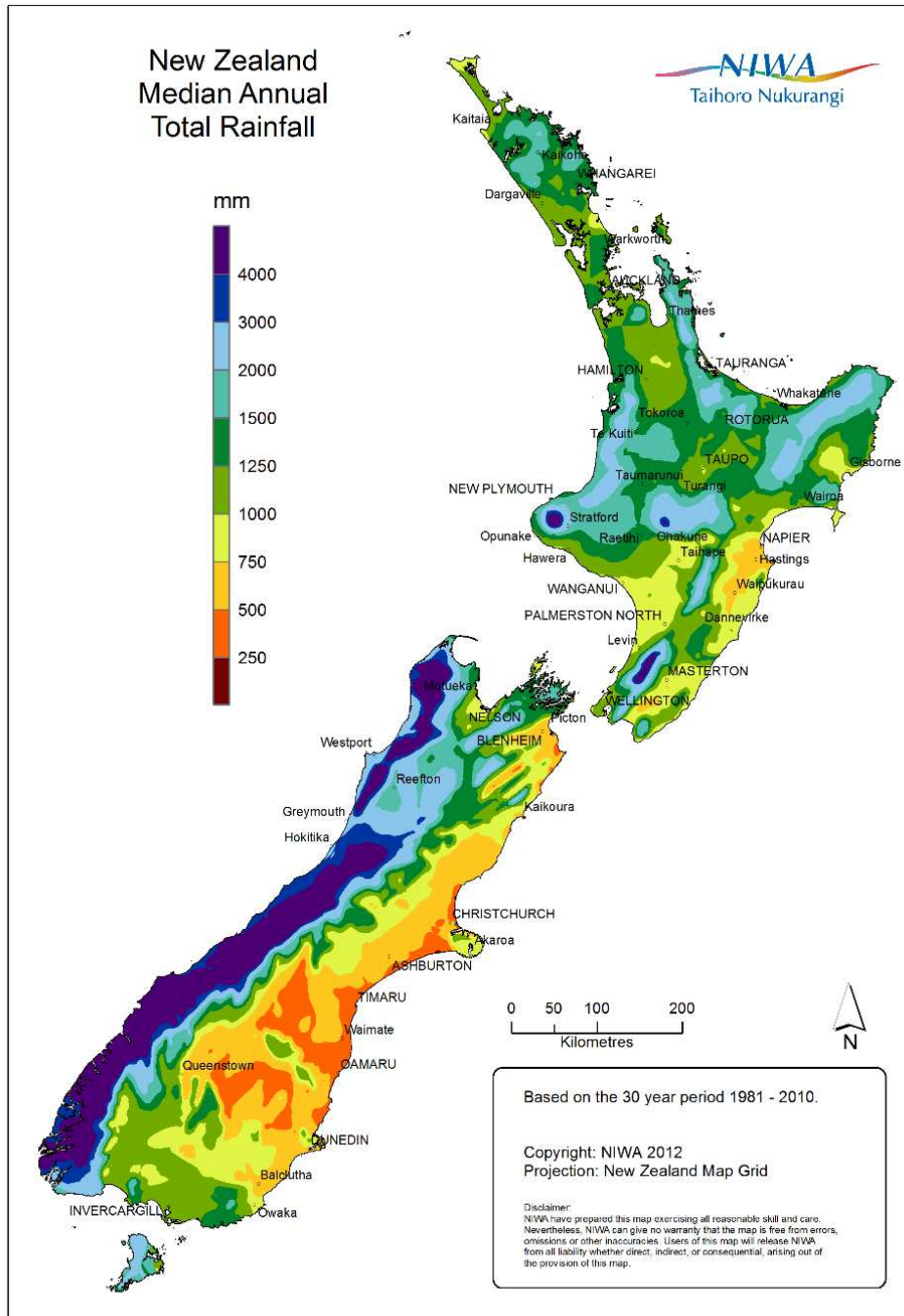
Figure 1: New Zealand median annual total rainfall based on the 30 year period 1981-2010.

2.2   Bay of Plenty

Rainfall data for six stations in the Bay of Plenty (Tauranga, Whakarewarewa, Waihi, Motu, Opotiki and Kaingaroa) were analysed by Griffiths *et al.* (2003) for the years 1900-2002 inclusive. Amongst large year to year variability in rainfall, several trends were identified in the study (The definitions of the various rain terminology used are included in Appendix A):

- *Total rainfall* generally decreased in the Bay of Plenty since the 1960s or 1970s, but this reduction was only statistically significant at the 95% level at Tauranga. Year to year variability of total annual rainfall was found to be large in the region.

- Typically there are about 95 *rain days* per year in the Bay of Plenty at coastal sites such as Tauranga and Opotiki, but this has risen to as high as 134 days per year during extreme years.

- There has been a significant, long-term trend towards fewer *rain days* at some stations in the Bay of Plenty over the study period, with much of this reduction occurring since the 1960s or 1970s. In very wet years, the number of *rain days* was typically high, with the converse also true.

- An *extreme rain* index was calculated measuring the fourth largest rainfall amount per year. Extreme (large) daily rainfall has not changed significantly over the 20th century in the Bay of Plenty. However, in the short term, the years from 1970-2002 have been atypical, in that extreme daily rainfalls have been generally lower than seen elsewhere in the historical climate record (at least at coastal or lower elevation stations). For this reason, planning or policy decisions should not be made based on this part of the record alone. Variability in *extreme rainfall* in the region remains very large and needs to be considered.

- The frequency of *extreme daily rainfall* has decreased across the Bay of Plenty over the last 100 or so years, but the decrease is significant only at Tauranga. Regardless, the climate between circa 1970 – 2002 was atypical, in that *extreme daily rainfalls* were less frequent than recorded elsewhere in the historical climate record.

- The average magnitude of the top four (very extreme) daily rainfalls per year has not significantly changed in the last 100 years across the Bay of Plenty except at Tauranga, which shows a small decrease over the period 1910-2002. However, the 1980s and 1990s have been unusual at some stations in the region, in that *extreme daily rainfalls* have been generally smaller in magnitude than seen at other times in the past. These stations exhibit a large decrease in the *extreme intensity* index after the early 1970s, and therefore recent climate is not generally representative for long-term planning.

- Over the 50-year period 1951-2000, seasonal rainfall has decreased over most of the region in most seasons. Decreases have been larger in the west (Tauranga westwards) than in the east (Whakatane eastwards) and south. Tauranga rainfall has decreased by about 10% in winter to 30% in summer since 1951.

A subsequent study by Griffiths (2006) found that extreme daily rainfall over the eastern North Island has generally decreased in summer but increased in spring between 1930 and 2004. This trend was consistent with mean rainfall changes since 1977 described by Salinger and Mullan (1999). In addition, changes in total rainfall were found to be highly correlated with changes in extreme daily rainfall over the study period.

3 Climate Oscillations

Interannual variability in New Zealand's climate has been linked to a number of large-scale Southern Hemisphere climate modes. The interaction between these cycles and the alpine ranges running the length of the country impose strong spatial climate patterns and local climatic variations. The regional impacts of the Interdecadal Pacific Oscillation and El Niño Southern Oscillation on climate have been documented by a number of studies. Fewer studies on the Southern Annular Mode and the Indian Ocean Dipole have also been shown to have an effect on New Zealand's climate but on a lesser scale. This section provides a review of four large-scale natural climate cycles (The Interdecadal Pacific Oscillation, the El Niño Southern Oscillation, the Southern Annular Mode and the Indian Ocean Dipole) and their corresponding impacts on rainfall and flood flow in New Zealand with a specific focus on the Bay of Plenty region.
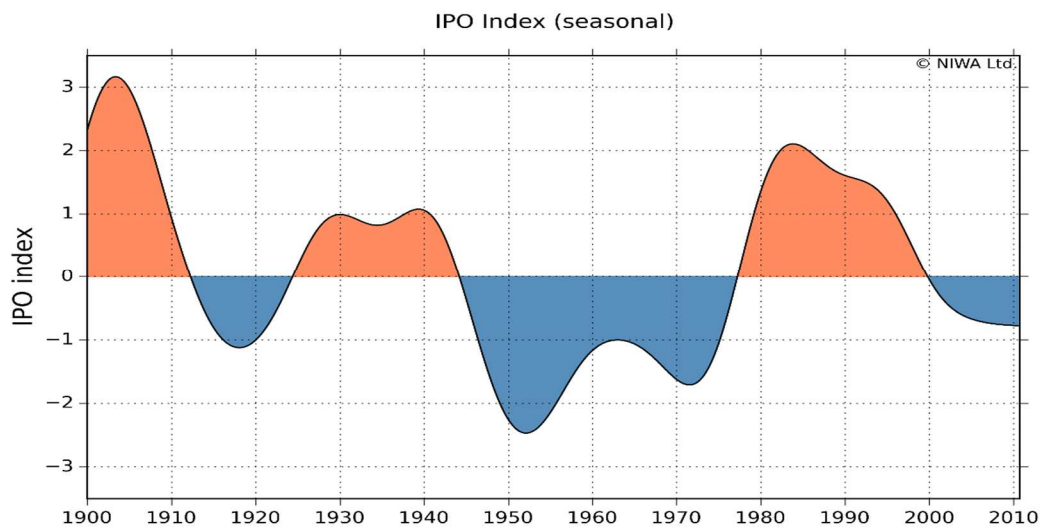
3.1 The Interdecadal Pacific Oscillation (IPO)

The Interdecadal Pacific Oscillation (IPO) is a natural fluctuation in climate over parts of the Pacific Ocean. A characteristic circulation pattern predominates for a 20-30 year period, and then the system switches to having a different distinguishing circulation pattern (The authors are not aware of any scheme for predicting when a shift may occur). These patterns are known as phases of the IPO. During the 20th century, three major phases of the IPO have been identified – a positive phase (1922–1945) with augmented westerly circulation over New Zealand, a negative phase (1947–1977) with weaker westerlies over the country, and another positive phase (1978–1999). The start of the 21st century has seen a return to negative IPO conditions (Figure 2).

Long term fluctuations in New Zealand's climate show an association with changes in the IPO. Typically, sea surface temperatures around New Zealand tend to be lower and westerly winds stronger during the positive IPO phase (Salinger et al., 2001). As displayed in Figure 3, this circulation

leads to drier conditions along the eastern coasts of New Zealand and higher than normal rainfall along the west coast of the South Island. The opposite is true for the negative phase of the IPO. Sea surface temperatures in the western Pacific cool and more easterly and northeasterly flows over New Zealand are favoured which in turn bring enhanced precipitation to northeastern regions.

These patterns are the "average" response and do not mean that every year of a particular IPO phase will behave in the same way.

Figure 2: Phases of the Interdecadal Pacific Oscillation. Positive values indicate periods when stronger westerlies occur over New Zealand, and more anticyclones over northern New Zealand. Negative values indicate periods with more northeasterlies to northern regions. Data courtesy of the Hadley Centre, UK Meteorological Office.
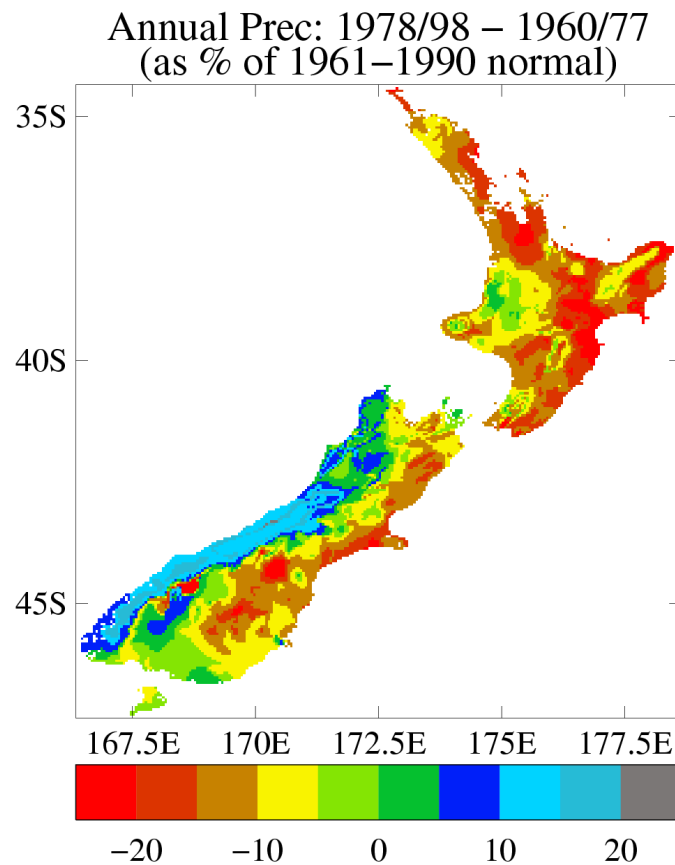
Figure 3: Percentage change in average annual rainfall, for the 1978-1998 period compared to the 1960-1977 period. (*Note: From 1978-98 the IPO was in its positive phase, compared to the previous 18 years when the IPO was negative. Any local rainfall response due to global warming would also be contained within this pattern of rainfall trends*).

3.1.1 The effect of the Interdecadal Pacific Oscillation in the Bay of Plenty Region

As described in the previous section, the positive phase of the IPO is associated with dryness along eastern parts of New Zealand with the opposite effect taking place during the negative IPO phase. This general pattern has also been found to apply to the Bay of Plenty Region.

Since 1951, the Bay of Plenty has been characterised by a decrease in rainfall, particularly in western areas about Tauranga (Griffiths *et al.*, 2003). The increase of a westerly flow associated with a change in IPO phase from negative to positive can be partly attributable to this pattern.

A study on the IPO and river flow patterns in the Bay of Plenty by McKerchar and Henderson (2003) observed trends consistent with changes in rainfall totals. Since 1978, river flows were found to be less variable with fewer severe floods occurring in the Bay of Plenty region. When looking at the interquartile range (difference between 25th and 75th percentile values) of river flow data, this difference was most pronounced for the Rangitaiki at Te Teko, Whakatane and Whirinaki records.

Statistical F-tests[1] for both natural and log-transformed data showed that the differences identified in the flow records were statistically significant. These shifts in the hydrological regime can be reasonably attributed to the shift in IPO phase from negative to positive as well as the associated increase in the frequency of El Niño (this interaction is detailed in Section 6).

Due to the positive phase of the IPO active during the end of the 20th century, flow data recorded for the period 1978-1999 might not be a reliable guide to the future. Since the start of this century the IPO has switched back to its negative phase and thus weaker westerlies and increased rainfall in the Bay of Plenty over the next decade or so should be expected. Updated river flow records encapsulating the start of the current negative phase are examined in Section 4 to determine if peak flows have indeed increased since the start of the century in the Bay of Plenty.

3.2   The El Niño Southern Oscillation (ENSO)

The El Niño Southern Oscillation (ENSO) is a natural fluctuation of the global climate and refers to the variation in sea surface temperatures across the equatorial Pacific Ocean and in surface air pressure in the tropical western Pacific. El Niño and La Niña refer to opposite extremes of the ENSO cycle and occur every 3-7 years. A common measure of the intensity and state of ENSO events is the Southern Oscillation Index (SOI) (Figure 4). This index is derived by calculating the air pressure difference between Tahiti and Darwin. Persistence of the SOI below -1 coincides with El Niño events, and periods above +1 with La Niña events.

When neither El Niño nor La Niña are present, (usually referred to as "neutral" or normal conditions), trade winds blow westward across the Pacific, piling up warm surface water so that Indonesian sea levels are approximately 50 cm higher than those off the coast of Ecuador. Cool, nutrient-rich sea water wells up off the South American west coast, supporting marine ecosystems and fisheries.

During an El Niño, trade winds weaken which leads to a reduction in upwelling off South America and a rise in sea surface temperatures in the eastern equatorial Pacific. The opposite is true during La Niña events, when the trade winds strengthen to produce an intensified pattern of "normal" conditions with enhanced upwelling of cool water off the South American west coast.

Climatic differences arising from the ENSO cycle are seen most clearly in the tropics but the climate of New Zealand is also affected. In general, during an El Niño, New Zealand experiences a stronger than normal southwesterly airflow leading to wetter than normal conditions in western areas and drier than normal conditions in the east of the country (due to the rain shadow effect) (Figure 5a). Conversely, during La Niña, more northeasterly flows ensue leading to wetter than normal conditions in the north and east of the North Island (Figure 5b). Individual ENSO events can differ

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[1] The F-test is a statistical parametric test that compares the ratio of two variances and tests whether they are equal. In the McKerchar and Henderson (2003) study it was used to determine if any statically significant differences exist between river flows during the negative and positive IPO phases in the Bay of Plenty.

substantially from this pattern and El Niño and La Niña effects are not exactly equal and opposite (Mullan, 1995).

ENSO can occur at any time of the year but its peak usually occurs during the Southern Hemisphere spring and summer. For this reason it is important to look at seasonal data when predicting New Zealand climatic variability instead of only considering annual values (Mullan and Thompson, 2006). The recent development of computer models which simulate the coupled ocean-atmosphere dynamics of the central Pacific have been reasonably successful in forecasting the onset, development and breakdown of ENSO events. Research on past events shows that El Niño and La Niña events tend to follow similar patterns of development and decay. Therefore, once El Niño or La Niña events have commenced, their evolution is partly predictable for the coming few months.
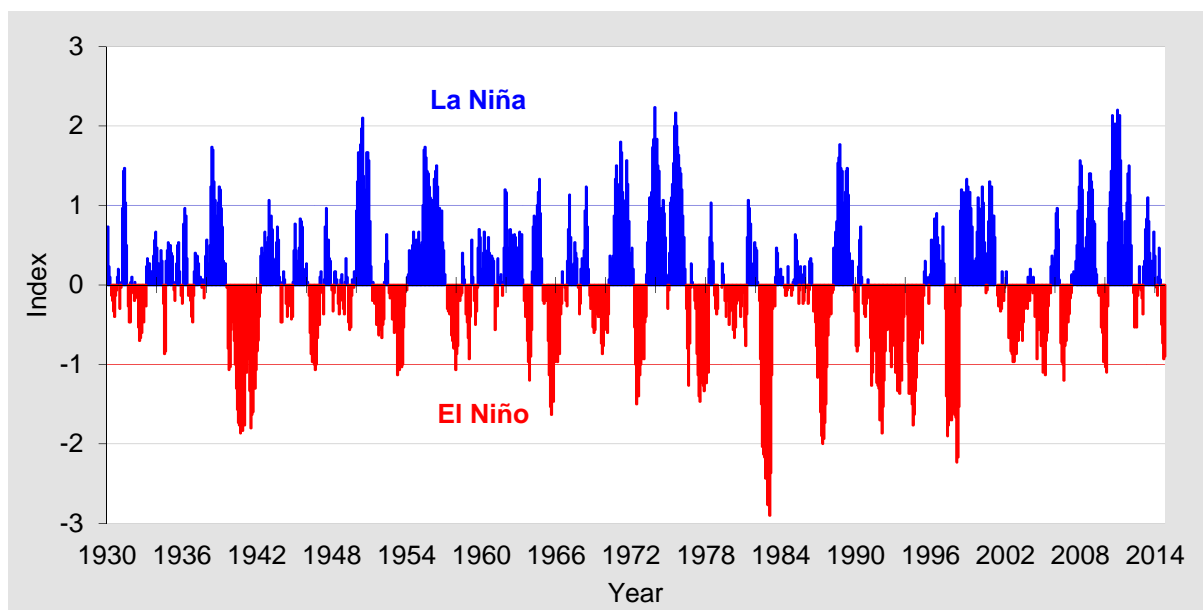
Figure 4: Time series of the Southern Oscillation Index from 1930-2014.
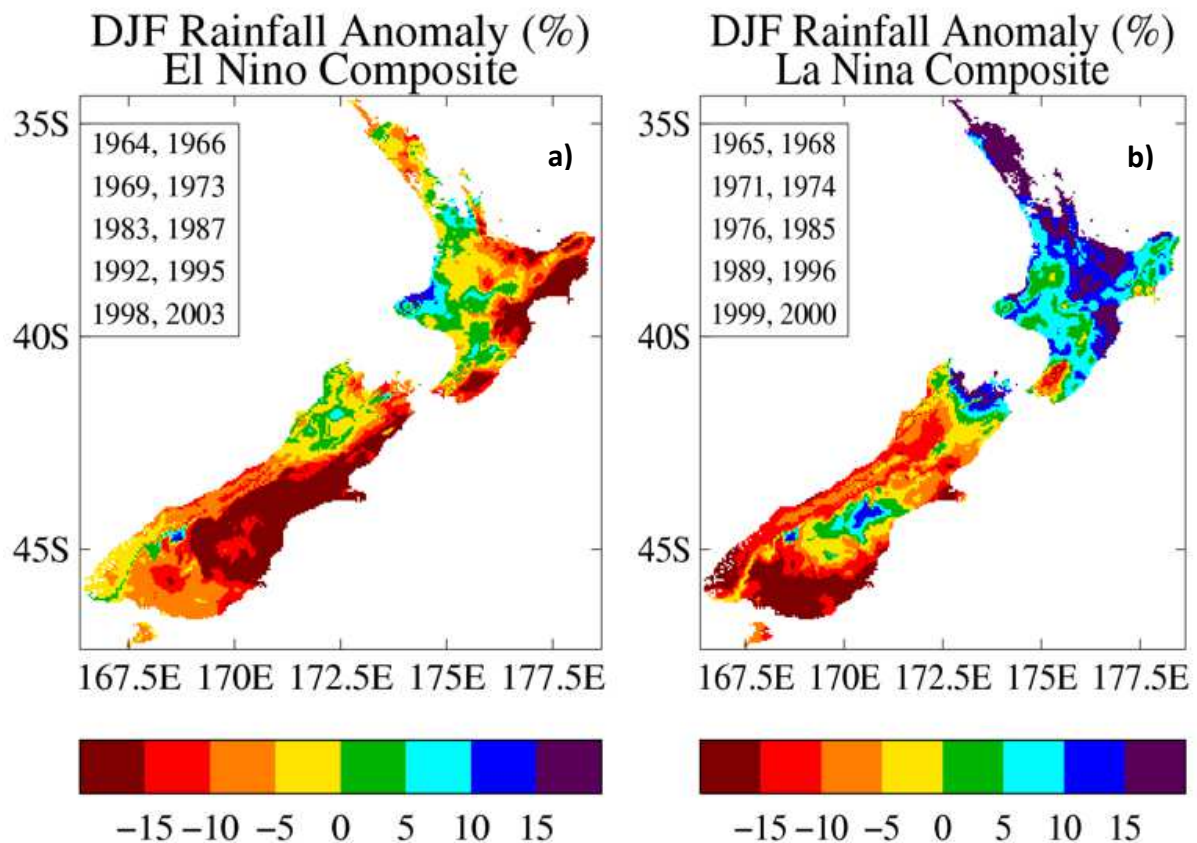
Figure 5: ENSO composite rainfall anomalies (in %) for summer (December-February), for the 10 strongest events 1960-2007 for New Zealand during El Niño (a) and La Niña (b) conditions. (The insert boxes indicate the years used, where 1964 is December 1963 to February 1964, etc.).

3.2.1 The effect of El Niño in the Bay of Plenty Region

The impact of ENSO in the Bay of Plenty follows the general pattern described for New Zealand's eastern regions with wetter conditions occurring during La Niña years and drier conditions during El Niño years. Ummenhoefer (2007) has found that the decrease in annual rainfall totals was as much as 400mm below normal during El Niño years in the northeast of the North Island. Griffiths *et al.* (2003) affirmed this pattern by finding positive correlations throughout the Bay of Plenty region between La Niña conditions and increased rainfall. The opposite effect also holds true during El Niño events. The strongest correlation between ENSO and rainfall was found to be around Whakatane in spring, but high correlation existed over much of the Bay of Plenty region in both winter and spring. Although the correlations were statistically significant, they are not large and overall year to year variability in Bay of Plenty rainfall remains large.

Mosley (2000) assessed the impact of ENSO on river flows around New Zealand. Three of the streamflow records analysed in the study were in the Bay of Plenty region (Kaituna at Rotoiti outlet, Rangitaiki at Te Teko, Motu at Houpoto). For peak flows, North Island rivers tended to have

increased flood peaks during La Niña episodes whereas El Niño periods were associated with a significant reduction in peak flow. When assessing the relationship between ENSO and low flows, both positive and negative deviations to normal conditions occurred for the Rangitaiki River, particularly during La Niña. Despite this, a general pattern of marked deviations from long term average flows could be discerned. Large and sustained low flow conditions occurred during El Niño conditions whilst during La Niña, flow was more variable but generally higher than normal. The effect of ENSO on flood frequency was weaker than the relationship between ENSO and low and peak flood flows. Decreased flood frequency has occurred in the Motu River during El Niño conditions and slightly increased flood frequency during La Niña. Although the responses to El Niño and La Niña for the Bay of Plenty rivers included in the study were largely equal and opposite, it was highlighted that this should not be assumed as a general rule.

Scarsbrook *et al.* (2003) was able to discern a similar pattern to Mosley (2000). Increasing values of the SOI and thus La Niña conditions were associated with increased river flows in the eastern North Island region which encompassed Bay of Plenty monitoring sites. Conversely, El Niño conditions were found to be associated with a general decrease in river flows.

3.3   The Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) is a ring of climatic variability circling the South Pole and extending to the latitudes of New Zealand. The SAM generally describes the position of the westerly wind belt which in turn influences the strength and position of cold fronts, windiness and storm activity between the middle latitudes, where New Zealand lies (40-50°S), and higher latitudes, over the southern oceans and Antarctic sea ice zone (50-70°S). New Zealand is positioned in a zone where the SAM displays the greatest seasonality. The orography of the country also means that there is a strong dependence of climate anomalies on wind speed and direction (Kidson, 2000). As the SAM is associated with pressure anomalies centred over Antarctica, the relative influence of the SAM is considered more dominant over the South Island than the North (Ummenhofer, 2007).
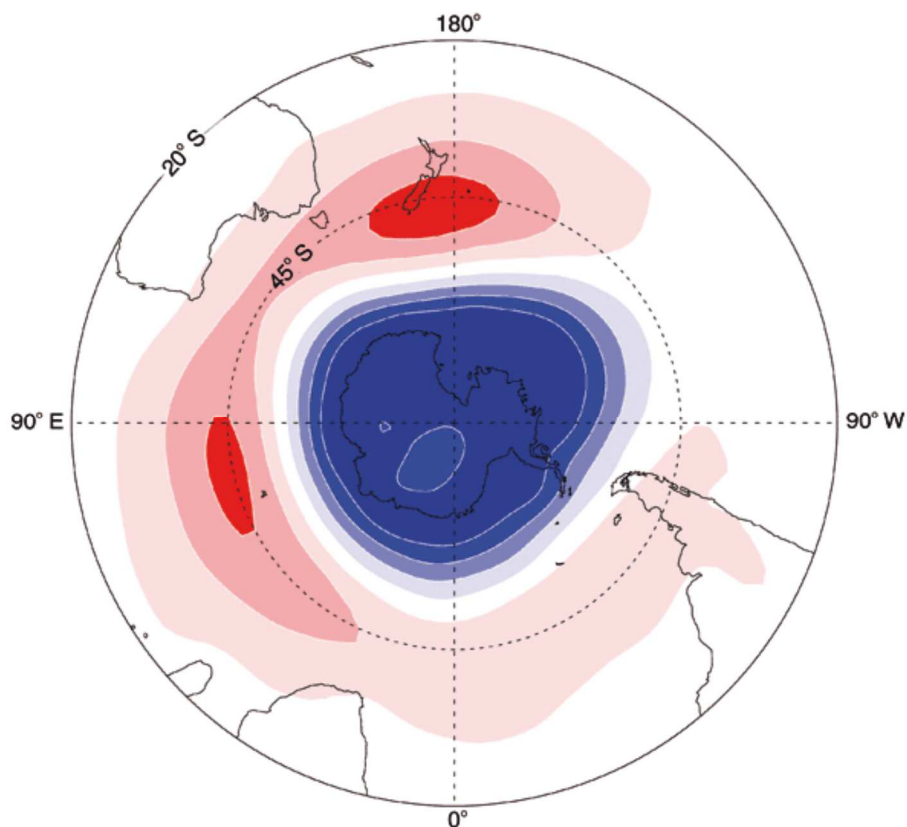
In its positive phase, the SAM is associated with relatively light winds and settled weather over New Zealand (Figure 6). Wind anomalies (differences from normal) over the summer are easterly and become northeasterly over the North Island and northwesterly over the southern South Island in winter (Kidston *et al.,* 2009). Conversely, the negative phase of the SAM results in more unsettled conditions with increased westerly winds.

Seasonal relationships between the SAM and New Zealand rainfall are a reflection of the prevailing circulation and the orographic effect. Kidston *et al.* (2009) found that the positive phase of the SAM during summer induced wetter conditions along coastal region in the north and east of the North Island, Nelson and Marlborough and coastal north Canterbury with drier conditions elsewhere. Likewise, the positive phase of the SAM in winter was found to bring wetter conditions to the Bay of Plenty, Gisborne and parts of the Hawke's Bay, Wellington, Nelson, Fiordland and Westland with drier conditions elsewhere.

On a week-to-week basis, the SAM can alternate between states, either causing windier or calmer weather over New Zealand. This occurs in an unpredictable way and apparently at random. Although these changes in the SAM cannot be predicted more than few days in advance, once changed, the phases tend to persist for several weeks.

Over the past two to three decades, there has been a trend in the SAM towards more periods of the positive phase. The trend appears to be related to the reduction of stratospheric ozone over Antarctica and, to a lesser amount, the increase in greenhouse gases in the troposphere (Arblaster and Meehl, 2006; Thompson *et al.,* 2011).

Figure 6: Pattern of the pressure variations associated with the positive phase of the SAM. Blue shading indicated below-average pressures and red shading indicates above average pressures.

3.3.1   The effect of the Southern Annual Mode in the Bay of Plenty Region

Few studies have looked at the impacts of the SAM specifically over the Bay of Plenty region. In general, during a positive phase of the SAM, an increase of northeasterly flows means that there is less subsidence of dry air along the east coast, the result being that increased rainfall in the Bay of Plenty is more likely.

Kidston *et al.* (2009) found positive correlations between the SAM and extreme rainfall events in Tauranga during spring (September to November). This implies increased rainfall extremity during positive SAM, consistent with the northeasterly flow anomalies over the North Island. Ummenhoefer (2009) was also able to discern wetter conditions along the east coast during positive SAM with the opposite true during negative SAM conditions.

3.4   The Indian Ocean Dipole (IOD)

The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon in the Indian Ocean defined by the difference in sea surface temperature (SST) between two areas/poles – a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the eastern Indian Ocean south of Indonesia. The SST difference usually develops and peaks between June and October. A positive IOD is associated with above average sea surface temperatures and increased precipitation in the western Indian Ocean region with a corresponding cooling of water in the eastern Indian Ocean. The reverse effects prevail during negative IOD conditions.

Across New Zealand, the positive phase of the IOD is related to weakened storm track activity with a corresponding reduction in rainfall from June-November over northern parts of the country (Ashok *et al.,* 2007). In the negative IOD phase, cyclone related precipitation tends to be significantly enhanced over northern parts of New Zealand.

Indian Ocean sea surface temperature patterns are also known to modulate winter circulation patterns about New Zealand. Warmer Indian Ocean water in autumn is generally followed by more rainfall in western South Island and drier conditions in areas exposed to the north and east (Mullan, 1998).

There have been no specific studies which relate the phases of IOD to precipitation or river flows in the Bay of Plenty region. However, some recent studies have shown high correlation between ENSO and IOD in recent years (Yuan and Li, 2008) with the negative IOD phase associated with La Niña. As a result, a general effect of increased rainfall in the Bay of Plenty during a negative IOD phase is likely.

4 Reanalysis of Bay of Plenty flood records

4.1 Assembly of data

River flow records for nine catchments in the Bay of Plenty region were selected and assembled from Bay of Plenty Regional Council and NIWA archives. The records and the catchment areas are listed in Table 1 and depicted spatially in Figure 7. The earliest records commence in 1948 and continue to the present, giving records of up to 66 years in length. These records are an exceptionally rich data resource: few other regions of the country have flow records of these lengths and there are only a few rainfall records for the region that extend over 60 or more years.

Rating curves for these records have not been checked as part of this study, and the curves archived are taken as the best available.

Table 1: Flow records assembled for the Bay of Plenty region

Number	River and site	Catchment area (km^2)	Date start (yyyymmdd)	Date end (yyyymmdd)
14614	Kaituna at Te Matai	948	19860806	20141028
15302	Tarawera at Awakaponga	906	19480528	20141106
15408	Rangitaiki at Murupara	1184	19480601	20141014
15410	Whirinaki at Galatea	534	19521203	20141014
15412	Rangitaiki at Te Teko	2893	19480602	20140715
15511	Waimana at Waimana Gorge	440	19501001	20131111
15514	Whakatane at Whakatane	1557	19560731	20140722
15901	Waioeka at Gorge Cableway	641	19580318	20140722
16501	Motu at Houpoto	1393	19570408	20140709
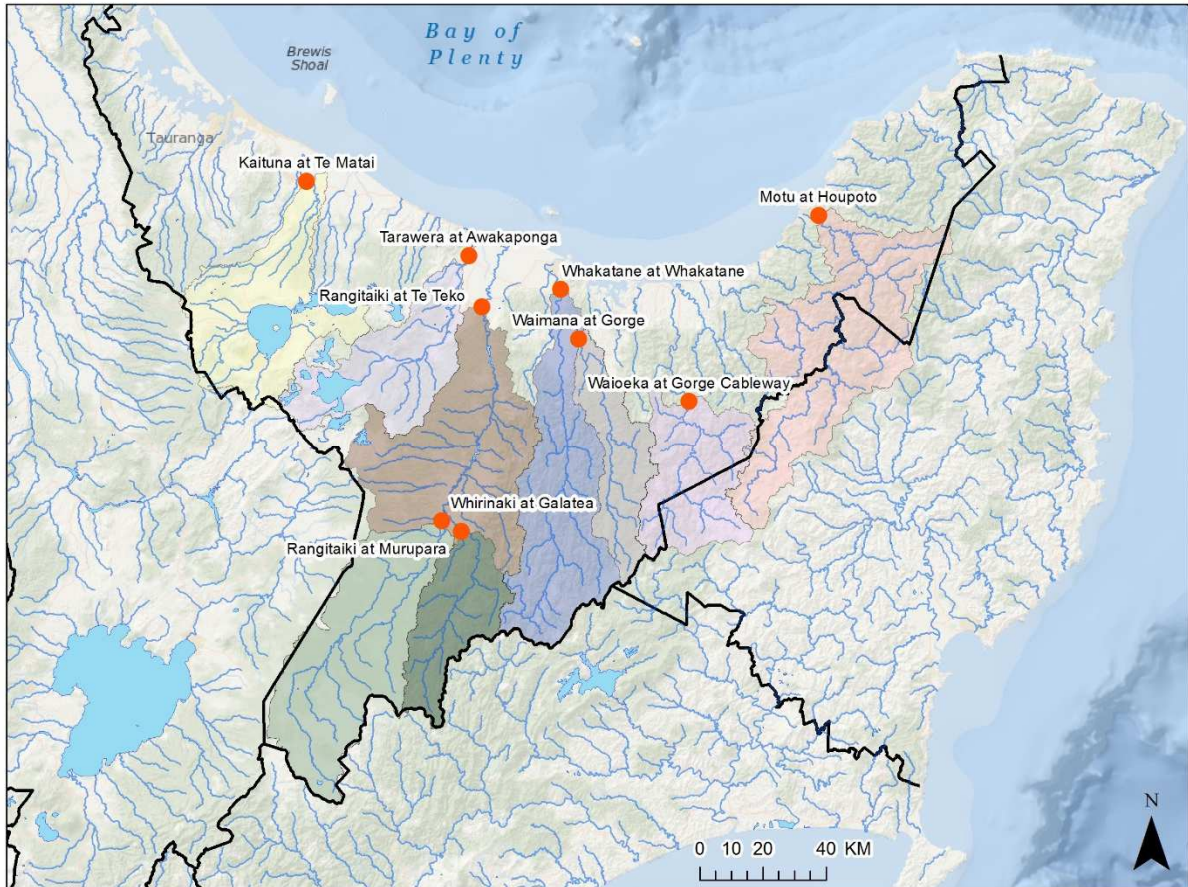
Figure 7: Map of the Bay of Plenty region displaying the position of flow recorders used for the study and their associated catchments.

Although there are some anthropogenic (human) activities affecting the flows in these rivers, (e.g. forestry in the Tarawera catchment, hydropower developments in the Rangitaiki catchment), the overall influences on flood flows are expected to be minimal. Nevertheless, under flood conditions in the lower Rangitaiki River, some reductions in peak flood flows are achieved by drawing down the storage reservoir formed by the Matahina Dam before floods peak (construction of the Matahina Dam was completed in 1967.) Thus the variations seen in the long term records are likely to be consistent with variations in the magnitude and frequency of extreme storms.

4.2   Examination of data

The complete hydrographs for the six main catchments (Kaituna, Tarawera, Rangitaiki, Whakatane, Waioeka, and Motu) are plotted on one sheet in Figure 8. This is to facilitate a comparison of the records. A horizontal line drawn across each hydrograph shows an estimate of the 1 in 10 annual exceedance probability (0.1 AEP or 10 year return period) flood. For the purpose of this study, floods exceeding this line are regarded as large floods.

Figure 9 presents similar plots for two upstream tributary sites on the Rangitaiki River, and also the Waimana River, a tributary of the Whakatane River.

Inspection of the plots shows a number of interesting features:

- First, it is apparent that floods often occur over several catchments at the same time. In particular, many of the larger floods for the Rangitaiki, Whakatane and Waioeka are coincident: this is consistent with the scale of storms systems that affect the region. The largest recorded events in both the Rangitaiki and Whakatane occurred in July 2004.

- Second, no trend towards either increasing or decreasing values is evident in any of the records.

- Third, there is a clear clustering of larger floods into the earlier years, from 1948 to about 1975, and from the late 1990s to 2012 at least. Few large floods occurred in the interval from 1975 to 1995, and only one event exceeds the 0.1 AEP threshold, and that is for the Motu, which is on the periphery of the region. This feature is examined further.

4.3   Clusters of floods

A New Zealand-wide study that examined shifts in flow regimes and used six of the records listed in Table 1 was reported by McKerchar & Henderson (2003). The Interdecadal Pacific Oscillation (IPO) was introduced and described as a decadal scale oscillation across the Pacific Ocean. In the negative phase the IPO favours La Niña occurrences and in the positive phase El Niño occurrences are more frequent (this interaction is detailed in Section 6). A La Niña favouring phase was considered to have occurred from about 1947 to about 1977 and an El Niño favouring phase from 1978 to 1999. Subsequently, it appears that the oscillation switched again in about 2000 to bring in another La Niña favouring phase.

As detailed in the previous section, El Niño conditions generally result in more westerly wind than usual across the country and drier than usual conditions in the north and east of the country, while La Niña conditions favour the reverse: more north easterly wind than usual across the country and wetter than usual conditions in the north east. This concept was advanced as an explanation for the clustering of the larger floods seen in several of the Bay of Plenty records.

The clustering is illustrated in Figure 10. In this figure boxplots are presented for each of the three intervals for each of the nine records. Each boxplot shows summary statistics for the annual maxima floods in each interval. The statistics shown are the maximum, the values exceeded in 25% and 75% of years, the median and the minimum. The tendency towards lower flood maxima over the interval 1978-1999 is evident for the Tarawera, Rangitaiki, Whirinaki and Whakatane records, though in some cases higher values after 2000 have not eventuated. Thus the influence of the IPO, at least in terms of changes in flood regime, is not consistent. Furthermore, the Waioeka and the Motu catchments, that lie adjacent to the Whakatane, but to the east, do not show this influence at all.

Nor is the influence apparent in the shorter Kaituna River flow records which comprise the outflows of Lakes Rotorua and Rotoiti.

4.4   Discussion

The Bay of Plenty region is exceptionally well-endowed with river flow records, several of which extend over at least six decades. These long records facilitate an assessment of the possible influences of the Interdecadal Pacific Oscillation (IPO) and the El Niño Southern Oscillation (ENSO) phenomena on occurrence of floods.

An update of the results for floods reported by McKerchar & Henderson (2003) shows some support for the concept of the IPO phases influencing flood magnitude on some Bay of Plenty rivers, but the supporting evidence is patchy. However, it is clear that when all the records are examined (Figures 8 & 9) that the two decade interval 1975-1995 experienced few major floods.
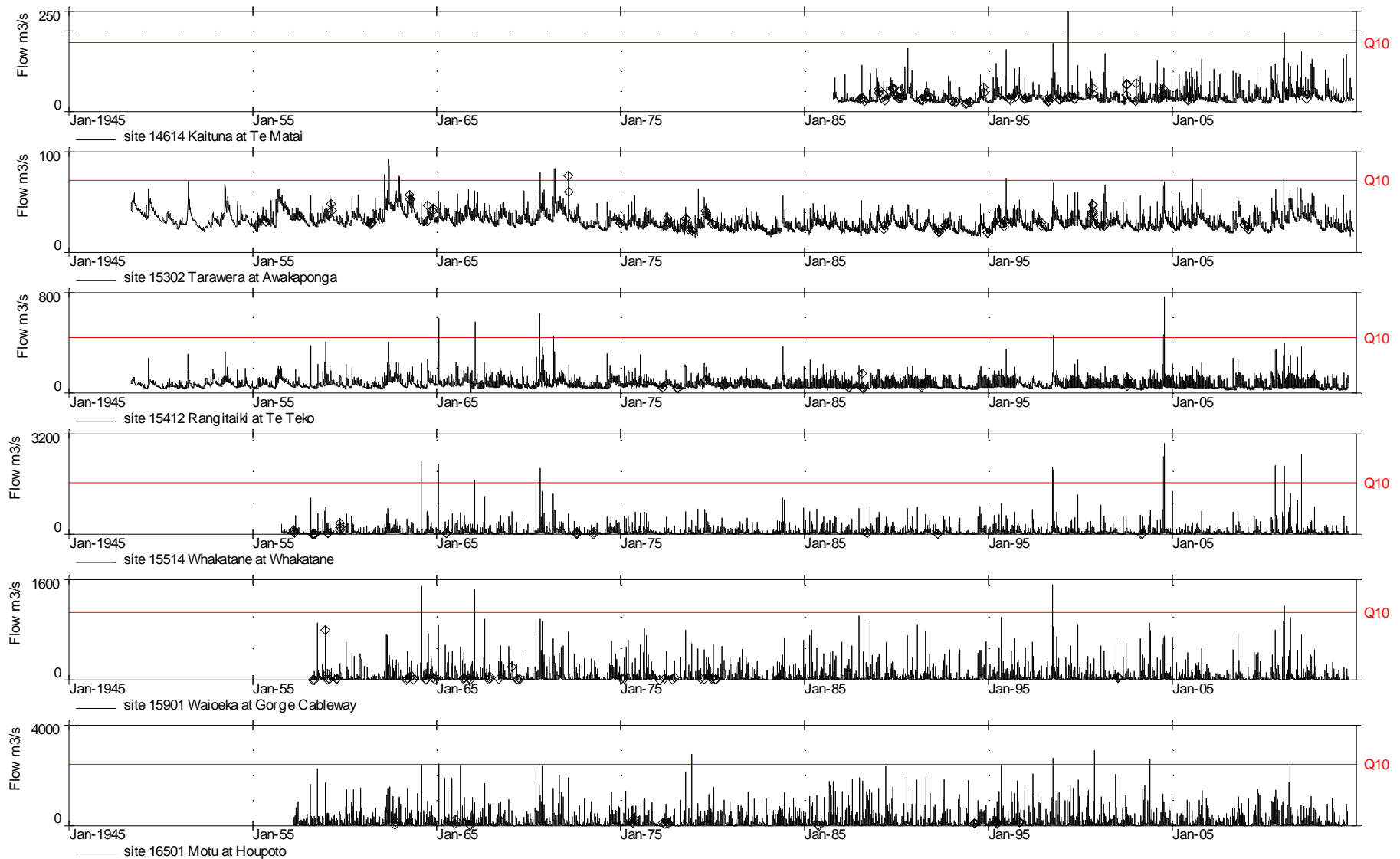
Figure 8: Hydrographs for six Bay of Plenty catchments. Note that the red line is an estimate of the 0.1 AEP flood for each record.
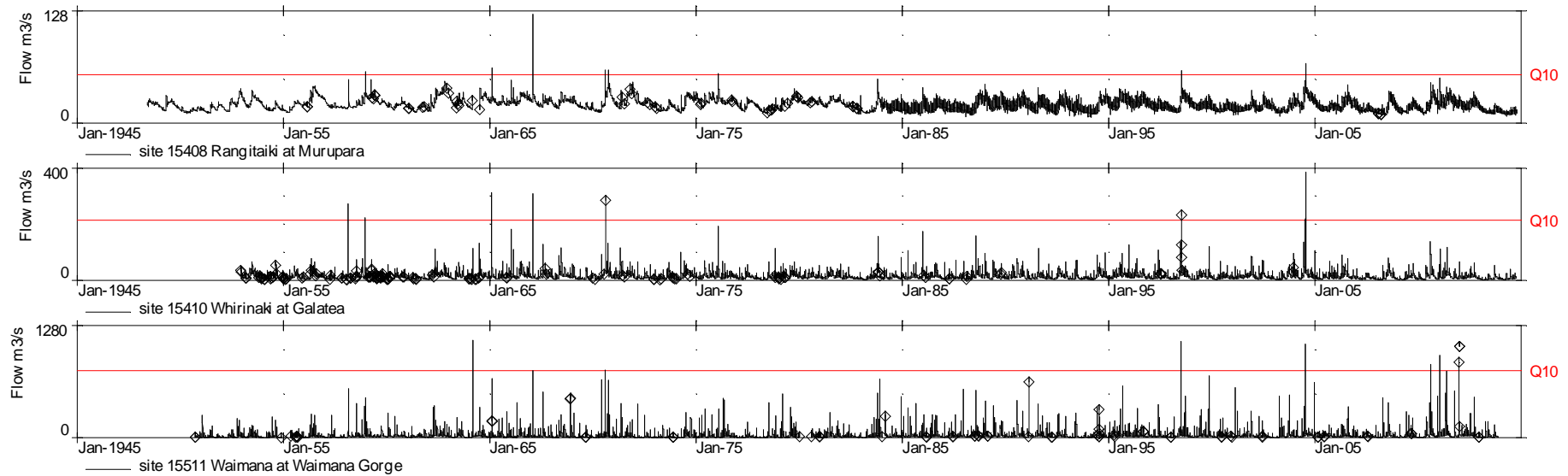
Figure 9: Hydrographs for three Bay of Plenty tributary catchments. The Rangitaiki at Murupara and the Whirinaki sites are located upstream of the Rangitaiki at Te Teko site and the Waimana at Gorge site is a tributary to the Whakatane River. Note that the red line is an estimate of the 0.1 AEP flood for each record.
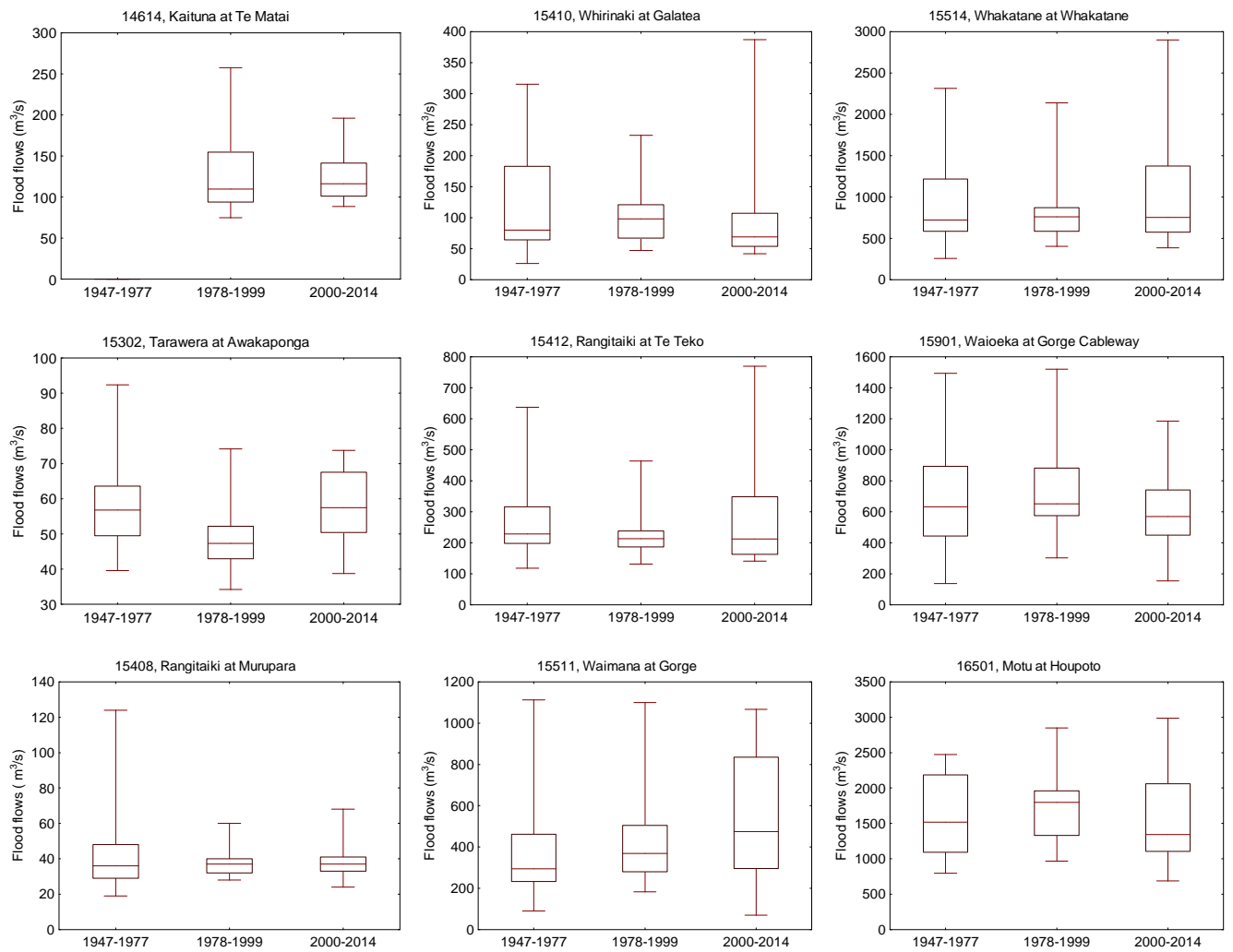
Figure 10: Boxplots of annual maxima for the intervals 1947-1977, 1978-1999, 2000-2014.

5   Climate Change

Although climate change is not directly assessed in this report it should be noted that the climate cycles described above will be superimposed on top of the impacts of climate change. Because of this, adaptation to changes in precipitation and flood flow will need to incorporate both the shorter scale natural climatic variations as well as long term trends.

Present guidance for New Zealand (MfE, 2008) suggests that a currently-experienced extreme rainfall (e.g., 24-hour extreme with a 100-year return period) could occur approximately twice as often (i.e., 50-year return period) under a local warming of about 2°C. These more intense extreme rainfall events are projected to elevate future flood risk.

The increased flood peak resulting from increased precipitation extremes will also interact with rising sea levels making coastal settlements and stormwater drainage in low-lying areas particularly vulnerable (Hennessy *et al.,* 2007). Furthermore, several studies have shown that the increase in flood flow will be significantly greater than the percentage increase in short-term rainfall. This non-linearity arises due to a difference in infiltration rates and ground detention storage. The newly released IPCC AR5 WGII report list changes to flood frequency as a "key risk" in New Zealand (IPCC, 2014).

6 Interaction between Climate Oscillations

The climate cycles described in this review do not occur in isolation and can impose modulating effects on one another. The greatest interaction occurs between the IPO and ENSO cycles. Salinger *et al.* (2001) investigated the effect of the IPO on the South Pacific climate for the period 1931-1998. It was found that the IPO had a modulating influence on ENSO with a particular bias during the positive IPO phase during which stronger interactions between the two oscillations was apparent. Although the two cycles operate on different timescales, there are similarities in their expression in tropical Pacific sea surface temperatures. A positive IPO phase is, on average, associated with enhanced and more frequent El Niño events. Salinger *et al.,* (2001) found that the frequency of El Niño months went up from 12% to 27% during the positive IPO phase. Conversely, the negative phase of the IPO is associated with an increase in La Niña conditions, and thus increased rainfall and river flows in eastern regions such as the Bay of Plenty (Figure 11).

Griffiths *et al.* (2003) suggested that the higher frequency of El Niño's during the 1978-1998 positive IPO phase appeared to be the main driver associated with decreased rainfall in the Bay of Plenty region over this time period. In addition, a long running dry-spell in the early 1940's also coincided with a persistent El Niño and the earlier 1922-1944 positive IPO period. As the IPO has switched to its negative phase, more frequent La Niña events and increased rainfall in the Bay of plenty region should be expected over the coming decade or so.

Recent studies examining the relationship between the IOD and ENSO have also found linkages between the two cycles. A study by Yuan and Li (2008) found insignificant correlations between the two cycles between 1940-1969. However, from 1970-2003 this relationship significantly increased. Most El Niño events were found to coincide with a positive IOD signal and almost every positive IOD happened in an El Niño year. It was suggested that the increased association between the two cycles was caused by the enhanced linkage between sea water between the eastern Indian Ocean and the western Pacific.

In summary for the Bay of Plenty, increased rainfall and streamflow is associated with negative IPO, La Niña, positive SAM and negative IOD phases.

As mentioned in Part 5, climate change will interact with the natural oscillations described above with several potential compounding effects. Existing flood risk near river mouths will be exacerbated by storm surge associated with higher sea level. Higher rainfall intensity and peak flow will also increase erosion and sediment loads in waterways.

A detailed analysis on the impacts of land use change on Bay of Plenty flood risk is outside the scope of this study but a general review encompassing New Zealand has been written by Blaschke *et al.* (2008). Changes in vegetation (afforestation/deforestation) can alter the frequency, magnitude and duration of small flood waves in medium to large catchments. However, it is noted that changes in hydrology do not necessarily translate to reduced flood risk. When moderate to large flood waves spill across a floodplain, damage can still occur to people, building, infrastructure and economic activities. Historical flood damage in New Zealand has been largely caused by factors which

afforestation cannot influence. These include under-designed flood protection schemes, unpredictable failures and the development on flood prone land. However, there have been some cases of reduced over-bank flooding as a result of afforestation in New Zealand. This was found to be largely influenced by the effect of afforestation leading to decreased sediment yield which in turn improves channel flood capacity.
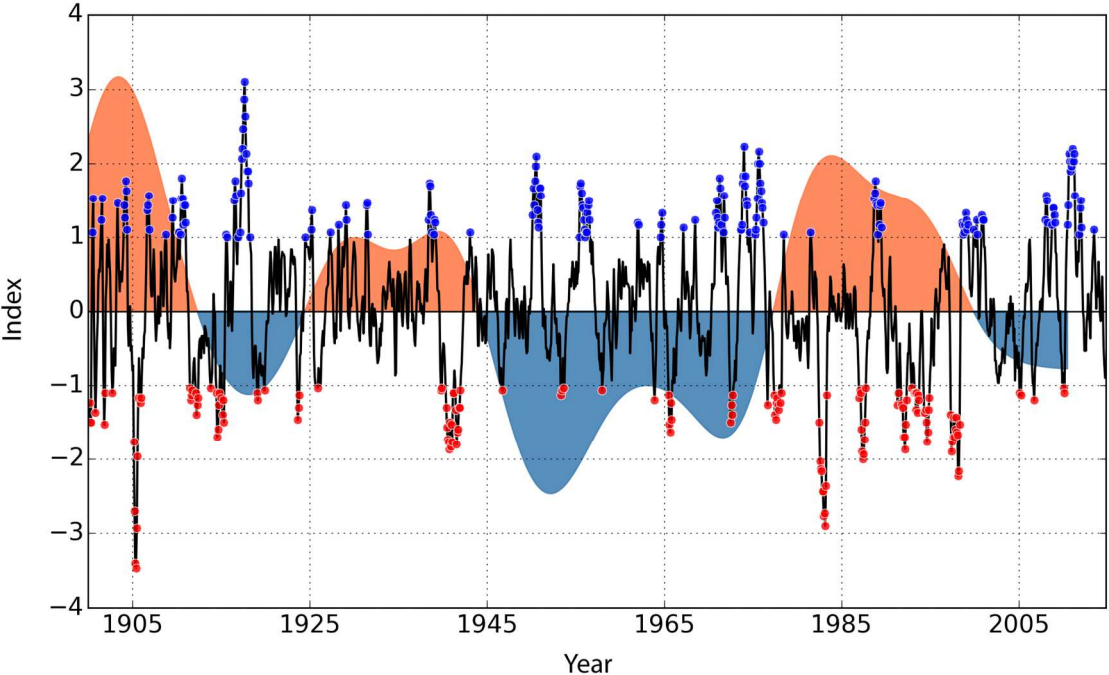
Figure 11: Time series of the seasonal IPO index (Red shading indicates the positive phase and blue shading marks the negative phase) and 3-month running mean SOI values (black line). Exceedances if -1 (El Niño) and +1 (La Niña) SOI values are marked by blue and red dots respectively.

7   Conclusion

Most aspects of the natural environment are well adjusted to mean climatic conditions and show little sensitivity to small perturbations about these means. Consequently, the critical impacts of climate are generally driven by extreme events as opposed to mean values. The ability for the environment to adjust without stress and damage markedly decline as conditions become progressively more extreme (Salinger and Griffiths, 2001). Because of this, the effects of climate cycles on extreme rainfall and increased stream flow using current and future climate scenarios should be carefully considered when planning future infrastructure.

This review of the impacts of climate oscillations on Bay of Plenty rainfall and river flows provides some supporting evidence for the longer-term climate cycles (ENSO and IPO) likely having an influence on the observed temporal clustering of floods (described in Section 4), although the relationship is not always clear. There is some ability to forecast ENSO occurrences several months ahead. Also, the IPO appears to persist for decadal scales, however the authors are not aware of any scheme for predicting when a shift may occur.

An issue that is not addressed in this study is the reliability of the flood flow estimates. The flood extremes are dependent on extrapolations of stage-discharge rating curves. While some of the flow measurement sites probably yield very good data, there are well-recognised difficulties with estimates of extremes for rivers where the scour of sediment (sand and gravel) during high flows can change the hydraulic control between recorded water level and estimated flood flow.

Until firmer guidance becomes available, the best course of action for designers estimating design parameters for permanent works such as bridges and stopbanks, and for planners seeking to delineate flood hazard areas and to schedule priorities, is to use all the available records, particularly those extending over two or more phases of the IPO, as a guide for frequency analyses.

At present, we suggest that there is insufficient evidence for delaying infrastructure expenditure based on the timing and effects of the climate cycles analysed in this report. However, we strongly recommend continued collection of river flow, rainfall and other climate data throughout the region, and the re-examination of the relationships between flood flow and climate cycles approximately every 10 years. It is possible that with more data (including, in all likelihood, more flood flow data), the weak relationships identified in this report may be strengthened and therefore be used in future infrastructure investment planning. Also, such continued monitoring will be vital in any future assessment of the potential impacts of climate change.

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Appendix A   Rainfall terminology and definitions

Term	Definition
Total rainfall	Amount of rain recorded in total measured in mm.
Rain day	Day with 2mm or more of rain recorded.
Extreme rain	Size of the fourth highest rainfall (99th percentile). Measured in mm.
Extreme intensity	The average size of the highest four daily rainfall events. Measured in mm.