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TAUPŌ DISTRICT FLOOD HAZARD STUDY

Lake Taupō Foreshore

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Prepared by
Helli Ward
Francie Morrow
Reuben Ferguson

Reviewed by Jack McConchie

Approved for release by Jack McConchie

Opus International Consultants Ltd
Wellington Environmental Office
L8, Majestic Centre, 100 Willis St
PO Box 12 003, Thorndon, Wellington 6144
New Zealand

Telephone: +64 4 471 7000
Facsimile: +64 4 499 3699

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Executive Summary

Quantifying the flood hazard of Lake Taupō involves a number of issues which are not present when establishing the flood hazard for a specific river. Water levels within Lake Taupō are not simply the result of rainfall and runoff. Rather, the water level is a function of the interaction of a number of factors, including: rainfall and runoff; lake level management for flood mitigation and hydro power generation; wind generated waves (and boat wakes to a minor degree); seiching (both 'natural' and as a result of seismic activity); and tectonic deformation of the lake bed and shoreline. These factors include physical processes which can be modelled, but also a range of human, economic, and regulatory factors which operate independently.

Assessing the flood hazard therefore involves quantifying the magnitude and frequency of a large number of factors. Implicit in these analyses is the stationarity of data. Stationarity assumes that the same processes and relationships that existed in the past will continue to apply in the future. This has particular implications when considering the long term effects of land use and climate change, and ground deformation.

The risk of flooding, and the extent and depth of inundation around Lake Taupō, is therefore a multi-factor problem. A number of factors combine to form a particular water level, and the same water level can be reached by the coincidence of different combinations of factors. It is possible to have the same water level with different frequencies, different water levels with the same frequency, and different water levels with different frequencies. In addition, the effect of a change in water level at the shore varies with topography and beach profile and material; and its potential consequences may depend on the level of capital investment and development. The interaction of the water level with the shore, and whether flooding will occur is therefore both a temporal and spatial problem.

The various factors that affect water level fall into two groups: those that affect the static water level (e.g., lake level, seiche, climate change, land use and tectonic deformation); and those that act upon this static water level (e.g., waves and wave run-up). The potential effect of each of these groups of factors can be managed with different strategies.

A building-block approach was consequently adopted with each factor analysed from both temporal (magnitude and frequency) and spatial perspectives. The impact of each factor on the effective water level for the 2.33, 5, 10, 20, 50, 100, 200 and 500-year return period events around the lake shore was quantified. The combined effect of multiple parameters on the effective water level at the shoreline was also assessed.

Higher water levels and wave run-up can be overlaid on a high resolution digital terrain model (DTM) derived from LiDAR information. The DTM can then be used to identify those areas which would be flooded by a particular combination of factors, and the depth of any inundation. As well as illustrating the overall flood risk posed by particular parameter combinations, the potential impact of effective water levels on specific sites down to a 2m resolution can be analysed using the DTM.

Analysis showed that lake level variations and wave run-up have the greatest potential effect on the extent and depth of flooding. Locally tectonic deformation can have a significant effect on relative water levels over the longer term.

Two hazard zones have been defined. The first is the 100-year static water level. This level includes the combined effects of lake level variation, seiche, climate change and tectonic deformation. A second, and higher level, represents the 100-year ARI, or 1% AEP effective water level. The effective water levels is defined using the actual lake level record combined with the modelled wave run-up. This results in a single 'risk variable' with a single probability. Since these data are based on historic daily values adjustments are required for the potential impact of seiche, climate change, and site-specific tectonic deformation.

Contents

Preface

Opus International Consultants were commissioned jointly by the Waikato Regional Council and the Taupō District Council to investigate the flood hazard to land adjacent to the shoreline of Lake Taupō. The flood hazard to land adjacent to the major tributaries draining to the lake has been quantified separately. The study was part of a wider investigation leading to the development of the Lake Taupō Erosion and Flood Strategy. The overall aim of this strategy was to determine effective long-term solutions to reduce flood and erosion risks around the shore of the lake.

The flood risk to land adjacent to Lake Taupō was approached as a multi-factor problem. Factors analysed included lake level variability; both over time, and as a consequence of the interaction of a range of controls, seiche (which is the 'sloshing effect' experienced by water in a contained area), land use and climate change, tectonic deformation, and the effect of waves. The various factors that affect water level fall into two groups: those that affect the static water level, and those that act upon this static water (such as waves and wave run-up). While seiche is not actually 'static' it was included in this group of variables since it applies to the entire lake and not just a particular area. The frequency and magnitude of each factor, and its variability around the lakeshore, were studied to provide a complete assessment of the flood risk. The results of the Flood Hazard Study were reported in Opus (2008).

Since that study considerable additional work has been undertaken relating to the flood hazard to land adjacent to Lake Taupō; particularly on how best to assess and quantify the combined risk of high lake levels and large waves acting at the shore.

There is also now considerably more information and data available relating to those factors which affect the flood hazard. For example, there is 14-years of additional information relating to lakeshore deformation; at least 7-years more wind and wave data; and 5-years more data relating to the variation in the water level of Lake Taupō.

Consequently, Taupō District Council decided to review and update the previous Flood Hazard Study (Opus, 2008). This report therefore includes all the latest information and reflects the current understanding of the various processes which affect the water level of Lake Taupō and consequently the flood hazard.

It should be noted that the inclusion of the additional data and analyses have not altered the basic conclusions of the previous study (Opus, 2008). The nature of the flood hazard and its controls, and the magnitude and variation of the hazard around Lake Taupō have been confirmed following consideration of all information now available.

1 Introduction

Under the Resource Management Act (1991) regional councils and other territorial authorities are required to develop provisions that avoid or mitigate the effects of natural hazards. Areas near Lake Taupō are vulnerable to flooding, particularly over the longer term, as a result of large inflows, high lake levels, big waves, land deformation, and the topography and geology of the surrounding area. Major tributaries to the lake also pose a flood risk which is exacerbated when high lake levels impede flood drainage. Waikato Regional Council and the Taupō District Council are therefore investigating the flood risk so that they can monitor and manage this hazard (Environment Waikato, 2005).

This study has been prompted by:

- Waikato Regional Council and the Taupō District Council being required, under sections 30 and 31 of the Resource Management Act (1991), to avoid and mitigate the effects of natural hazards;
- Section 35 of the Resource Management Act (1991) that requires Councils to monitor the environment, and maintain records of natural hazards;
- The need to provide definition, justification, description, and interpretation of the flood hazard area rules in the District Plan;
- Central Government's review of flood management in New Zealand; and
- Waikato Regional Council's Project Watershed which aims to address flood protection, soil conservation, and river management in the Waikato River catchment.

The primary objective of this Taupō District Flood Hazard Study is to identify the flood risk to land adjacent to Lake Taupō. Flooding can be triggered by processes acting within and upon the lake, and its major tributaries. These processes can act either individually or collectively to produce various depths and extents of inundation around the lake. Maps of the flood hazard from different levels and types of risk, resulting from various factors and combinations of factors, have been developed. These maps were analysed individually, and collectively, to identify those areas at greatest risk of flooding. This will allow the formulation of various standards for development in areas subject to particular levels and types of risk. This is one of a number of studies that will allow the development of a Lake Taupō Foreshore Risk Management Strategy. The information in this report will subsequently be incorporated into Waikato Regional Council's regional plans and policy statements, and Taupō District Council's District Plans and land use planning.

This phase of the Taupō District Flood Hazard Study addresses flooding of the lake foreshore (Figure 1.1). Subsequent phases investigate the flood risk associated with each of the major tributaries.

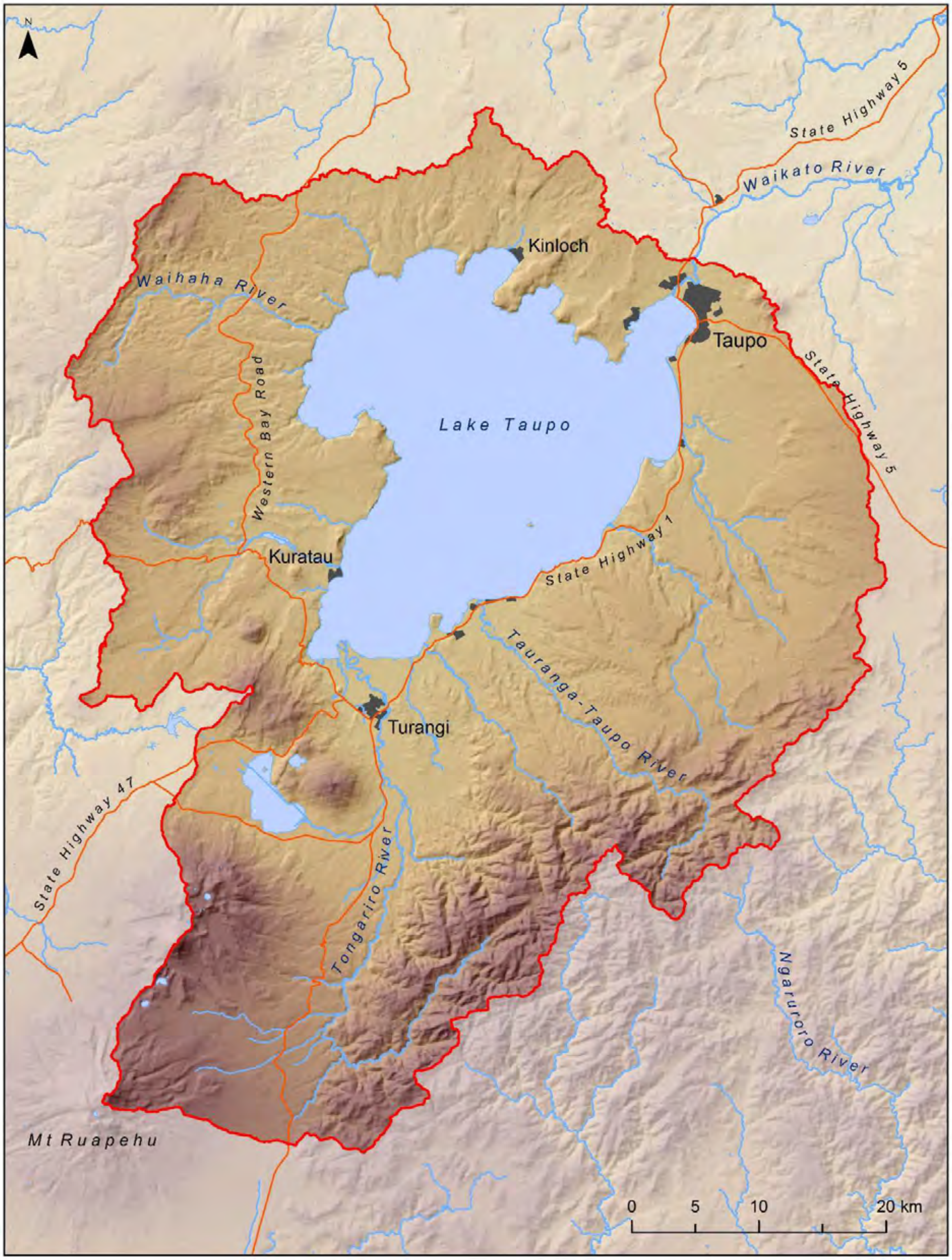


Figure 1.1: Lake Taupō catchment showing the main tributaries and settlements.

1.1 Lake Taupō flood hazard

Quantifying the flood hazard posed by Lake Taupō involves a number of issues which are not present when establishing the flood hazard for a specific river. Water levels within Lake Taupō that affect the flood hazard are not simply the result of rainfall and runoff. Rather, the levels are a function of the interaction of a number of factors, including: rainfall and runoff; lake level management for hydro power generation and flood mitigation down the Waikato River; regulation imposed conditions; wind generated waves (and boat wakes to a minor degree); seiching (both cyclic and as a result of seismic activity); and tectonic deformation of the lake bed and shoreline. These factors include physical processes which can be modelled, but also a range of human, economic, and regulatory factors that operate independently.

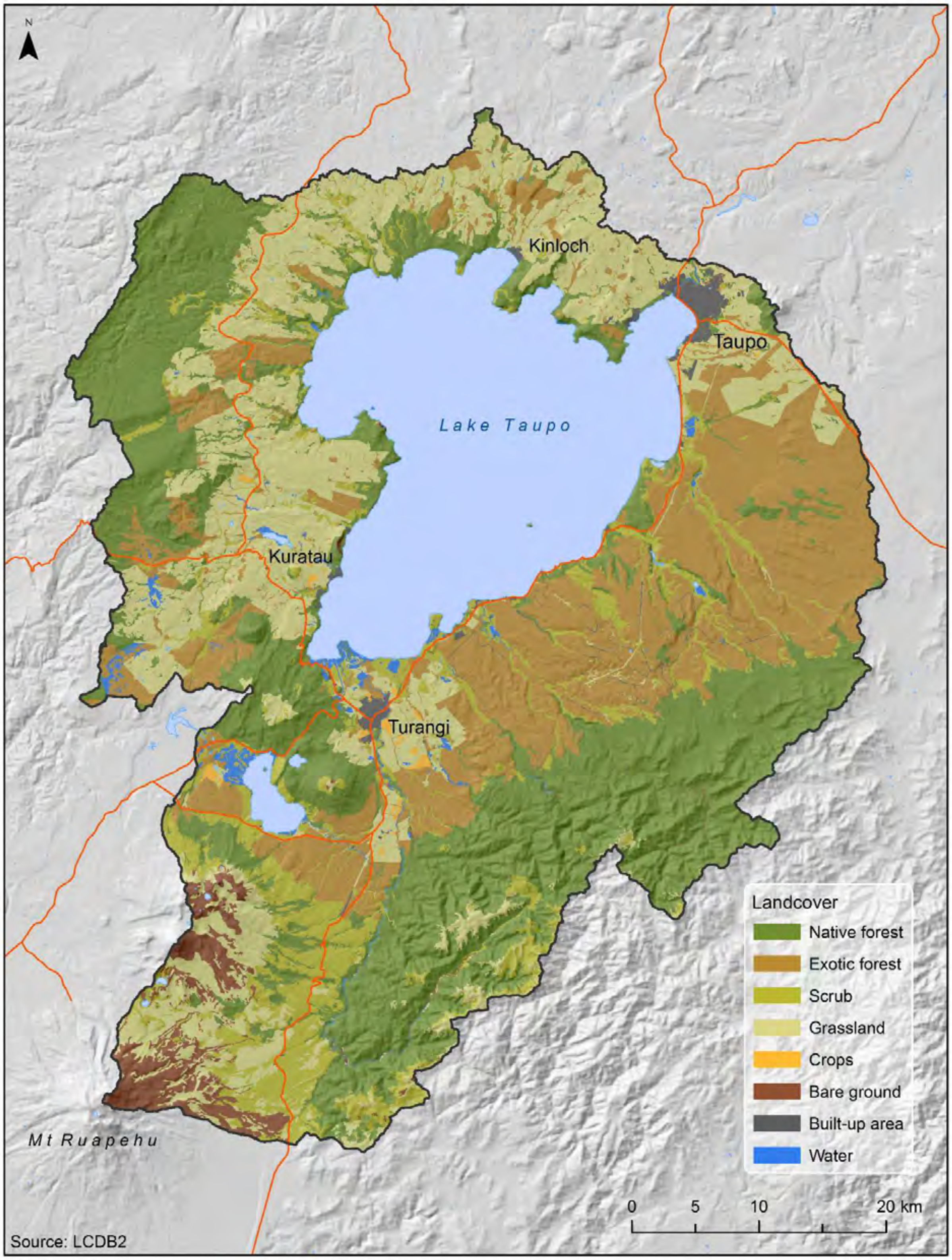
While some of these factors have a greater effect on the water level than others, all need to be considered. In this report the various factors are considered in two groups: those that affect the static water level (e.g., lake level variability, seiche, climate change, and tectonic deformation); and those that act upon this static water level (e.g., waves and wave run-up). Each group of factors may be managed by different strategies. That is, the risk of large waves may be managed differently from the risk of high water levels.

With regard to assigning a level of risk, the multi-parameter control of water level poses additional problems. Each factor varies within a particular range and frequency distribution of values. As a result, there are numerous ways particular factors can combine to affect the flood risk. Each combination is associated with a particular likelihood of occurrence and maximum water level. It is possible to have the same water level with different frequencies, different water levels with the same frequency, and different water levels with different frequencies.

A ‘building-block’ approach was therefore adopted where the magnitude and frequency distributions of the various factors that influence water level are considered independently. These individual effects can then be added in various (potentially infinite) ways to identify how the factors interact to produce a particular flood level and extent.

1.2 Lake Taupō catchment

The Lake Taupō catchment covers an area of approximately 3289km^2; including a lake area of 615km^2. The elevation ranges from 2797m at the top of Mt Ruapehu, down to approximately 356m at the lake outlet. The terrain is steep forest and tussock-covered mountains, through to flat and rolling grass-covered farmland (Figure 1.2). The mean annual precipitation varies from over 4000mm on Mt Ruapehu to approximately 1000mm at the Taupō Township (Figure 1.3).



Source: LCDB2

Figure 1.2: Land use within the Lake Taupō catchment (LCDB2-2004).

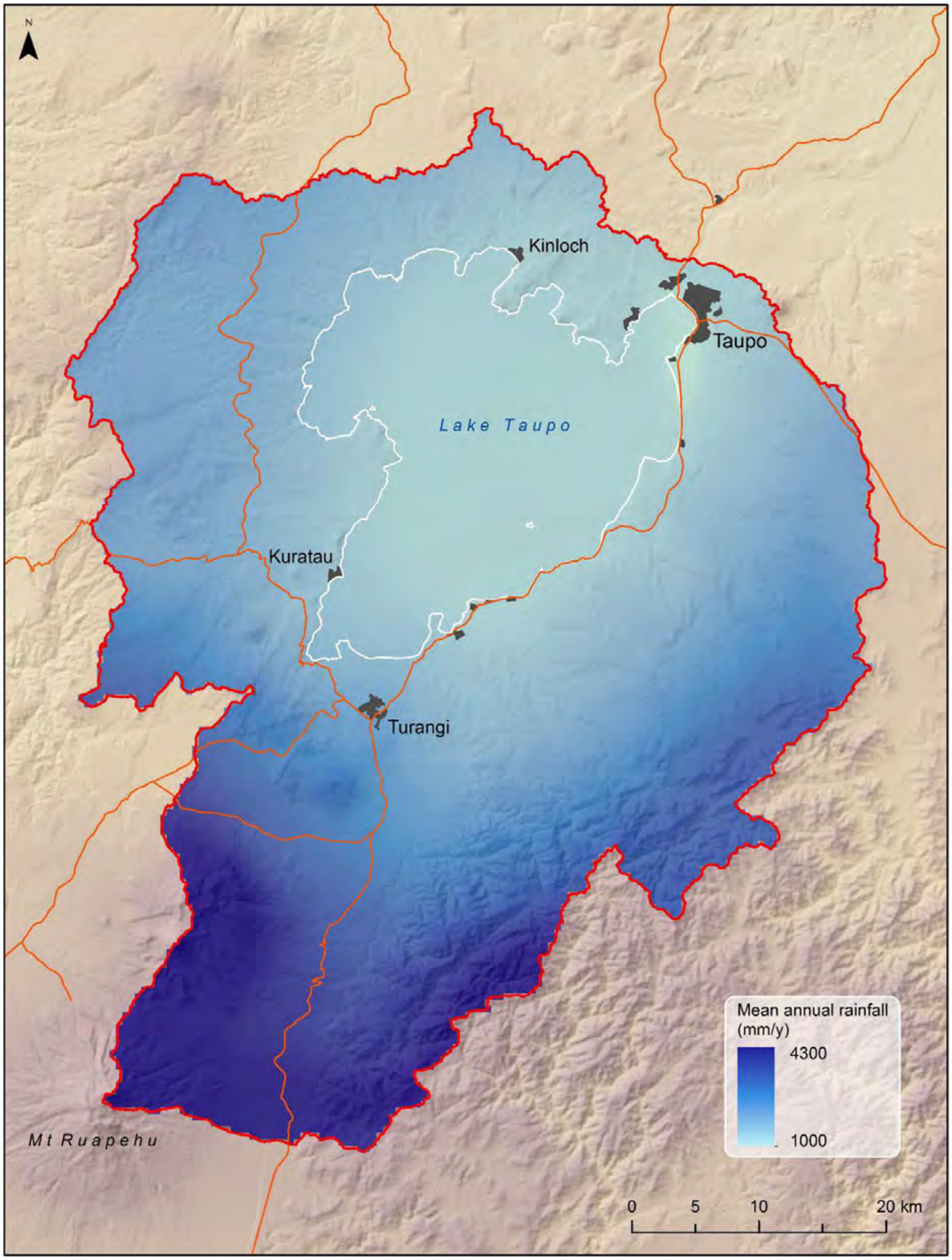


Figure 1.3: Mean annual rainfall (mm) throughout the Lake Taupō catchment (NIWA Mean annual rainfall surface for New Zealand).

The majority of the Taupō catchment is mantled by airfall or re-deposited, relatively young, unconsolidated, volcanic deposits erupted from the Ruapehu, Tongariro, Taupō and Okataina volcanic centres (Figure 1.4). These unconsolidated volcanic deposits are highly porous and permeable. As a result they can absorb the majority of rainfall under all but the most extreme events. This precipitation is then released slowly via the groundwater system resulting in broad flood hydrographs, high baseflow and a low coefficient of flow variation.

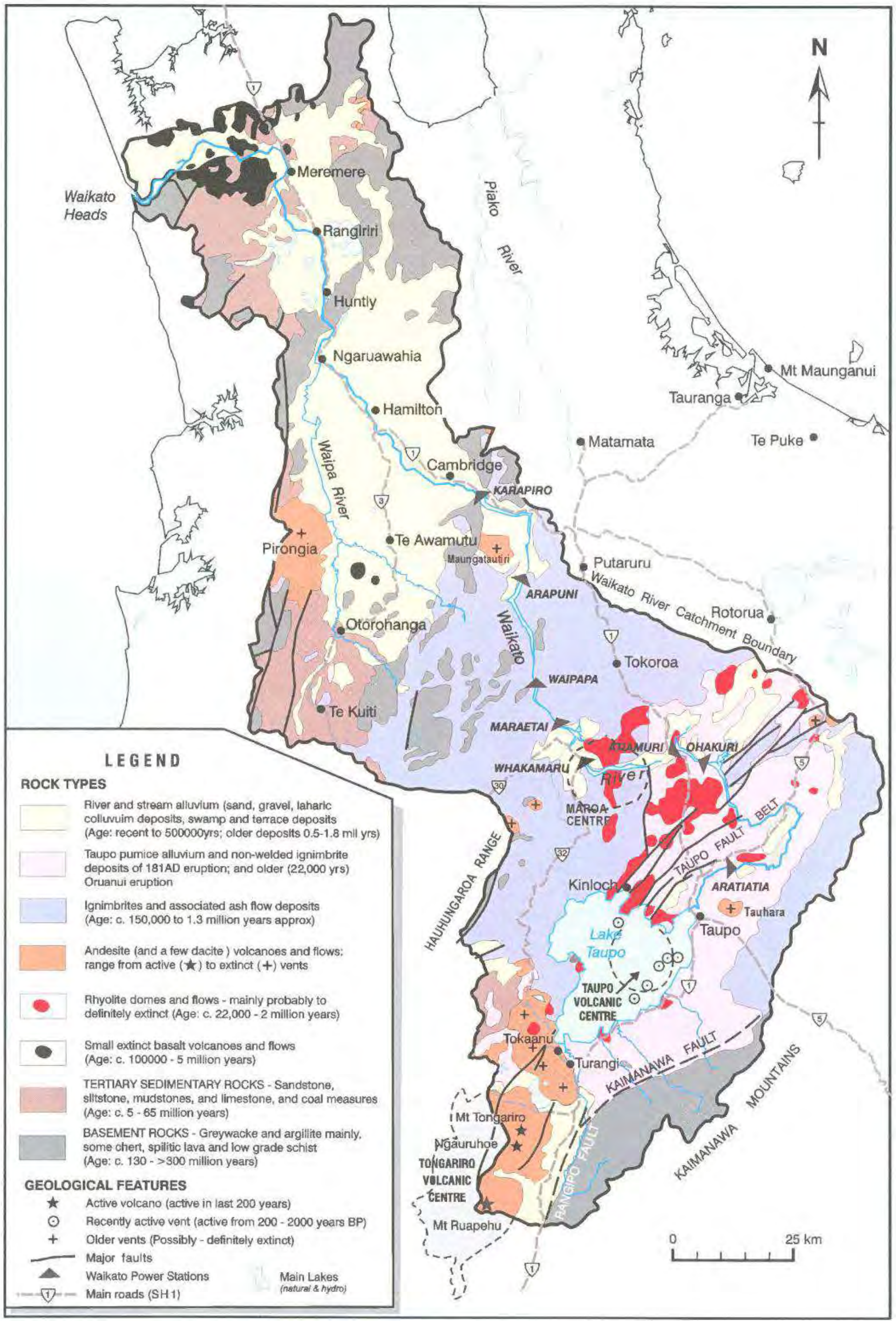


Figure 1.4: Geology of the Waikato River (Hancox, 2002).

2 Flood Modelling Approach

2.1 Introduction

As discussed, the risk of flooding and the potential extent and depth of inundation around Lake Taupō is a multi-factor problem. A number of factors combine to form a particular water level within the lake, and the same water level can be reached by the coincidence of different factors. It is possible to have the same water level with different frequencies, different water levels with the same frequency, and different water levels with different frequencies. The potential effect of a change in water level at the shore varies with topography, and beach profile and material; while its consequences may depend on the level of capital investment and development. The interaction of the water level with the shore, and whether flooding and inundation will occur, is therefore both a temporal and spatial problem.

2.2 Approach

Because of the above issues, this project has been approached from both temporal (magnitude and frequency) and spatial perspectives. A number of factors that affect the static water level of Lake Taupō (and therefore flooding and inundation) have been investigated. These include lake level, ground deformation, seiche, waves, and the potential effects of land use and climate change.

For each factor a literature search was conducted to identify, and where possible quantify, the potential effect of this factor on water levels within Lake Taupō. All available data relating to each factor were analysed to determine the magnitude and frequency of the factor's effect. The potential impact of each factor on the effective lake level for the 2.33, 5, 10, 20, 50, 100, 200 and 500-year return period events was quantified.

A high resolution digital terrain model (DTM) of the shoreline, and extending inland for 300-400m was constructed from LiDAR data. The majority of the LiDAR information was 'captured' during 2006. Additional data were subsequently obtained in 2009 for two areas; Waihi and Taupō Township. The DTM was therefore derived using the most recent data available for a particular area. The DTM was extended for approximately 1km along the lower reaches of the Tauranga Taupō and Tongariro Rivers to allow consideration of the additional flood risk posed by these rivers. The spatial resolution of this model was 2m, with an elevation accuracy of ±0.1m.

The magnitude and frequency data for each factor was mapped around the shoreline to provide a spatial coverage of its potential effect. These coverages have a spatial resolution of 2m. Each 'layer' of information can be analysed independently, or in combination, and overlaid on the DTM and aerial photographs to quantify the effect of any particular event and its potential impact.

Since the water level responds to various factors operating at the same time it was necessary to quantify the potential total effect of different combinations of factors. The total effect of these combinations of factors on lake level was then overlaid on the DTM to show which areas will be inundated, and to what depth. As well as illustrating the overall effect of particular parameter combinations, their effect on specific sites down to 2m resolution can be analysed.

The conversion of the various flood factors to spatial coverages, and their combination with the DTM, would allow 'fly-through' models to be constructed so that the effect of flooding on the landscape can be visualised as well as quantified.

2.3 Stationarity

Stationarity is a key assumption in all frequency analyses, including those used in this study. Stationarity implies (and it is therefore assumed) that the maxima or minima data series used in the analysis exhibit no trends or cycles; and that the extremes are drawn randomly and independently from a single statistical distribution. Implicit in this assumption is that the same processes and relationships that existed in the past will continue to apply in the future. For example, the relationship between rainfall and runoff during particular events will be the same. However, should anything change this relationship e.g., climate or land use change, the building of the Taupō Gates; the operating rules for the Taupō Gates; new regulations or resource consent conditions; or the operational management of the Waikato Hydro Scheme; then stationarity may no longer apply. When this occurs, the reliability of the frequency analysis, and any derived design events, may be questioned. Longer records have a greater likelihood of containing information relating to extreme events. Such records also tend to smooth any errors and other 'noise' which may be present in a data set. However, longer records increase the chance of violating the basic rule of stationarity because they have the potential to be more affected by land use, climate, or other changes.

3 Lake Level

3.1 Lake control

Flow down the Waikato River is controlled for power generation and flood mitigation purposes via the Taupō Gates that were commissioned in 1941. The Taupō Gates (and new outlet channel from Lake Taupō) manage outflow from the lake, and consequently their operation affects the water level in Lake Taupō. In 1947 the Lake Taupō Compensation Claims Act specified the maximum working level of Lake Taupō for power generation purposes (i.e. now accepted as 357.387m above mean sea level relative to the Moturiki Datum, 1956). If the water level exceeds this height, then affected landowners may claim for damages under certain situations. Table 3.1 shows a timeline of significant events that have influenced the management of the water level of Lake Taupō.

Table 3.1: Significant events that have influenced the operation of the Lake Taupō gates (Freestone, 2002).

Date	Event
June 1929	Arapuni Dam and power station commissioned
September 1941	Taupō Gates commissioned
1947	Lake Taupō Compensation Claims Act, maximum control level 357.387m
May 1947	Karapiro Dam and power station commissioned
1952	Maraetai dam and Maraetai I power station commissioned
1956	Whakamaru dam and power station commissioned
November 1958	Atiamuri dam and power station commissioned
January 1961	Ohakuri dam and power station commissioned
April 1961	Waipapa dam and power station commissioned
March 1964	Aratiatia dam and power station commissioned
1969	Seasonal Maximum Control Level*
July 1970	Maraetai II power station commissioned
February 1971	Western Diversion TPD commissioned
1972	Flood Rules developed and implemented
1977	Tongariro Offset Works Agreement
October 1979	Eastern Diversion TPD commissioned
September 1992	Whanganui intake minimum flow decision came into effect. 3m^3/s minimum flow at Whakapapa Intake
February 1993	Whanganui intake minimum flow decision came into effect. 29m^3/s minimum flow at Whanganui River at Te Maire
August 2003	Mighty River Power Ltd resource consents granted, but appealed
December 2004	Genesis Energy resource consents granted
April 2006	Mighty River Power Ltd resource consents came into effect

* Maximum Control Level is the maximum lake level set by Waikato Regional Council under current resource consent conditions.

In addition to utilising runoff from the catchment tributaries, the Tongariro Power Development (TPD) scheme was constructed to provide generation through the Tokaanu and Rangipo Power Stations and increase flow into Lake Taupō (Figure 3.1). The western diversion, which was commissioned in February 1971, diverts flow from the headwaters of the Whanganui River into Lake Rotoaira via a tunnel and canal system. The eastern diversion, which has been operating since October 1979, diverts water from the Moawhango River and tributaries of the Whangaehu River into the Tongariro River. Both schemes divert water through the Tokaanu Power Station. The TPD diversions cease when the maximum control level of Lake Taupō is reached (357.25masl) or for operational reasons; such as during floods to minimise the transport of sediment into the system.

Figure 3.1: The Tongariro Power Development (Te Ara, 2008).

During flood conditions in the lower Waikato River outflow from Lake Taupō is regulated. The High Flow Management Plan and Flood Management Rules document how the Waikato Hydro System will be managed in the lead up to, and during, flood conditions. The High Flow Management Plan outlines the objectives when managing the flood risk, while the Flood Rules specify prescriptive actions necessary during the flood event.

Mighty River Power Ltd's resource consent conditions state that water cannot be held in Lake Taupō for electricity generation purposes when the lake level is above 357.25masl. The Taupō Gates were not designed as a flood management system, and therefore Mighty River Power Ltd's ability to modify the levels of Lake Taupō is limited (Mighty River Power, 2005). Outflow can, however, be managed to some extent at the request of Waikato Regional Council, and in conjunction with the flood rules, to limit downstream flooding. This is particularly relevant if the Waipa River is also in flood so as to avoid the coincidence of the flood peaks in the lower Waikato River (refer to the Flood Management Rules).

The normal operating range of Lake Taupō varies between a minimum control level of 355.85m and a maximum control level of 357.25m (Figure 3.2). During flood events the maximum control level can be exceeded, but the lake must be operated in accordance with the Flood Management Rules. The July 1998 flood peaked at 357.49m and had a return period of 117 years (using the 1980-2013 actual lake level record and assuming a PE3 statistical distribution). This was less than the highest recorded lake level of 357.72m; but that occurred in 1909 prior to commissioning of the Taupō Gates and the construction of a larger outlet channel.

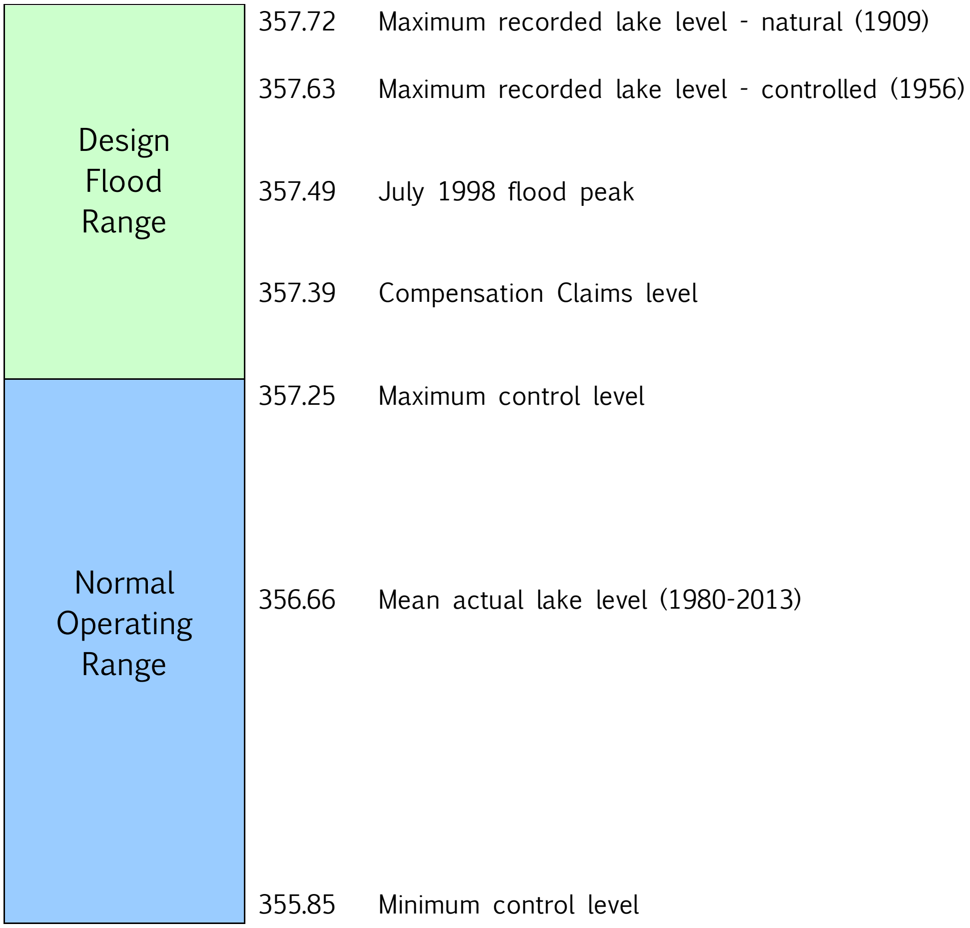


Figure 3.2: Key levels for Lake Taupō (m). Note: These are static levels using 3-hour average lake levels (ignoring any wave effects). Elevations are relative to mean sea level defined by the Moturiki datum (1956). The limits are rounded to two decimal places.

3.2 Taupō lake level

Mighty River Power Ltd's hydrometric archive, maintained by Opus International Consultants, contains two Lake Taupō level records. The first is the actual lake level recorded relative to the Taupō Fundamental Benchmark, levelled to the Moturiki datum in 1956. The second is a synthesised 'natural' lake level record which assumes that: Lake Taupō has no control structure; that the outflow channel capacity had not been increased; and that water is not diverted into the lake via the Tongariro Power Development Scheme. Both these records contain 3-hourly average water level data.

Since the installation of the Taupō Gates, the variation in actual lake level has been very similar to what would have occurred under a natural regime, except for a brief period of high levels during the mid-1940s. This was prior to the passing of the Lake Taupō Compensation Claims Act (Table 3.1). Between 1980 and 2013 the actual record had a mean lake level of 356.663m compared to what would have been a mean natural lake level of 356.665m. That is, the mean actual lake level was only 2mm lower than what the estimated mean natural lake level would have been over this period.

Figure 3.3 compares the simulated and actual lake levels from 1941 to 2013. This is the situation since the installation of the Taupō Gates, but it includes the record prior to the commissioning of the Tongariro Power Development Scheme. The figure shows only small variations between the actual levels and what would have been the natural levels. Overall the actual lake level has been slightly higher than under natural conditions (i.e. ~150mm), although the maximum lake levels are very similar. Slightly lower levels have also been maintained on occasion.

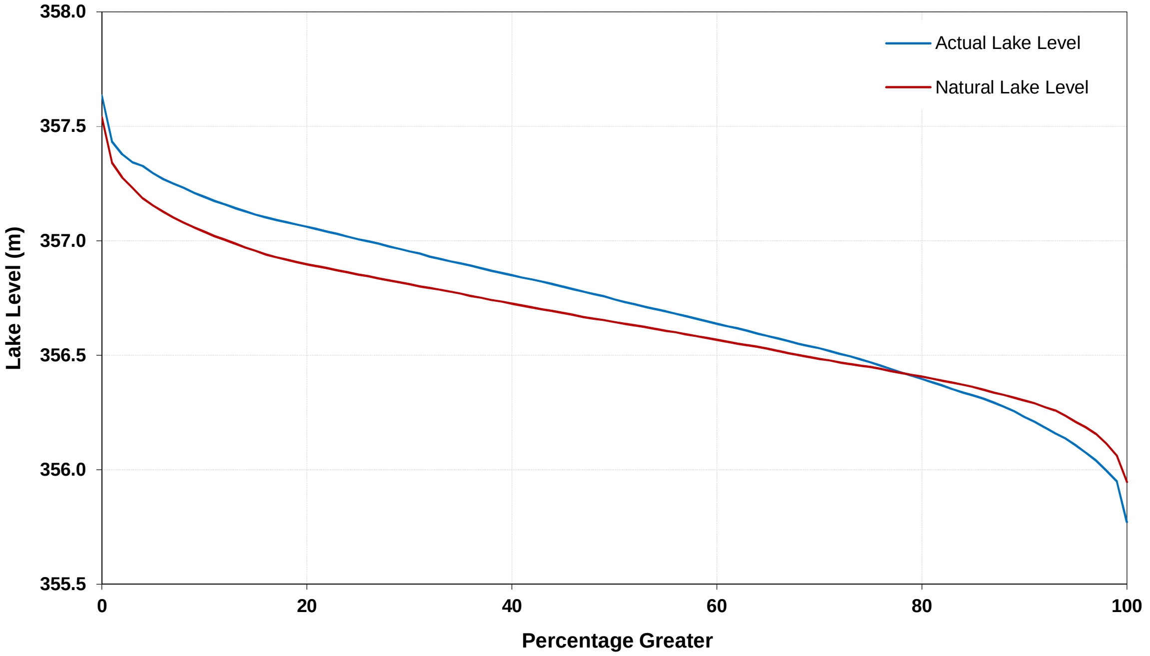


Figure 3.3: Percentage of time that lake levels were exceeded (1941-2013).

Figure 3.4 compares the distribution of lake levels only between 1980 and 2013. This is the period since the commissioning of the TPD Scheme. It includes the period since Mighty River Power Ltd have been operating the Waikato Hydro System, and following the granting of the current consents in 2006. This period excludes the high lake levels experienced during WWII following the commissioning of the Taupō Gates. Under natural conditions Lake Taupō would have spent slightly more time above 357.2m, while the actual lake level has spent slightly more time below 356.5m.

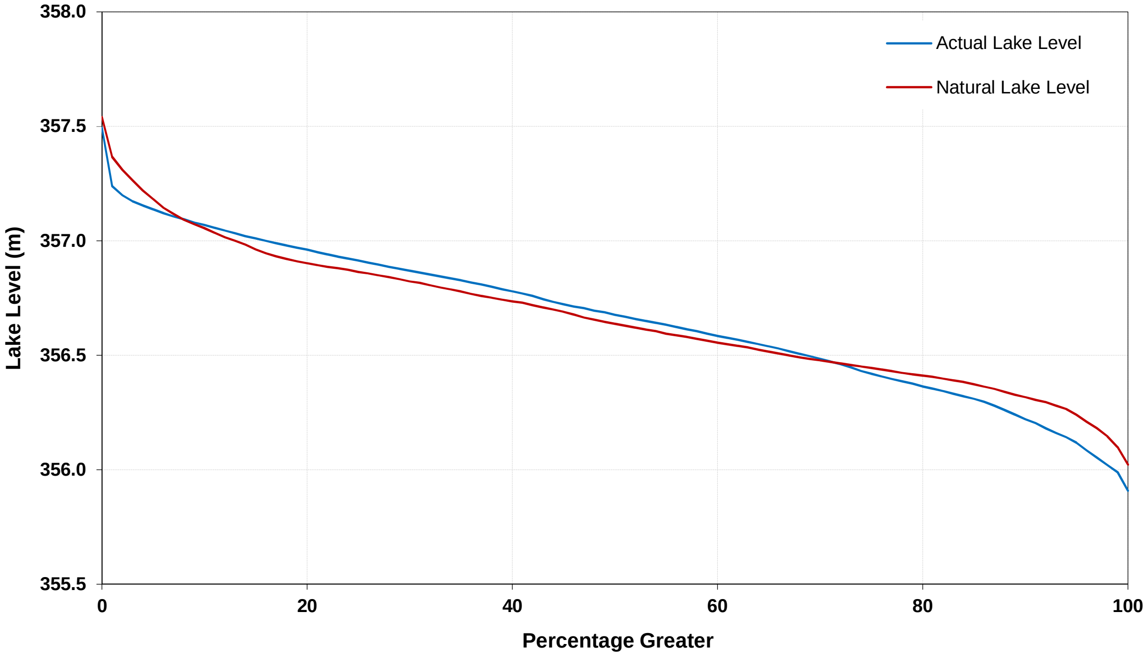


Figure 3.4: Percentage of time that lake levels were exceeded (1980-2013).

Figure 3.5 compares the actual (managed) and what would have been the natural lake levels between 1941 and 2013. While the actual levels differ slightly, the seasonal and annual patterns of change in water level are almost identical in the two records.

Table 3.2 lists the annual maximum lake level based on both the actual and the natural lake level records; and the actual inflow to, and outflow from, Lake Taupō. The largest 10 events are highlighted in bold text. The highest lake levels occurred in the early part of the record; prior to the commissioning of the Taupō Gates and the increased outlet channel. The largest inflows and outflows have predominantly occurred since the completion of the Tongariro Power Development Scheme. It should be noted that this is despite the fact that inflow from the Tongariro Power Development Scheme reduces, and potentially ceases, during major flood events.

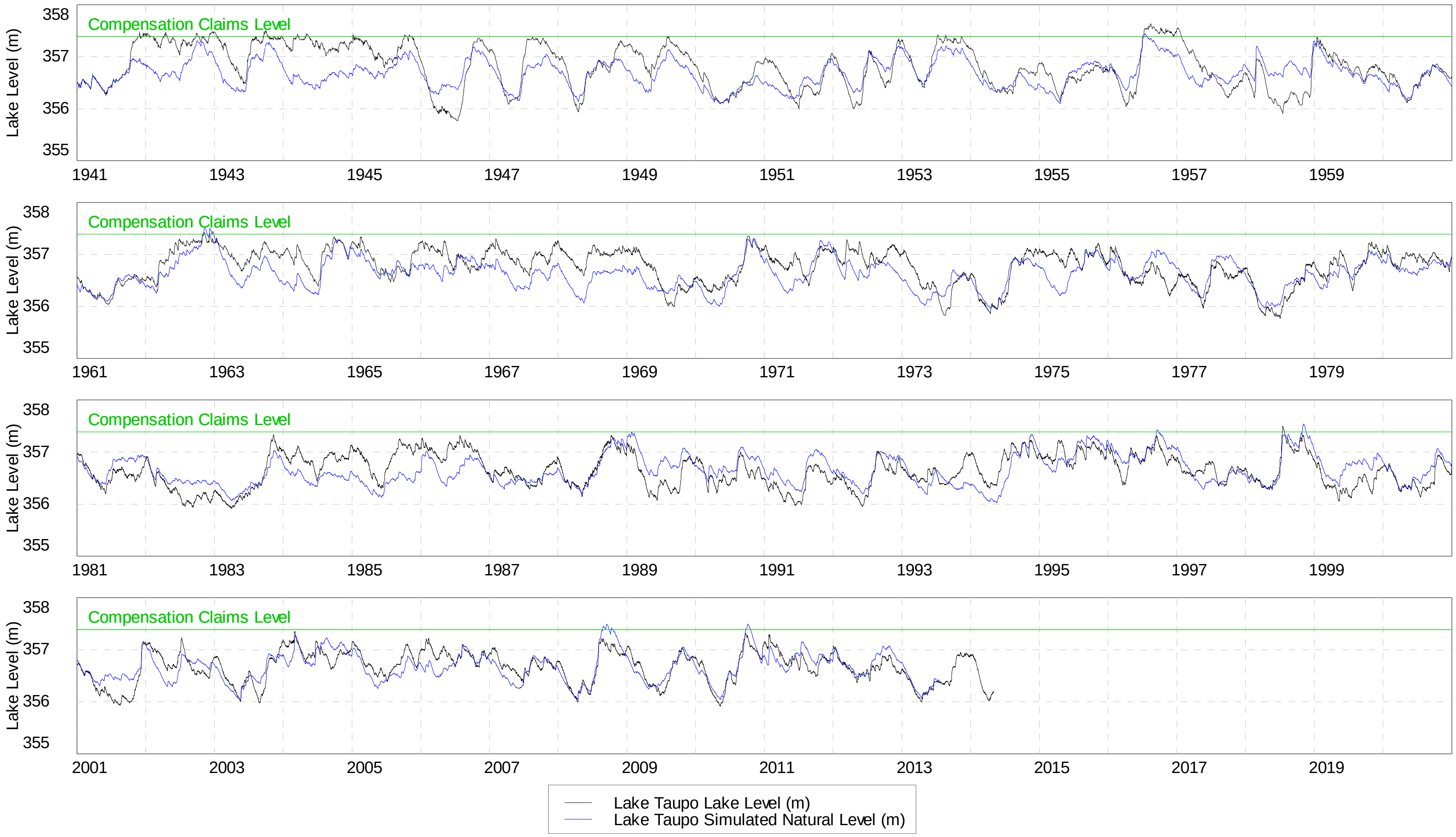


Figure 3.5: Comparison of Taupō Actual and the Taupō Natural lake level records (1941-2013). The Compensation Claims level of 357.387m is marked in green.

Table 3.2: Annual maximum recorded 3-hourly lake levels (both actual and natural), which has also removed any seiche signal, and the average daily inflows and outflows from Lake Taupō.

Year	Actual Lake Level (m)	Natural Lake Level (m)	Outflow (m^3/s)	Inflow (m^3/s)
1906	357.235	357.228	186	415
1907	357.418	**357.410**	208	**858**
1908	356.991	356.988	159	367
1909	**357.723**	**357.723**	246	446
1910	357.119	357.120	173	412
1911	356.839	356.838	143	306
1912	357.235	357.235	186	365
1913	357.052	357.052	166	321
1914	357.037	357.038	164	326
1915	357.144	357.144	176	673
1916	357.205	357.204	183	412
1917	357.235	357.234	186	336
1918	357.174	357.174	179	317
1919	357.052	357.053	166	423
1920	356.991	356.987	159	247
1921	356.930	356.930	152	316
1922	356.930	356.930	152	333
1923	356.839	356.839	143	347
1924	356.991	356.990	159	289
1925	357.296	357.296	193	665
1926	**357.631**	**357.631**	235	802
1927	**357.455**	**357.455**	212	467
1928	357.388	357.388	204	438
1929	357.116	357.113	173	339
1930	357.174	357.174	179	330
1931	356.869	356.869	146	234
1932	356.710	356.713	130	280
1933	356.748	356.736	134	377
1934	356.748	356.748	134	804
1935	357.174	357.174	179	406
1936	357.235	357.235	186	584
1937	356.839	356.839	143	508
1938	356.717	356.717	130	514
1939	356.813	356.808	140	397
1940	357.001	356.991	160	514
1941	**357.464**	356.969	176	461
1942	**357.479**	357.307	214	453
1943	**357.494**	357.278	280	532
1944	**357.433**	356.794	273	551
1945	357.418	357.114	278	557
1946	357.357	357.189	276	451
1947	357.372	357.046	258	487
1948	357.311	356.965	219	415
1949	357.388	357.138	216	597
1950	356.925	356.639	182	492
1951	357.068	356.969	186	544
1952	357.342	357.207	219	535
1953	357.421	357.210	239	506
1954	357.162	356.860	174	384
1955	356.885	356.915	181	411
1956	**357.634**	**357.442**	240	656
1957	**357.555**	357.058	194	360
1958	357.222	357.301	206	**1357**
1959	357.372	357.305	211	549
1960	356.863	356.837	173	495
1961	356.623	356.615	200	348
1962	357.418	**357.504**	274	696
1963	357.314	357.327	267	516
1964	357.342	357.281	266	719
1965	357.336	357.128	219	557
1966	357.266	356.999	249	629
1967	357.305	356.911	237	776
1968	357.253	356.824	215	487
1969	357.141	356.763	225	469
1970	357.348	357.309	289	544
1971	357.174	357.272	280	567
1972	357.287	357.065	**350**	658
1973	357.083	356.707	259	747
1974	357.125	356.936	267	532
1975	357.215	357.097	274	677
1976	357.150	357.089	267	718
1977	356.868	356.990	252	751
1978	356.863	356.704	253	694
1979	357.239	357.075	278	627
1980	357.175	357.004	279	504
1981	356.983	356.948	266	457
1982	356.914	356.890	260	729
1983	357.332	357.026	291	497
1984	357.137	356.785	282	417
1985	357.252	356.626	293	634
1986	357.319	357.013	293	**850**
1987	356.912	356.700	265	604

Year	Actual Lake Level (m)	Natural Lake Level (m)	Outflow (m³/s)	Inflow (m³/s)
1988	357.319	357.276	293	832
1989	357.176	357.380	283	670
1990	356.997	357.099	272	791
1991	356.775	357.054	257	778
1992	357.023	357.012	274	552
1993	356.989	356.873	254	594
1994	357.233	357.336	291	**887**
1995	357.232	357.315	289	**859**
1996	357.311	**357.433**	297	717
1997	356.900	357.092	268	451
1998	**357.493**	**357.541**	**316**	**998**
1999	356.841	357.044	261	700
2000	356.946	357.070	277	**842**
2001	357.159	357.128	293	**960**
2002	357.223	357.098	**298**	634
2003	357.192	356.931	273	678
2004	357.348	357.277	**318**	**986**
2005	357.161	357.039	**302**	520
2006	357.221	357.101	**308**	662
2007	357.048	356.889	294	490
2008	357.214	**357.491**	**309**	720
2009	357.077	357.054	**299**	484
2010	357.316	**357.494**	**319**	625
2011	357.297	357.150	**317**	**1024**
2012	357.074	357.077	292	747
2013	356.952	356.763	291	638

Frequency analyses of both lake level records were conducted to estimate the lake levels of the annual (2.33), 5, 10, 20, 50, 100, 200 and 500-year return period events. The entire record (1906-2013); the record for the managed operation since the commissioning of the Taupō Gates and prior to TPD (1942-1970); and the record since the commissioning of the Tongariro Power Development Scheme (1980-2013) were analysed. Differences exist between the estimates of the lake level for various return periods under the different regimes. For example, the passing of the Compensation Claims Act and changes to the Maximum Control Level have influenced the occurrences of high lake levels.

Gumbel, Pearson 3 (PE3), and Generalised Extreme Value statistical distributions were all fitted to the annual maxima series to check which provided the best model of extreme values. The PE3 statistical distribution was preferred for all three periods of record (Figure 3.6). Table 3.3, Table 3.4, and Table 3.5 list the lake levels 'expected' for eight return periods, using different periods of record and the most appropriate frequency distribution.

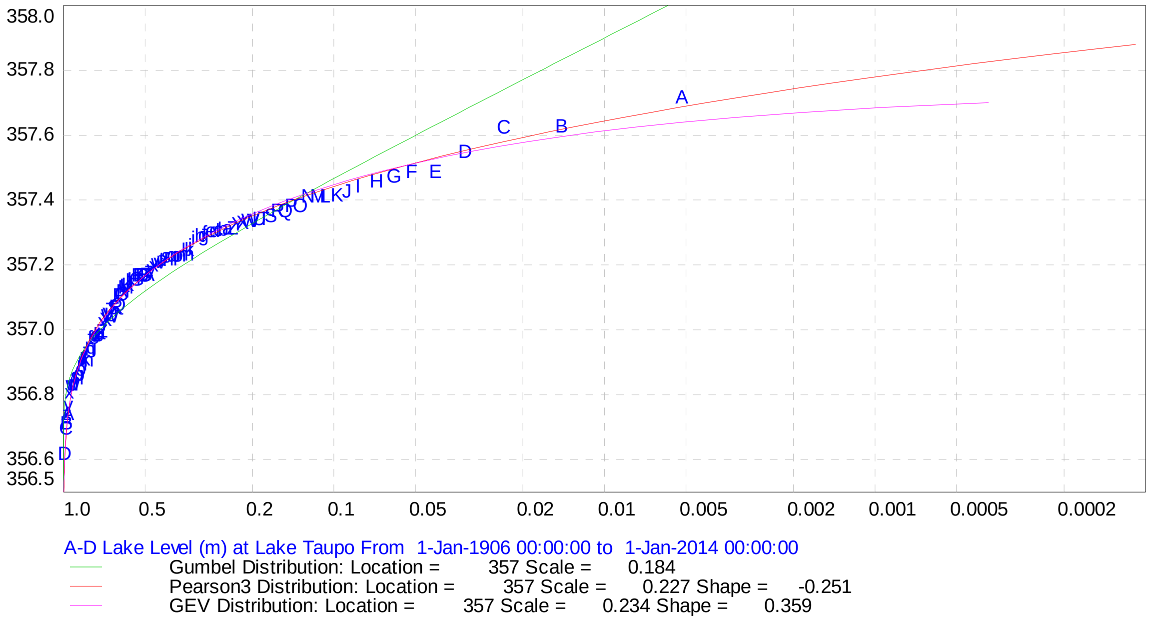


Figure 3.6: Lake Taupō level frequency analyses graph, 1906-2013.

Table 3.3: Lake Taupō level frequency analyses, 1906-2013 (PE3 distribution).

Return Period	Actual Lake Level 1906-2013 (m)	Natural Lake Level 1906-2013 (m)
2.33	357.21	357.11
5	357.35	357.27
10	357.44	357.38
20	357.51	357.48
50	357.59	357.59
100	357.64	357.66
200	357.69	357.73
500	357.74	357.82
Maximum Recorded	*357.72*	*357.72*

Table 3.4: Lake Taupō level frequency analyses, 1942-1970 (PE3 distribution).

Return Period	Actual Lake Level 1942-1970 (m)	Natural Lake Level 1942-1970 (m)
2.33	357.37	357.14
5	357.46	357.29
10	357.50	357.38
20	357.53	357.45
50	357.54	357.52
100	357.55	357.57
200	357.55	357.61
500	357.56	357.66
Maximum Recorded	*357.63*	*357.50*

Table 3.5: Lake Taupō level frequency analyses, 1980-2013 (PE3 distribution).

Return Period	Actual Lake Level 1980-2013 (m)	Natural Lake Level 1980-2013 (m)	Mighty River Power Ltd's consented levels
2.33	357.18	357.11	
5	357.28	357.27	*357.25*
10	357.35	357.39	
20	357.40	357.49	*357.39*
50	357.45	357.60	
100	357.49	357.68	*357.50*
200	357.52	357.75	
500	357.55	357.85	
Maximum Recorded	*357.49*	*357.54*	

It should be noted in Table 3.5 that the 'target' exceedance levels set in Mighty River Power Ltd's resource consent conditions (granted in 2006) for operating the Taupō Gates are very close to the levels estimated for the same return periods in this study. The small differences are the result of the additional data which have been collected since the resource consent process.

3.3 Assumptions

In this study the data record from 1980 to the end of 2013, and therefore the estimates of lake levels in Table 3.5, are preferred. Although this is a shorter length of record, it includes only data from when the lake and its inflows have been managed in a more consistent manner. For example, this is the period since the commissioning of the TPD, since Mighty River Power Ltd have been operating the Waikato Hydro System, and following the granting of the current consents in 2006. It therefore limits the potential impact of non-stationarity of data that may be an issue if the longer data record was analysed. This approach precludes the inclusion of the highest recorded lake level (i.e., 1909). However, discussions with Mighty River Power Ltd's operators, and reference to the Flood Management Rules, indicate that should such an event occur under current management the levels would not have been so high. Its inclusion in any analysis would therefore have the potential to distort unrealistically any estimates of extreme lake levels.

Impact of resource consents

This analysis has assumed that the future operation of the Taupō Gates will result in substantially the same pattern of lake level variation as discussed above. The most recent consents granted to Mighty River Power Ltd to manage the level of Lake Taupō were granted in 2006.

Figure 3.7 shows that the pattern of lake level variation is very similar over the 10-years prior to and after the granting of these resource consents. The dominant control on lake level variation is the inflow regime; not management decisions relating to flood mitigation or hydro power generation.

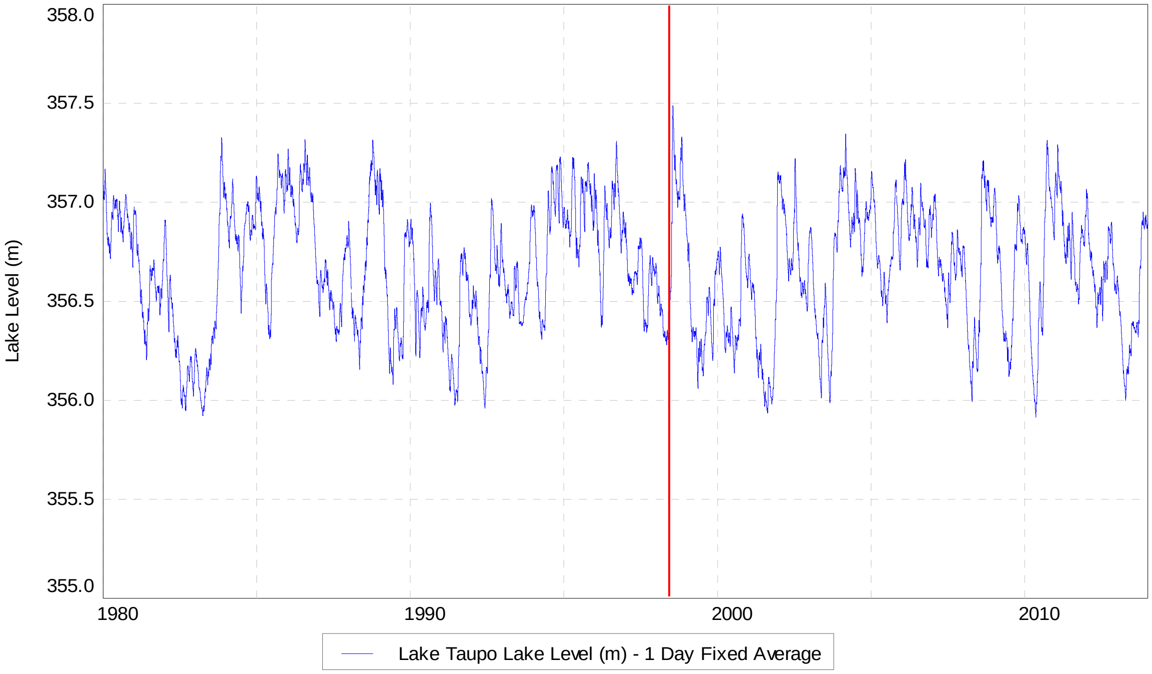


Figure 3.7: **Daily average lake levels between 1980 and 2013. The move to a single MCL is indicated by the red line.**

This is consistent with the findings of a detailed analysis of the variability of lake level and inflows over various time periods presented in Opus (2012). That analysis showed that:

- The actual lake level regime is very similar to what would have been the natural regime without the TPD inflows and construction of the Taupō Gates. The management regime, however, has reduced the incidence of extremely high lake levels.
- Both the natural variability and seasonality of lake level fluctuations have been preserved in the actual managed lake level record.
- Periods of higher than average lake levels are related to higher inflows from the tributaries rather than the influence of management decisions. In fact, the management regime has reduced some of the lake level variability that higher inflows would have caused under an entirely natural regime.
- The higher lake levels experienced during the 2004-2007 period reflect the fact that two of these years had significantly higher inflows than expected on average. The higher lake levels are a response to these higher inflows rather than a change in the

management regime. These higher lake levels were therefore a largely natural phenomenon.

- The maximum difference between actual and natural levels tends to occur during March to June. The difference experienced over the 2004-2011 period is about 40cm less than over the entire record, or from 1942-1971. That is, all other things being equal, the management regime of the lake actually kept the maximum water levels approximately 40cm lower over this period than would have occurred over the other time periods. Given that the inflows for this period were significantly higher than average, the current management regime appears to be controlling maximum lake levels better than in the past.

3.4 Summary

The water levels of Lake Taupō are a function of the interaction of a number of factors, including: the rainfall and runoff regime into the lake; lake level management for flood control and hydro power generation; and regulation imposed conditions.

In 1941 a new outlet from Lake Taupō was formed with a greater capacity than the original natural outlet. A set of gates were also installed to control the flow through the new outlet. Prior to 1941 therefore the water level of Lake Taupō fluctuated as function of the difference between the inflow and outflow through the natural channel. Following the construction of the new outlet, and the installation of the Taupō Gates, the level of Lake Taupō has varied as a function of the difference between inflows and controlled outflows. Consequently, since 1941 variations in lake level have to some degree been managed.

It should be noted therefore that 'natural' levels are not the same as 'un-managed' levels. The modelled natural lake level series assumes that the new outlet channel had not been formed, that there are no inflows from the Tongariro Power Development Scheme, and that there is no lake level management. Since the installation of the Taupō Gates an 'un-managed' regime is not possible.

The current consents for operating the Taupō Gates are for 35 years. Management strategies and priorities beyond this period are not known. However, assuming no dramatic shifts in societal goals and aspirations, and that management under the present consents proves to be sustainable, the most likely scenario for the future is that the lake level regime will be similar to that from 1980-2013.

The actual lake level record from 1980-2013 is considered to be the most appropriate to use in any analysis at this time. A PE3 distribution fits the annual maxima of these data most closely. Based on the above assumptions, the water level of Lake Taupō could be expected to reach the elevations listed in Table 3.6 during events with different frequencies of occurrence.

Table 3.6: Expected level of Lake Taupō for various return periods using data from 1980-2013 and assuming a PE3 distribution.

Return Period	Lake Level (m)
2.33	357.18
5	357.28
10	357.35
20	357.40
50	357.45
100	357.49
200	357.52
500	357.55
1000	357.57

It is therefore recommended that the estimates for the lake level at various return periods shown in Figure 3.8 (and in Table 3.6) are the most appropriate to use when quantifying the flood hazard. It should be noted that the total range in the maximum lake level likely to be experienced between once every 2.33 years and once every thousand years is only 0.39m.

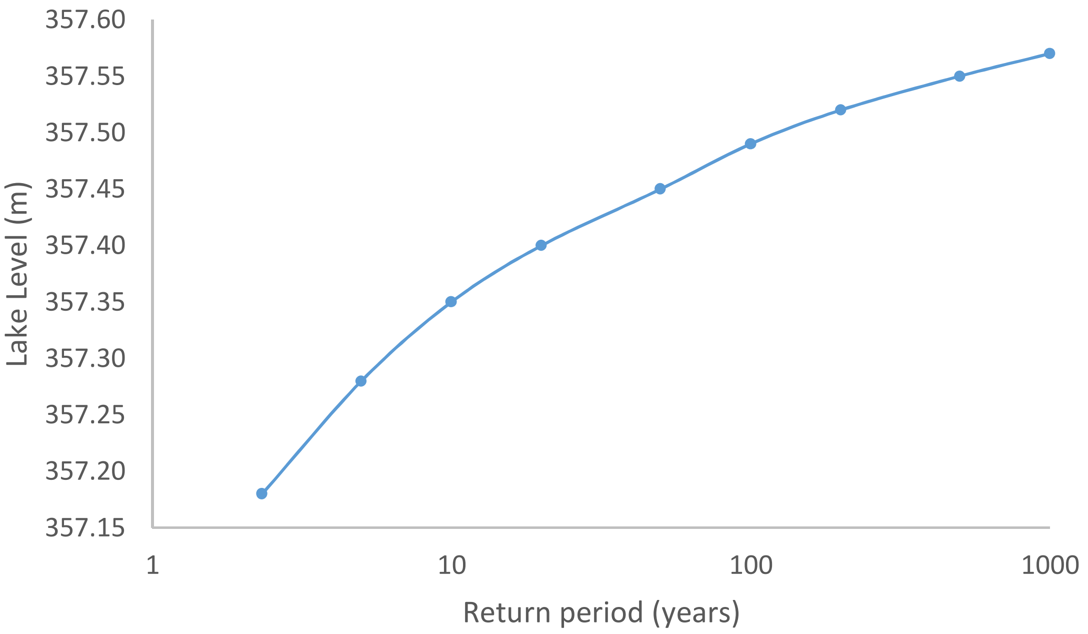


Figure 3.8: Estimates of lake levels at different return periods using data from 1980-2013 and assuming a PE3 distribution.

In addition to the flood levels presented in Table 3.6, and displayed in Figure 3.8, key lake levels (using the 1980-2013 actual lake record and a PE3 distribution) are:

- The maximum normal operating level of 357.25m has a 4-year return period;

- The Compensation Claims level of 357.387m has a 17-year return period; and
- The maximum recorded level of 357.49m (1998) has a return period of 117-years.

It should be noted that all lake level data for Lake Taupō are in terms of the 1956 level of the Taupō Fundamental Benchmark of 363.27m (Lake Taupō Compensation Claims Act 1947, 1979). The last time the level was brought from Moturiki Island to the Taupō Fundamental Benchmark was in 1977. The level at that time was 363.16m (Freestone *et al.*, 2001).

4 Climate Change Effects

4.1 Introduction

Global warming will cause more than just a rise in the world's temperature. Warmer temperatures mean that more water vapour will enter the atmosphere. Higher temperatures will also increase the ability of the air to hold moisture. Apart from higher temperatures therefore, the greatest effect of climate change is likely to be on water resources. Furthermore, sensitivity analysis has indicated that changes in rainfall are always amplified in runoff, and this effect is greater in drier catchments (Ministry for the Environment, 2008).

In New Zealand temperatures are likely to increase faster in the North Island than in the South Island; but generally less than the global average because of the moderating effect of the surrounding oceans. Rainfall is projected to increase in the west of the country and decrease in many eastern regions. This will increase regional differences. Extremely heavy rainfall events could become more frequent in many areas and this will increase the risk of flooding and erosion. While these general trends are considered relatively robust, the magnitude of the potential changes depends on which scenario, and which climate model, is used. This is particularly the case when considering local rainfall patterns. Therefore, while there is some confidence in the general trends expected, less certainty exists when predicting the changes in temperature and rainfall at particular places.

The Intergovernmental Panel on Climate Change (IPCC) have concluded that more intense, and more frequent, precipitation events are likely over many areas. One study concluded that the frequency of heavy precipitation events could increase up to fourfold by 2090; although it did not rule out that no discernible increase would occur. Areas most prone to such events include the central plateau of the North Island, but even in drought-prone areas the risk of extremely heavy rainfall is expected to increase (Ministry for the Environment, 2008).

4.2 Latest IPCC information

IPCC (2014) evaluates how patterns of risks and potential benefits are shifting because of climate change, and how these risks can be reduced through mitigation and adaptation. It recognizes that the risks of climate change will vary across regions and populations, and through space and time.

A series of new Representative Concentration Pathways (RCPs) are adopted that largely replace the IPCC emission scenarios (SRES). Projected climate change based on the RCPs is similar to the conclusions of the Fourth IPCC Assessment Report (AR4 – 2007) in both patterns and magnitude, after accounting for scenario differences. Global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3°C to 0.7°C (medium confidence). This assessment is based on multiple lines of evidence and assumes there will be no major volcanic eruptions or secular changes in total solar irradiance.

IPCC projects (medium confidence) that river flows originating in the north-east of the South Island and north of the North Island will decline. Rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure and housing (IPCC, 2014).

Temperatures are projected to rise at about 70% of the global rate, because of the buffering effect of the oceans around New Zealand. Continued decreases in frost frequency, and increases in the frequency of high-temperature extremes, are expected but have not been quantified (IPCC, 2014).

There is high confidence that the El Niño-Southern Oscillation (ENSO) will remain the dominant cause of inter-annual variability in the tropical Pacific, with global effects in the 21st century. As a result of the increase in moisture availability, ENSO related precipitation variability on regional scales will likely intensify. Natural variations of the amplitude and spatial pattern of ENSO are large and thus confidence in any specific projected change in ENSO and related regional phenomena for the 21st century remains low.

While it appears as though the spread of projections in IPCC (2014) is narrower than for the comparable scenarios in IPCC (2007), the relevant climate data have not been statistically downscaled for New Zealand. Consequently much of this later information cannot be used to predict the likely effects of climate change on the inflows and water levels of Lake Taupō.

4.3 Taupō Flood Studies

Opus (2008) used information in MfE (2008) to determine the potential increase in flood flows. That report was created as a guidance manual for New Zealand and incorporated the science produced by the IPCC in its Fourth Assessment (AR4) (IPCC, 2007). The Ministry for the Environment subsequently updated MfE (2008), and produced MfE (2010) *Tools for Estimating the Effects of Climate Change on Flood Flow.* Both these reports, however, use the science produced in the IPCC in its Fourth Assessment (IPCC, 2007). Consequently there is currently no change to the projected increases in temperature and rainfall with respect to Lake Taupō.

The IPCC Fourth Assessment (IPCC, 2007) developed 40 different future emissions pathways or scenarios (referred to as 'SRES' scenarios) which fall into four 'families' (A1, A2, B1 and B2). Each family envisages a different future, with different levels of technological development and global economic integration.

There are six SRES 'illustrative' scenarios, each broadly representative of its 'family' and spanning a reasonable range of plausible futures. From lowest to highest in terms of temperature projections, they are: B1, A1T, B2, A1B, A2 and A1F1. The Taupō Flood Hazard Study reports use the 'middle-of-the-road' A1B scenario.

To identify likely future climate changes across New Zealand projected changes from General Circulation Models are statistically downscaled. This method translates the coarse-scale information to the local scale. Historical observations are used to develop regression equations that relate local climate fluctuations to changes at a larger scale. These downscaled projections follow the approach of the Fourth Assessment report i.e. changes relative to 1980-1999, which can be abbreviated as '1990'. Changes are calculated for two future periods: 2030-2049, i.e. '2040'; and 2080-2099, i.e. '2090'. Thus, the New Zealand projections, and therefore those used in the Taupō Flood Hazard Study, are for changes over time periods of 50 and 100-years from the baseline climate ('1990').

Downscaled projections of the changes in mean temperature over New Zealand are divided into regional council areas. The Taupō Flood Hazard Study reports were based on the 'Waikato' predictions and the annual projected change was used rather than that for individual seasons. These changes in annual mean temperature has implications for a number of social and economic factors but also for physical/environmental factors. One of these factors is an increase in extreme rainfalls and consequently increased inflows and potentially higher lake levels.

4.4 Potential impact of climate change

The inter- and even intra-regional variation in estimates of potential changes in temperature and rainfall make the exact impact of climate change on the level of Lake Taupō difficult to quantify. This difficulty is compounded further by:

- The fact that the level of the lake is managed for flood mitigation and hydro-power generation purposes; and
- The Ministry for the Environment's climate change guidelines provide only estimates of the amount of warming, and consequently the assumed potential increase in rainfall. They do not predict changes in streamflow or lake levels, or any other potential effect on the hydrological cycle (MfE, 2008). This is a significant gap in the current climate change literature.

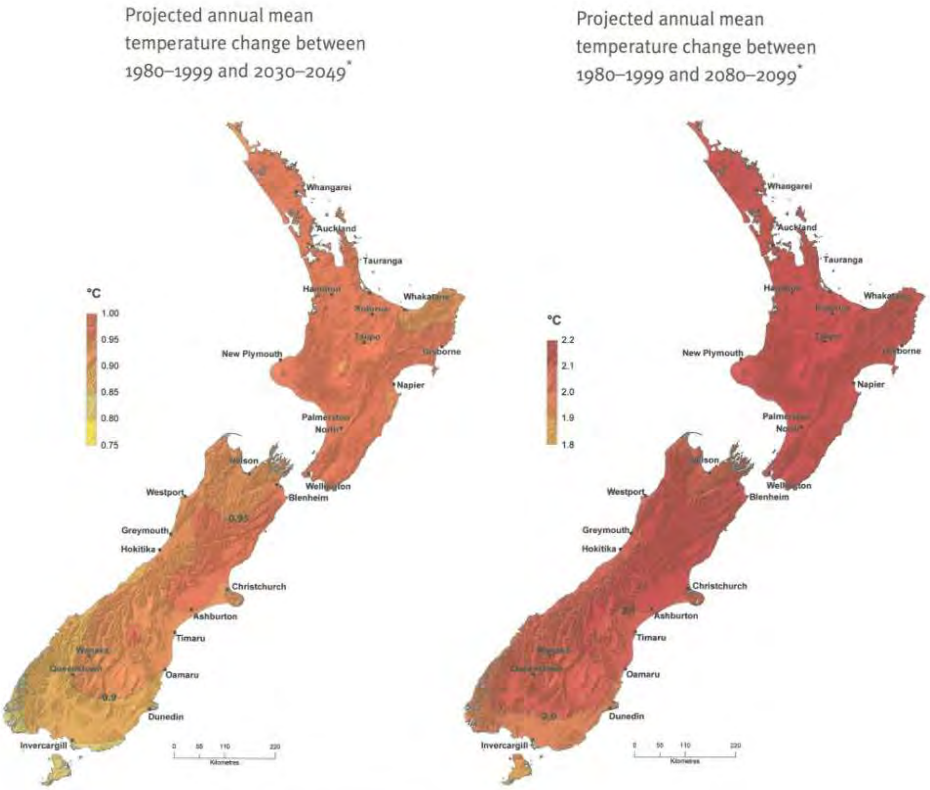
An attempt has therefore been made to correlate lake levels, inflows, and rainfall. Such an approach is valid given the large size of the Lake Taupō catchment, which should smooth any more subtle changes, and the buffering effect of the lake on inflows and outflows.

The operators of the Taupō Gates are required to maintain the level between an operating minimum and maximum of 355.85m and 357.25m respectively. The maximum outflow from the Taupō Gates and channel is approximately 310m³/s. Therefore, as long as inflows are less than this maximum outflow any increase as a result of climate change can be accommodated by increasing the outflow. It is important to note that the outlet channel capacity is now greater than that of the original natural channel.

Under most situations therefore any increase in inflow caused by climate change will not change lake levels significantly. However, during high or prolonged rainfall events when inflows exceed the maximum outflow capacity the lake level will rise. The frequency and magnitude of occasions when inflows exceed maximum outflows, and therefore lake levels rise, was therefore calculated both under the current climate regime (1980-2013) and projected climate change to the 2040s and the 2090s.

Methodology

A methodology has been developed for determining the projected increase in rainfall as a result of climate change in New Zealand (MfE, 2008 & MfE, 2010). The mean annual temperature for the Lake Taupō catchment is predicted to increase by between 0.2 and 2.4°C by the 2040s, and 0.6 and 5.6°C by the 2090s (Figure 4.1 and Figure 4.2). These data are summarised in Table 4.1.



Projected annual mean temperature change between 1980–1999 and 2030–2049*

Projected annual mean temperature change between 1980–1999 and 2080–2099*

Figure 4.1: Predicted increases in mean annual temperature by 2040 and 2090 relative to 1990; average of 12 climate models for A1B emission scenario (MfE, 2010a).

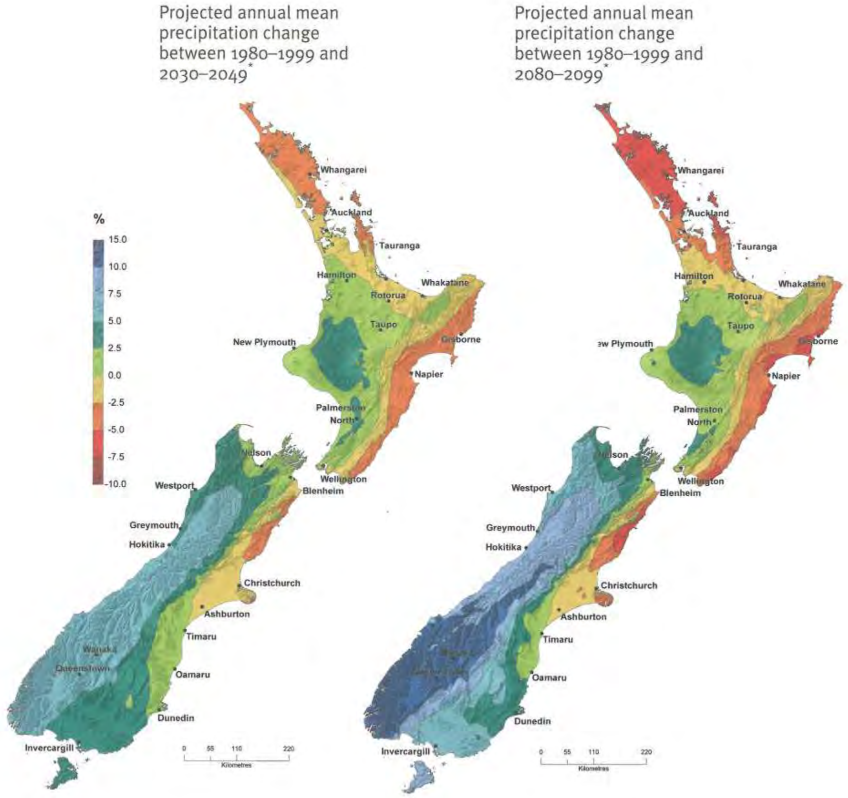


Figure 4.2: Predicted increases in rainfall by 2040 and 2090 relative to 1990; average of 12 climate models for A1B emission scenario (MfE, 2010a).

Table 4.1: Projected increases in mean annual temperature by 2040 and 2090 for the Lake Taupō catchment (MfE, 2010).

Scenario	2040 (°C)	2090(°C)
Lower limit	0.2	0.6
Average	0.9	2.1
Upper limit	2.4	5.6

Note: These data are from Tables 2 and 3 in Ministry for the Environment (2010). The original tables cover the period from 1990 (1980-1999) to 2040 (2030-2049) and 2090 (2080-2099) based on downscaled temperature changes for 12 global climate models, re-scaled to match the IPCC global warming range for six illustrative emission scenarios.

The MfE methodology recommends a percentage adjustment per degree of warming that should be applied to the high intensity rainfall totals to account for the effect of global warming. For example, a 24-hour duration 100-year return period rainfall will increase by 8 percent per degree of projected warming (highlighted in Table 4.2). Given the large size of both the Lake Taupō catchment and the lake itself a 24-hour duration rainfall event is considered appropriate when assessing the potential impact of climate change on inflows and lake levels.

Table 4.2: Percentage increase in rainfall per degree of warming for different rainfall durations.

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

Source: Ministry for the Environment, 2010.

Assuming temperature increases of between 0.2°C and 2.4°C (2040s) and 0.6°C and 5.6°C (2090s) for the respective scenarios, the 100-year return period rainfall likely to affect the Taupō catchment will increase by a maximum of 19.2% by 2040 and 44.8% by the 2090s (Table 4.3). This is based on the upper limits of the various global warming scenarios. The percentage increase will vary depending on the actual temperature increase, storm magnitude, and storm duration.

Table 4.3: Estimated percentage increase in 24-hour rainfall totals for Lake Taupō as a result of global warming.

Return period	2040			2090		
	Lower limit (0.2°)	Average (0.9°)	Upper limit (2.4°)	Lower limit (0.6°)	Average (2.1°)	Upper limit (5.6°)
2.3	0.9	3.9	10.3	2.6	9.0	24.1
5	1.1	4.9	13.0	3.2	11.3	30.2
10	1.3	5.7	15.1	3.8	13.2	35.3
20	1.4	6.5	17.3	4.3	15.1	40.3
50	1.6	7.2	19.2	4.8	16.8	44.8
100	1.6	7.2	19.2	4.8	16.8	44.8

Note: Guidelines for the effect of climate change on rainfall do not extend beyond 100 years

Relating rainfall to inflows and lake levels

As mentioned, there has been little work in New Zealand that quantifies the effect of global warming on runoff and lake levels. Therefore, since this study is particularly concerned with extreme events when catchment storage is approaching saturation, it has been assumed that an increase in rainfall will produce an equal and corresponding increase in runoff. This is likely to over-estimate the actual increase in runoff creating a conservative approach when assessing flood risk. Therefore the percentage increases in rainfall listed in Table 4.3 have been translated directly to percentage increases in inflow.

4.5 Uncontrollable rises in lake level

Daily average inflows between 1980 and 2013 were analysed to identify all occasions when inflows exceeded the maximum possible lake outflow (310m^3/s). These are periods when lake levels would rise even if there was no control of the Taupō Gates (Figure 4.3). By cumulating the excesses of inflow, and assuming a constant lake surface area of 615km^2, the potential 'natural' rise in lake level can be calculated.

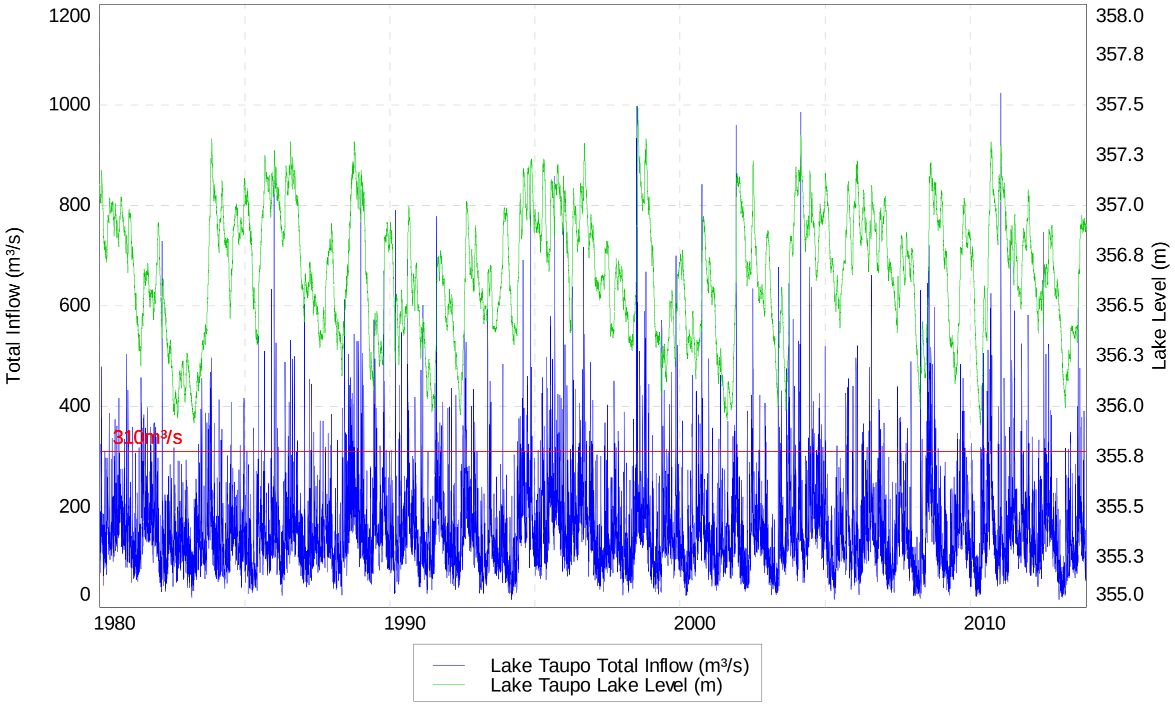


Figure 4.3: **Periods when inflows exceed the maximum outflow capacity of the Taupō Gates and the resulting 'theoretical' change in lake level (1980-2013).**

During this period (i.e. 1980-2013) average daily inflows exceeded the maximum average daily capacity outflow on 817 occasions (Figure 4.4). While the majority of these 'synthesised' flood events produce only minor increases in lake level, less than about 50mm, the December 2001 flood would have caused the lake to rise by approximately 296mm. This assumes that the Taupō Gates were discharging at maximum capacity (310m^3/s), and that no flow regulation or flood management actions were taken. If the Taupō Gates were shut, discharging the minimum required flow of 30m^3/s, the lake level would rise an additional 39mm each day.

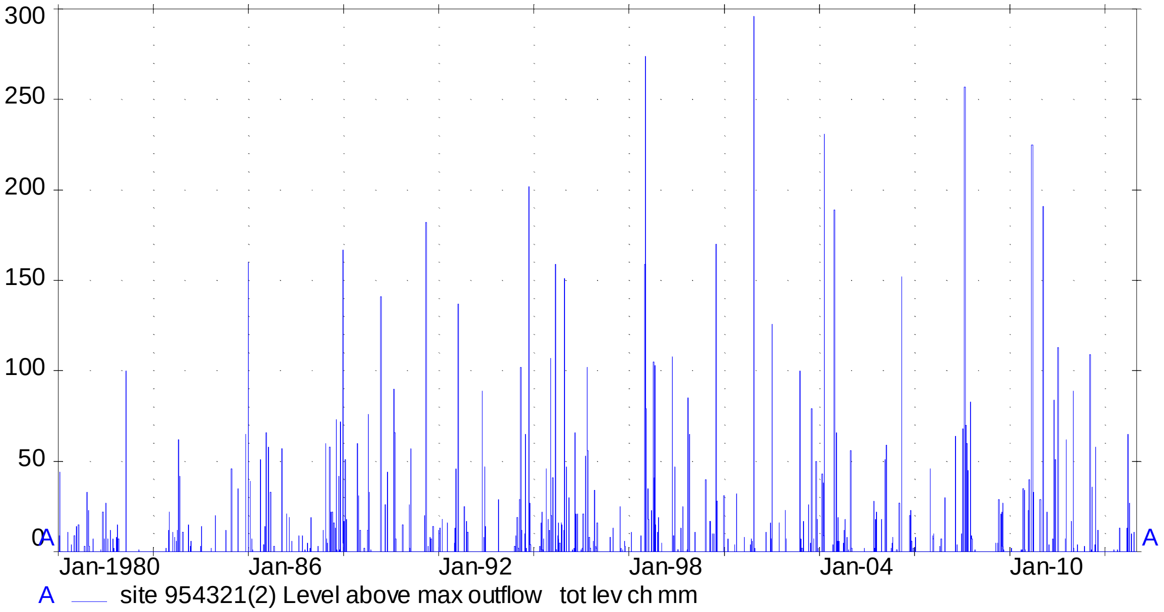


Figure 4.4: Increase in lake level for 'flood' events as a result of inflows exceeding the maximum outflow capacity of the Taupō Gates (1980-2013).

The longest consecutive period over which inflows exceeded the maximum outflow capacity was 14 days; during the 2010 flood. The maximum daily increase in lake level was 55mm during the July 1998 flood (Figure 4.5).

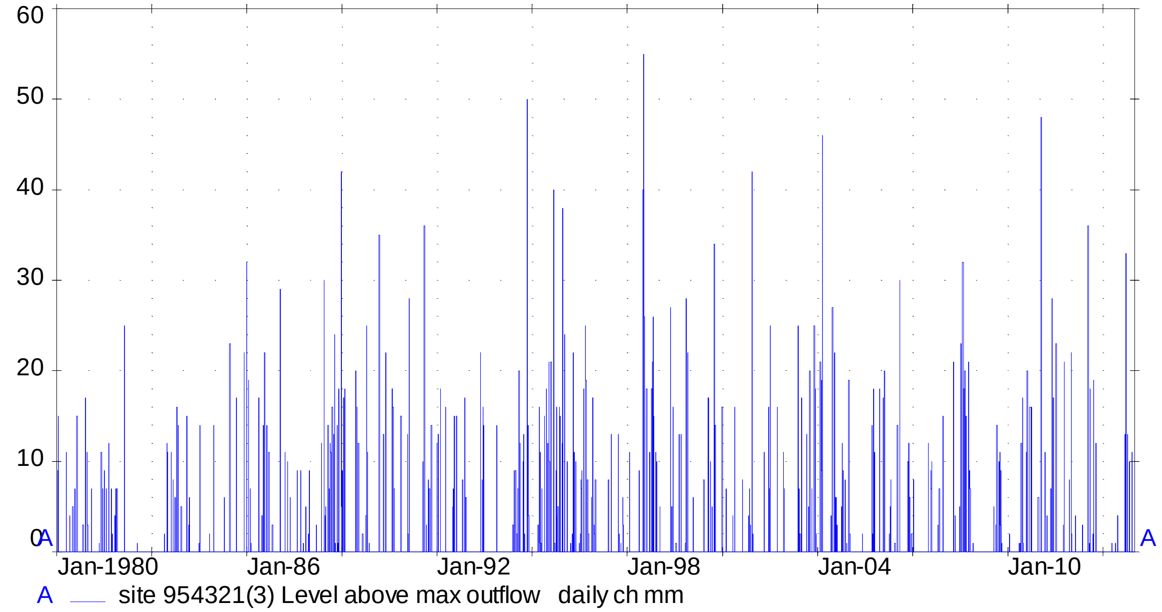


Figure 4.5: Daily increase in lake level for 'theoretical' flood events as a result of inflows exceeding the maximum outflow capacity of the Taupō Gates (1980-2013).

It is considered that the increase in lake level over the duration of an event is a better measure of the flood risk rather than daily increase. This is because long duration events during which inflows exceed outflows will generate higher cumulative lake levels.

The potential for an increase in lake level to cause lake shore flooding is related to the lake level at the start of an inflow event. The higher the lake level, the less it can rise before it is likely to have a significant affect. High inflows at high lake levels therefore represent the greatest risk. Figure 4.6, however, shows that the lake level change caused by high inflows is unrelated to the lake level at the start of any event. This means that the change in lake level caused by inflows is independent of the initial lake level, and therefore the two variables must be considered separately.

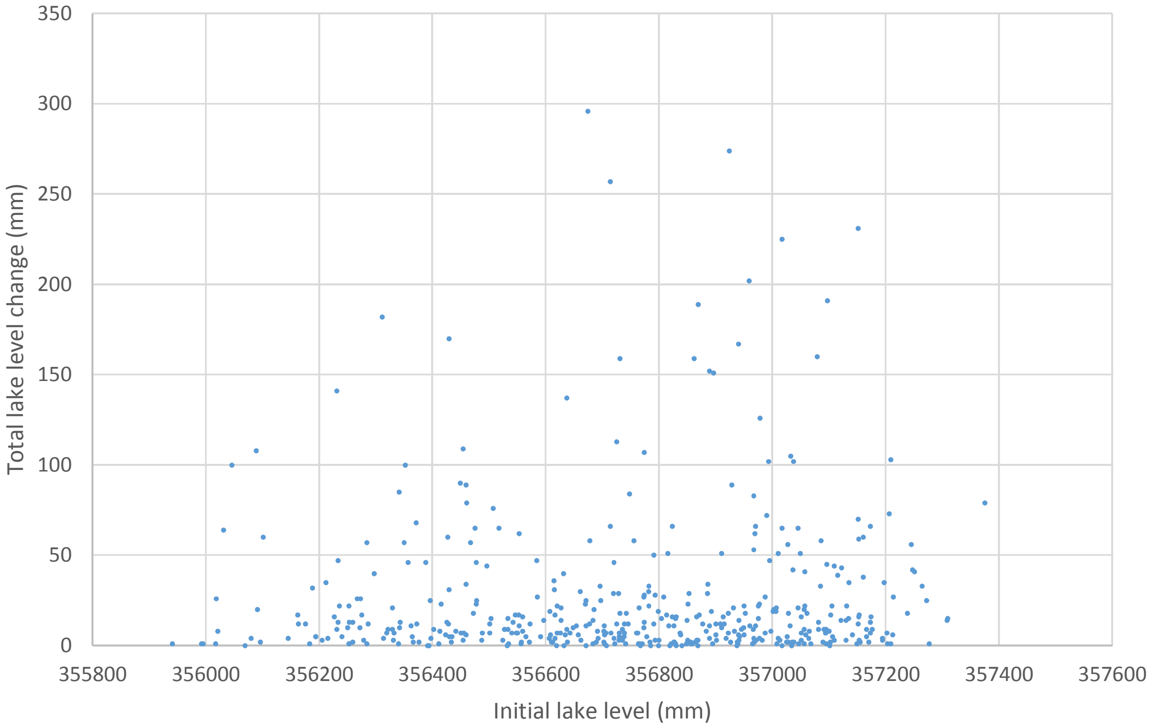


Figure 4.6: Total increase in lake level for specific inflow events is independent of the lake level at the onset of the event.

Potential impact of global warming

Assuming that the lake level inflow regime between 1980 and 2013 is typical of that into the future, the effects of global warming can be simulated by increasing all inflows by the percentage increase in rainfall caused by the temperature increases indicated earlier i.e., 7.2% for 2040s and 16.8% for 2090s assuming the average IPCC scenario for rainfall events with an annual recurrence interval of 50-years or more. Having increased the inflows to reflect the effect of global warming, the above analysis of lake levels caused by inflows exceeding the maximum outflow capacity was repeated.

The greatest effect of climate change is on events that produce a relatively small increase in lake level (i.e., less than 100mm total change), and on events with durations less than about

3 days (Figure 4.7 & Figure 4.8). The 2090 climate change scenario did result in an event when theoretical inflows would exceed outflows continuously for 17 days. However, each of these events would potentially cause a total increase in lake level of approximately 400mm. In comparison, the climate change adjusted 1998 flood event would cause a lake level change of 483mm over 10 days. Again, this assumes that the Taupō Gates are fully open. If they were shut to restrict flow to the required 30m^3/s then Lake Taupō would rise an additional 39mm/day.

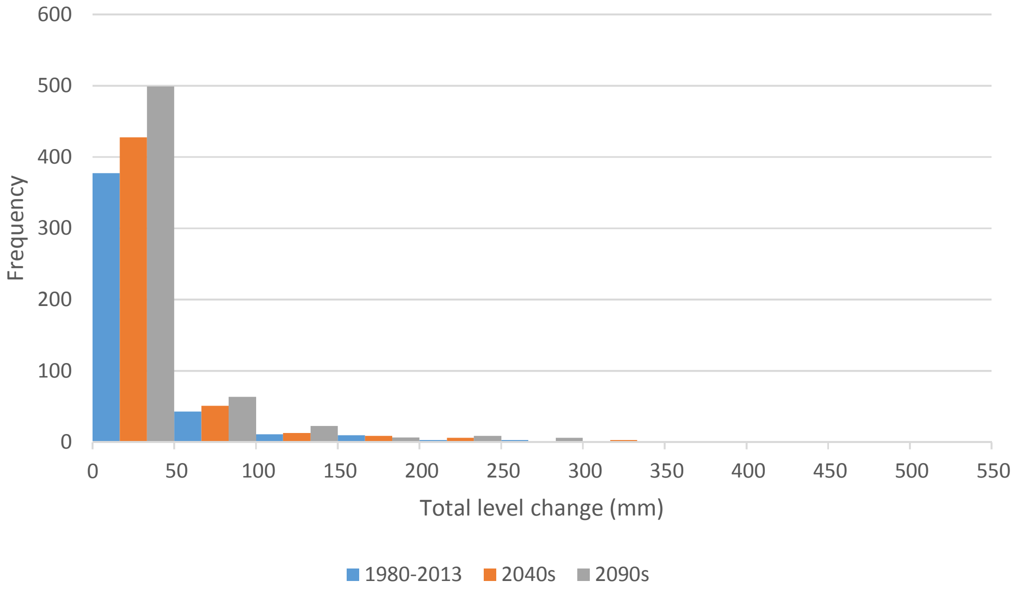


Figure 4.7: Frequency distribution of total change in lake level under three inflow regimes i.e., present, 2040s, and 2090s.

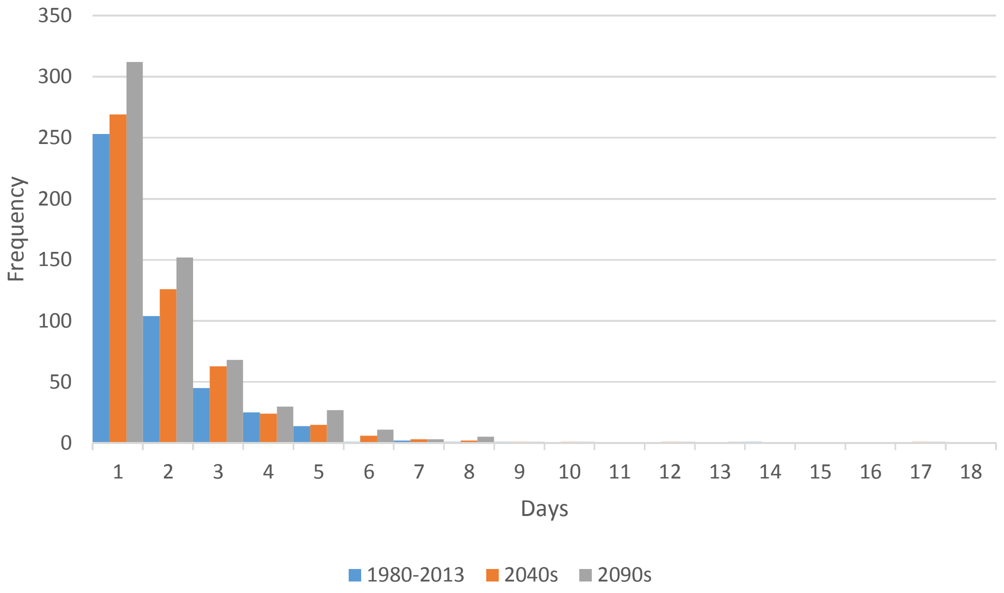


Figure 4.8: Frequency distribution of the duration of inflow events under three inflow regimes i.e., present, 2040s, and 2090s.

Because the total rise in lake level for specific inflow events is independent of the initial lake level, a frequency analysis was undertaken on the event-related increases in lake level record. Again, the synthesised inflow records under the three scenarios were analysed (i.e., 1980-2013, 2040s, and 2090s). The results of these analyses are presented in Figure 4.9.

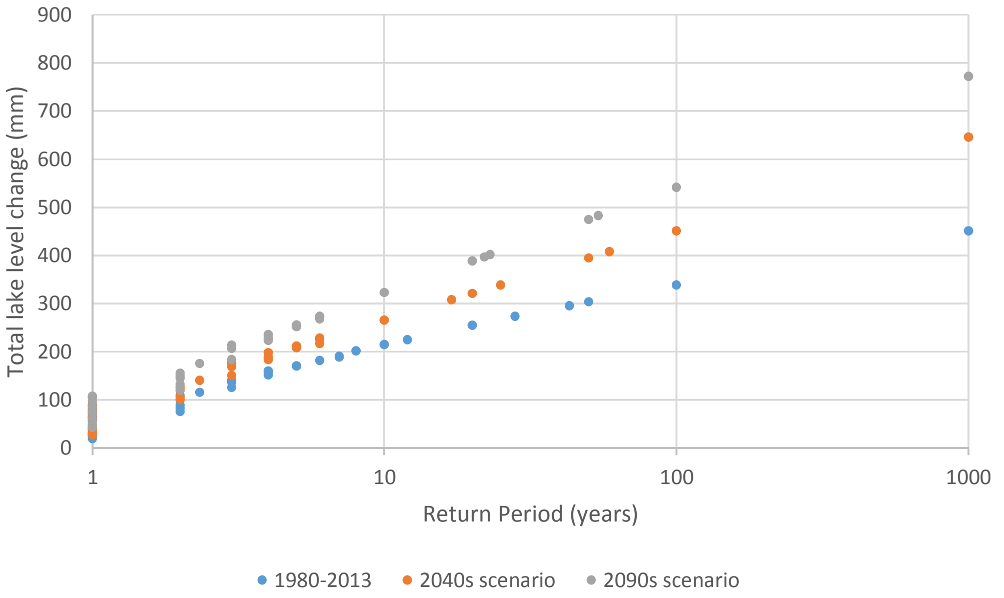


Figure 4.9: Magnitude of the increases in lake level caused by inflow events under three inflow regimes i.e., present, 2040s, and 2090s for different return periods.

The theoretical rises in lake level caused by inflows exceeding the maximum outflow capacity under the climate change scenarios for different return periods are listed in Table 4.4.

Table 4.4: Projected changes in total lake level as a result of global warming on inflows.

Return period	1980-2013 (mm)	2040s (mm)	2090s(mm)
	PE3	GEV	GEV
2.33	116	141	176
5	171	209	260
10	215	266	327
20	255	321	389
50	304	395	467
100	339	451	524

Note: These return periods extend out to 100 years as the climate change effect on rainfall, on which they are based, is limited to 90 years.

Impact on historic high flow events

Two specific flood scenarios were used to evaluate the potential impact of climate change on the level of Lake Taupō. The 2040s and 2090s percentage increase in runoff (7.2% and 16.8% respectively) were applied to the 1998 and 2004 flood flows. Table 4.5 & Table 4.6 detail the recorded flood events, the climate change adjusted flows, and the rise in lake levels assuming that the maximum flow through the Taupō Gates is 310m^3/s. The MfE guidelines only apply to events up to 24-hours duration. However, the percentage increase in rainfall becomes constant for more extreme events. Given that large and extreme events are simulated, the percentage adjustments are considered appropriate. A more detailed analysis is not possible at this stage.

Table 4.5: Impact of climate change on the 1998 flood.

1998 Flood	1998	Climate Change 2040s (7.2%)	Climate Change 2090s (16.8%)
Change in lake level (mm)	274	408	483
Average daily change in lake level (mm/day)	55	41	48
Days above maximum outflow (310m^3/s)	5	10	10

Table 4.6: Impact of climate change on the 2004 flood.

2004 Flood	2004	Climate Change 2040s (7.2%)	Climate Change 2090s (16.8%)
Change in lake level (mm)	231	263	306
Average daily change in lake level (mm/day)	46	53	61
Days above maximum outflow (310m^3/s)	5	5	5

Table 4.7: Impact of climate change on the 2010 flood.

2010 Flood	2010	Climate Change 2040s (7.2%)	Climate Change 2090s (16.8%)
Change in lake level (mm)	225	308	402
Average daily change in lake level (mm/day)	16	18	24
Days above maximum outflow (310m^3/s)	14	17	17

The actual lake level record shows that the 1998 flood resulted in the highest lake level since 1957. The lake rose from approximately 356.89m to 357.49m; an increase of 0.6m. The 2004 flood recorded a maximum lake level of 357.35m. The lake level rose from approximately 357.13m; an increase of 0.22m.

For the modelled 1998 flood event the increases in inflow equate to an additional 134mm and 209mm rise in lake level for the 2040s and 2090s climate change scenarios respectively. For the 2004 flood the increases equate to 83mm and 117mm. For the 2010 flood the increases equate to 83mm and 177mm. The duration of the 2004 event remains the same under both scenarios; 5 days. The duration of the 1998 event increases from 5 days to 10 days and for the 2010 event from 14 days to 17 days.

The assumption in the above analyses is that the Taupō Gates remain fully open during the each event. This did occur in 2004 and the actual rise in lake level was 217mm (compared with the 231mm predicted above). During 1998, however, the Gates were shut on several occasions; to store inflows under the provisions of the High Flow Management Plan and Flood Rules (Figure 4.10). The difference between having the Taupō Gates open or closed for the duration of the 1998 flood changes the potential rise in lake level from 374mm to 728mm (the actual rise recorded was 600mm which is consistent with the results of this analysis).

The position of the Taupō Gates therefore has a critical effect on potential lake level rise. However, the apparently 'random' manner in which the Gates are operated with respect to inflows makes their specific effect impossible to model explicitly.

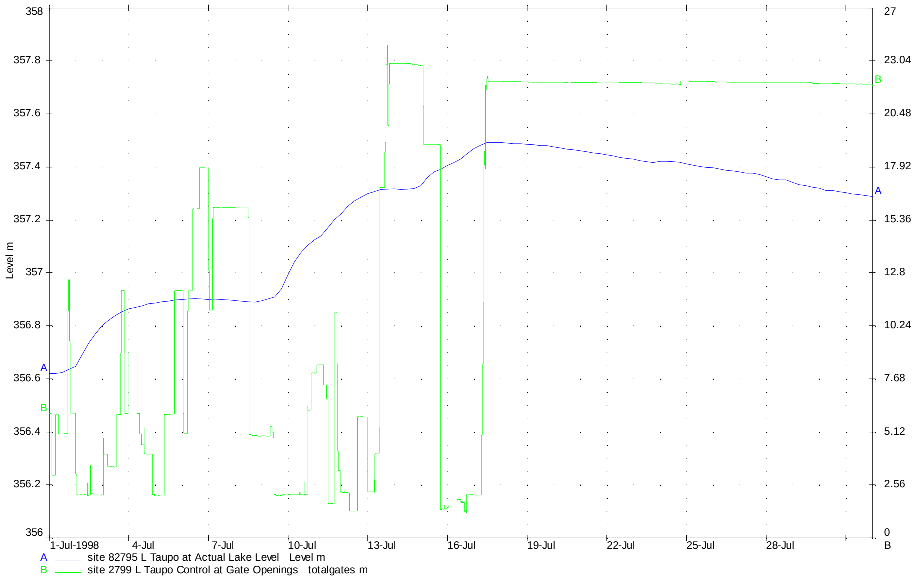


Figure 4.10: Lake Taupō levels and Gate operation during the 1998 flood event.

4.6 Summary and recommendation

The Ministry for the Environment climate change methodology was adapted to model lake levels. Translating the rainfall methodology to flow, and then using flow to model changes in lake level appears to be a valid approach.

As indicated in Table 4.8, the projected increase in lake level caused by global warming on a 100-year event by the 2090s would be 185mm. The values in Table 4.8 should be added to estimates of lake level for specific return periods to indicate the potential static water level, including the effect of climate change.

Table 4.8: Projected changes increases in total lake level as a result of global warming on inflows.

Return period	2040s (mm)	2090s(mm)
2.33	25	60
5	38	89
10	51	112
20	66	134
50	91	163
100	112	185

5 Climate Change Signature

5.1 Introduction

The above discussion of the potential effect of predicted climate change on the flood risk to Lake Taupō is largely theoretical. A number of assumptions were adopted regarding increases in temperature, and consequential increases in rainfall, runoff, inflows and therefore lake levels.

The Tongariro River provides the largest inflows to Lake Taupō (Figure 5.1). Variability of inflows from the Tongariro River can have a significant impact on the flood risk around Lake Taupō. Any relationship between the climate of this catchment and runoff is therefore relevant when considering changing flood risk. In addition, it is likely that the climate-rainfall-runoff relationships within the Tongariro catchment are similar to those of the other tributaries which drain into Lake Taupō. Consequently an attempt was made to investigate and quantify any climate signature within the Tongariro catchment, and the influence of temperature on the inflow regime.

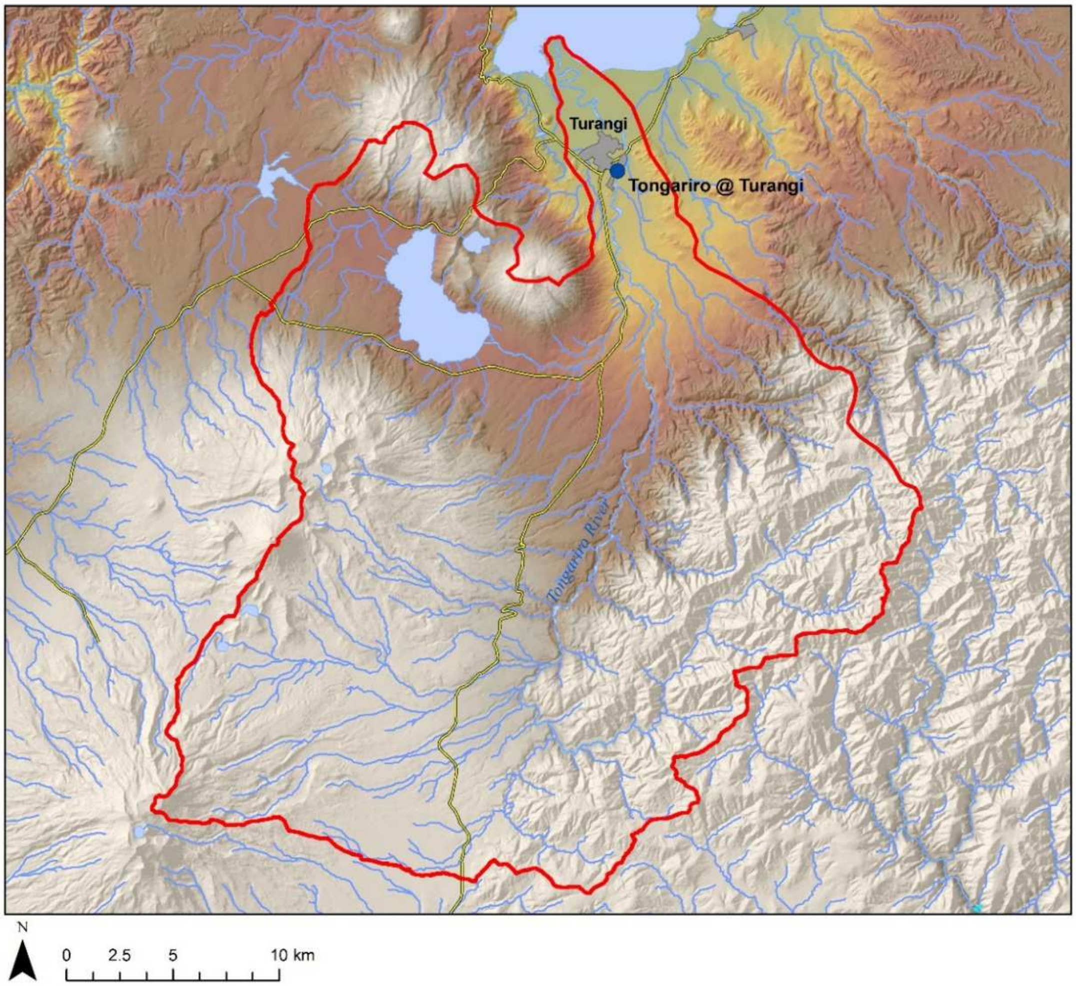


Figure 5.1: Tongariro River catchment and location of the water level recorder.

The accuracy of the estimation of design inflow events is largely a function of:

- The quality of the flow series, and particularly the accuracy of estimates of the magnitudes of large events; and

- The duration of the flow record.

In general, the longer the flow record, and the resulting flood maxima series, the more robust will be any estimates of the magnitudes of design inflow events. It is generally accepted that 'accurate' estimates of design flood events are possible to about twice the length of the annual flood maxima series i.e. a 57-year flood maxima series allows 'accurate' estimates of events up to an AEP of 1% (100-year ARI). Uncertainty of the design flood estimates, however, increases as the frequency of a design event decreases i.e. the event becomes more extreme and therefore less common.

The flow series for Tongariro at Turangi is summarised in Figure 5.2 and Table 5.1.

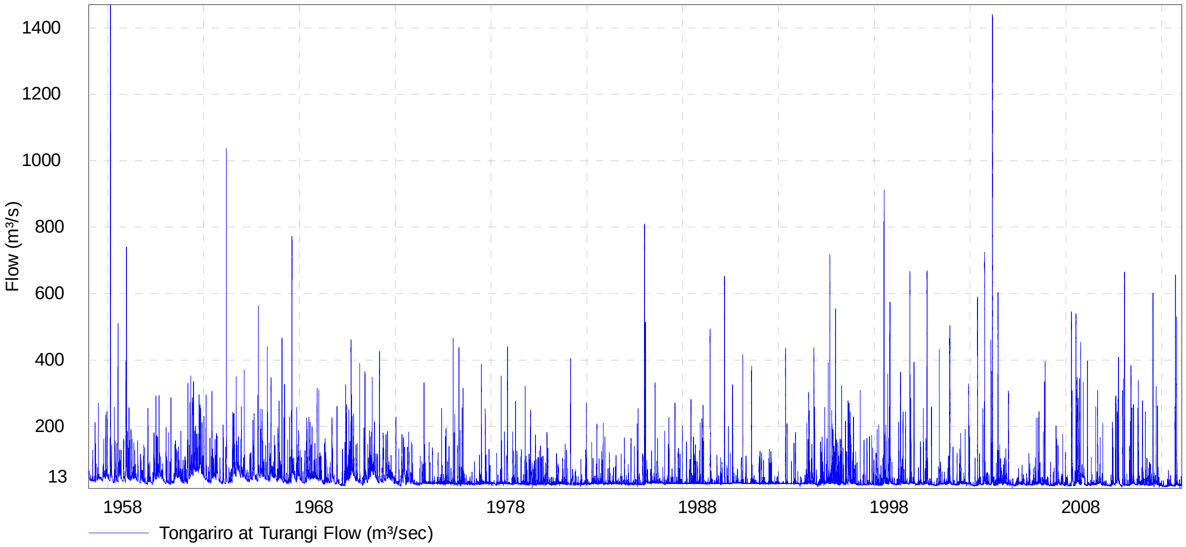


Figure 5.2: Flow series for the Tongariro at Turangi (1957-2013).

Table 5.1: Summary statistics for the flow regime of the Tongariro at Turangi from 1957-2013 (m³/s).

Site name	Min	Mean	Max	Lower Quartile	Median	Upper Quartile	Std Dev
Tongariro at Turangi	14.0	38.2	1470.0	26.9	29.3	40.1	28.2

5.2 Flow variability

The flow regime of the Tongariro River shows occasional large flood events interspersed with long periods of low to moderate flow. This pattern is expected for a river draining the Ruapehu volcanic centre and the axial ranges of the mid-North Island. The flow series shows no significant trends besides the expected seasonal pattern (Figure 5.2).

Likewise, the annual flood maxima series shows that both the magnitude and frequency of flood activity appear, at least visually, to be essentially random (Figure 5.3).

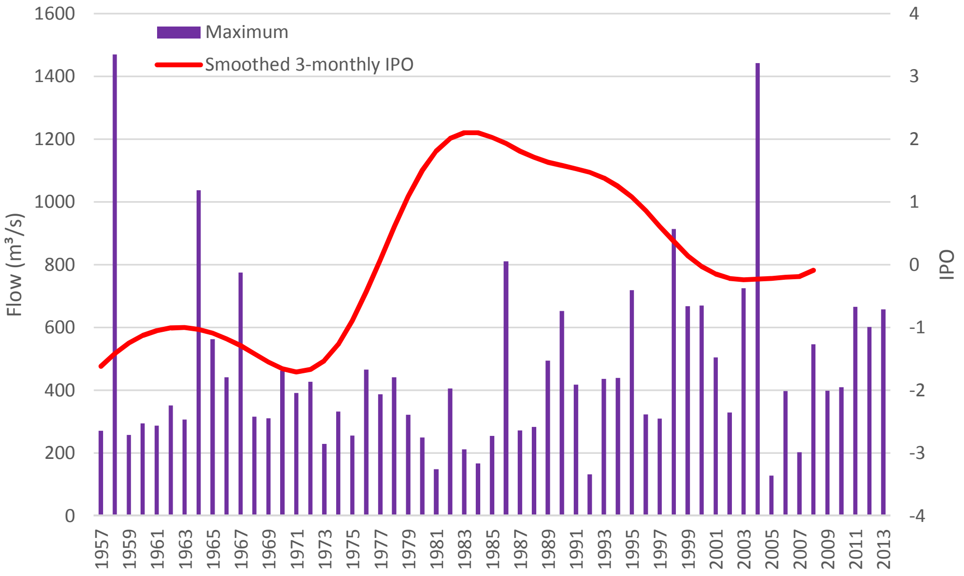


Figure 5.3: Annual flood maxima series for Tongariro at Turangi.

Such random behaviour, and the assumption of stationarity with regard to the rainfall-runoff relationship, are essential assumptions underlying robust frequency analysis; and consequently the estimation of the likely magnitude of design flood events.

These conclusions are supported by previous studies of the flow regimes of rivers in the lower North Island e.g. *"No trend or cycles are apparent in the data. Also, no significant shifts corresponding to IPO phases are evident. It is concluded from this inspection that the data are free of trend, shifts, persistence and periodicity and that the standard extreme value analysis methods are applicable."* (McKerchar, 2009)

Temporal variability of flood activity

As discussed, the annual flood maxima series for the Tongariro River shows no significant trend in the magnitude of larger flood events over the past 57-years (Figure 5.4).

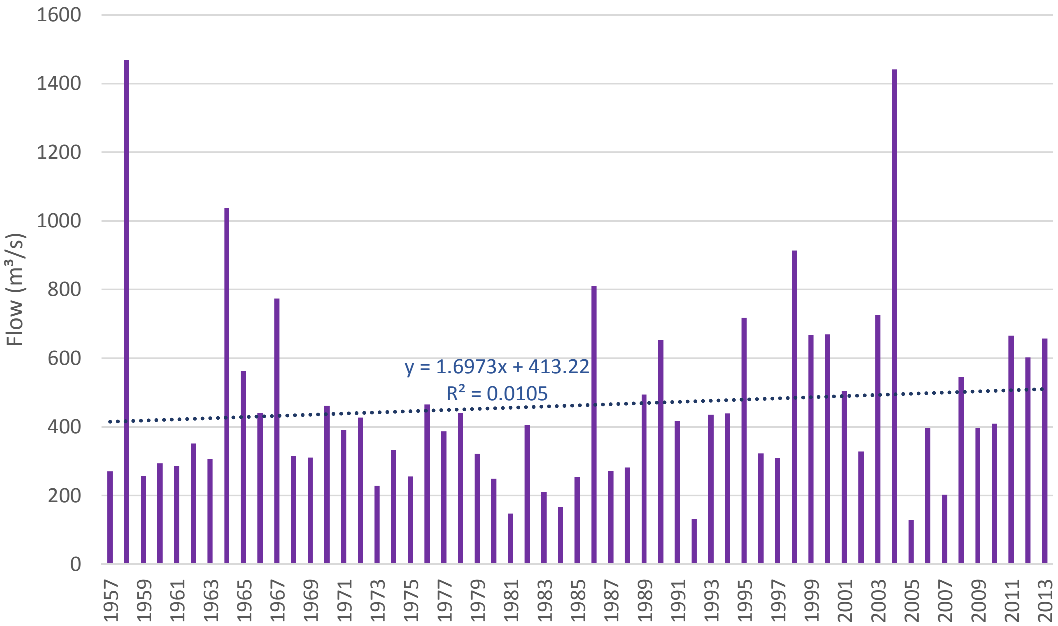


Figure 5.4: Annual flood maxima series for the Tongariro River (1957-2014).

Predicted increases in global temperatures are suggested to vary with the season. Any seasonality of flood activity is therefore of potential importance. A review of the 10 largest floods in the Tongariro River over the past 57-years shows that 40% of these occurred in 'summer'; with the 20% in each of autumn, winter and spring (Figure 5.5). Three of the four largest floods occurred in January and February.

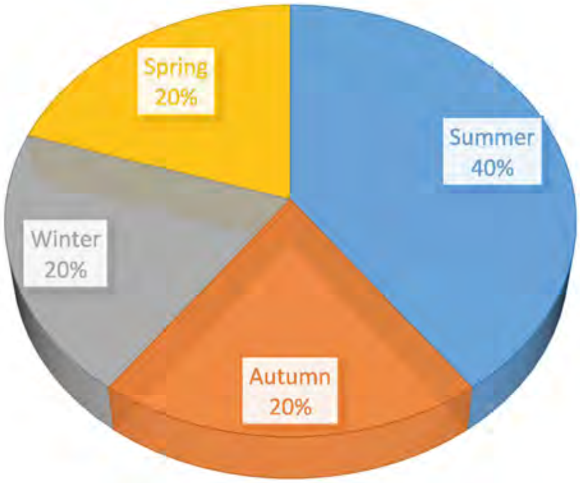


Figure 5.5: Seasonality of the 10 largest floods recorded in the Tongariro River (1957-2014).

At a 'gross scale', therefore, there seems to be at least a seasonal effect on the distribution of large floods, i.e. most occur in summer. The passage of weather systems and antecedent conditions within the catchment are, however, also likely to have a significant effect on flood magnitude activity. Both the effects of the passage of weather systems and antecedent conditions are inherent in the 57-year flow record of the Tongariro River; as is any effect of increasing temperature over the same period.

The strong seasonal effect of flood activity is reduced slightly when the entire 57-year annual maxima series is analysed (Figure 5.6). What is particularly significant is the apparent lack of flood activity, defined by the largest flood each year, during 'winter'. It is likely that in the Tongariro catchment this is because much of the precipitation at higher elevations during winter falls as snow.

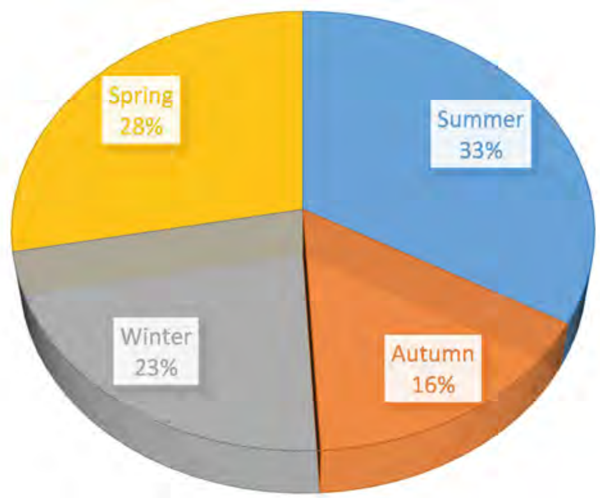


Figure 5.6: Seasonality of the annual flood maxima series recorded in the Tongariro River (1957-2013).

A review of the available flood maxima series for the Tongariro River therefore shows:

- The apparent 'randomness' of both flood magnitude and frequency over the past 57-years;
- No significant trend of increasing flood magnitude, particularly for larger floods, over time;
- The lack of strong seasonal control on major floods within the catchment; and
- That any temperature-induced signature in flood activity is potentially affected by other major controls; weather patterns, antecedent conditions, and topography.

5.3 Impact of climate variability

Background

The RMA (1991) requires that the potential effects of climate change are considered during the decision-making process. Incorporating the potential effects of predicted climate change into flood frequency analyses is problematic for a number of reasons; both statistical and practical. Of fundamental concern is that if climate change is affecting the rainfall-runoff relationship then stationarity cannot be assumed. Any frequency analysis would therefore be inappropriate. With respect to the Tongariro catchment, however, it has been shown that there are no trends or cycles present in the flood maxima series, apart from larger flood during summer.

Other areas of uncertainty when considering the potential effects of predicted climate include:

- The magnitude of predictions of increases in temperature. The uncertainty of predictions increases with the length of the period under consideration;
- The magnitude and significance of climate variability inherent in the annual flood maxima series;
- The relationship between increases in average temperature and increases in specific storm rainfall;
- The relationship between storm rainfall and event runoff and flood magnitude;
- The stability of the rainfall-runoff relationship with increasing flood magnitude and reducing flood frequency; and
- The ‘stability’ of any existing rainfall-runoff relationship in response to climate change.

At the present there is no definitive way to include the potential effects of climate change into any flood frequency analysis. Any methodology adopted must involve a significant level of professional judgement and there will always be residual uncertainty. This uncertainty must be accommodated through the use of conservative, but still realistic and reasonable, design flood estimates.

Local temperature records

There is a relatively long-term temperature record available for Turangi at the southern end of Lake Taupō. This record actually consists of data from three separate sites (Table 5.2). However, given the close proximity of the sites and the fact that they appear to have replaced one another, these sites were merged to provide a single long-term temperature record for Turangi over the past 46-years. The Turangi site provides measurements of the maximum and minimum daily temperatures over the duration of the record.

Table 5.2: Long-term temperature records.

Site name	Start date	End date	Length of record
Turangi	14 Dec 1967	19 Dec 1996	29 years
Turangi AWS	31-May-1996	3 Mar 2003	6 years
Turangi 2 AWS	5 Mar 2003	5 Mar 2014 (present)	11 years
Turangi Combined	*14 Dec 1967*	*5 Mar 2014*	*46 years*

To confirm that the three sites can be combined, a comparison of the maximum and minimum daily temperatures was undertaken for the period of overlapping records at the Turangi and Turangi AWS sites (May-Dec 1996). A strong linear relationship between data from the two sites is apparent (Figure 5.7). The coefficient of determination for maximum temperatures is 0.95 and for minimum temperatures 0.88. That is, 95% of the variation in daily maximum temperatures and 88% of the variation in daily minimum temperatures at Turangi can be explained by the daily temperatures at Turangi EWS. It is therefore appropriate to merge data from the two sites into a single long-term record.

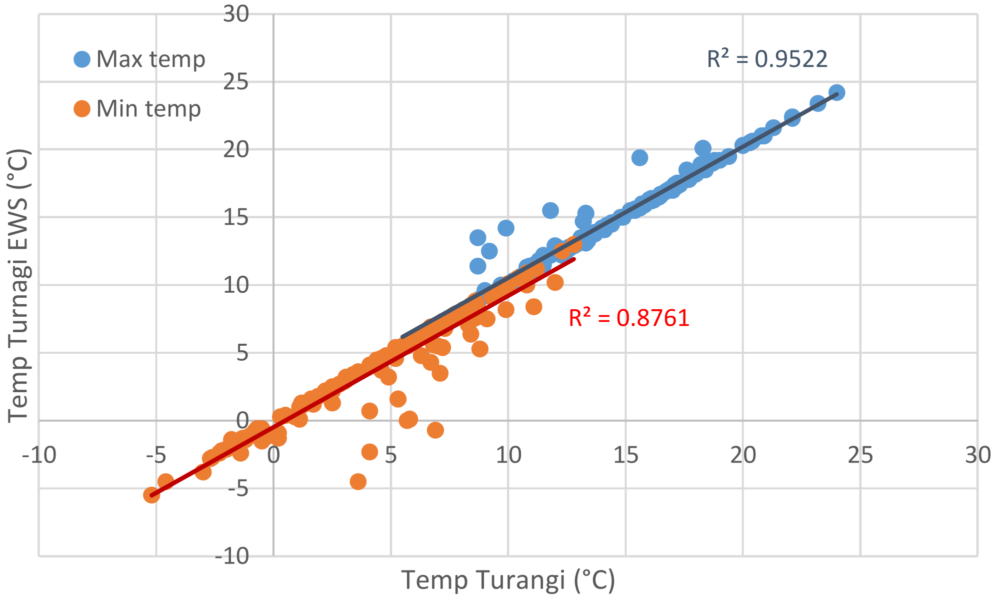


Figure 5.7: Comparison of maximum and minimum temperatures at Turangi and Turangi EWS sites.

Summary statistics for the maximum and minimum temperatures from the Turangi Combined record are listed in Table 5.3. The mean of the mean daily temperatures (that is the average of the maximum and the minimum daily temperatures) and the range of daily temperatures have been calculated.

Table 5.3: Summary statistics for the temperature records at Turangi.

	Max temp (°C)	Min temp (°C)	Mean temp (°C)	Temp range (°C)
Minimum	5.0	-10.0	0.35	0.40
Maximum	32.6	20.0	23.65	27.60
Mean	17.1	6.6	11.83	10.52
25th percentile	13.2	3.0	8.36	7.64
Median	16.8	6.7	11.67	10.30
75th percentile	20.8	10.2	15.27	13.26
Standard Deviation	4.7	4.9	4.42	3.78

In an attempt to isolate any potential trend in temperature from the scatter caused by daily variability the 1-year, 5-year and 10-year running means for each temperature parameter were also plotted (Figure 5.8 & Figure 5.9).

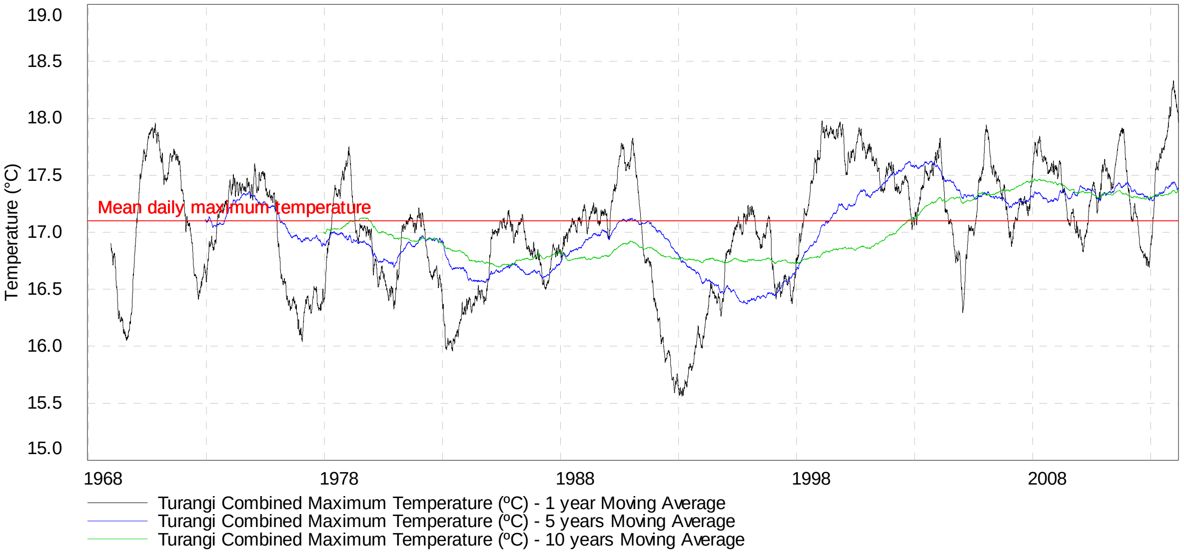


Figure 5.8: Variation in maximum temperatures recorded at Turangi.

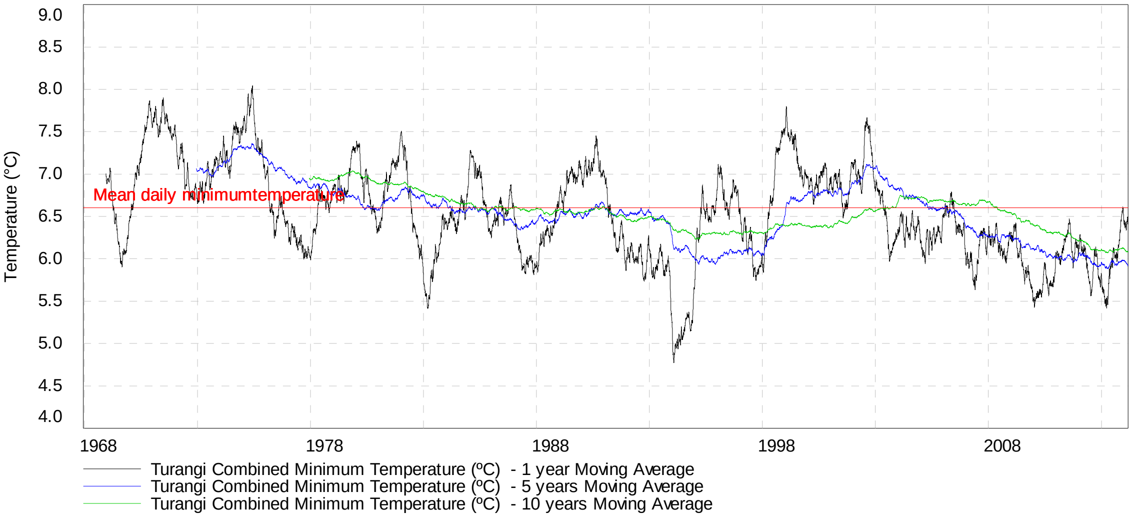


Figure 5.9: Variation in minimum temperatures recorded at Turangi.

Variation in mean daily temperature and daily temperature range are shown in Figure 5.10 and Figure 5.11.

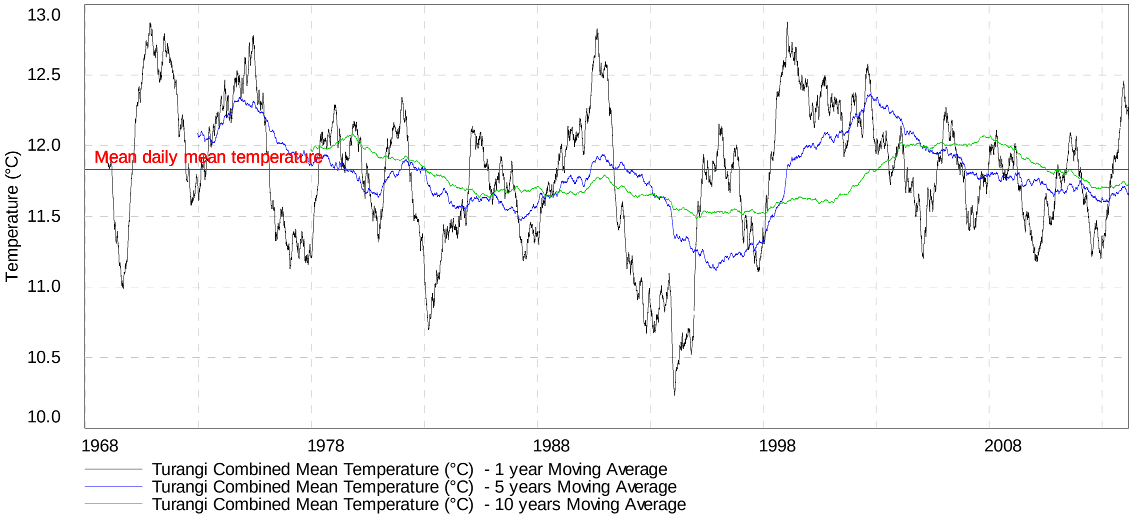


Figure 5.10: Variation in mean temperature recorded at Turangi.

There is a high degree of variability in all of the various daily temperature parameters (i.e. maximum, minimum, mean, and range). Superimposed on this daily variation are seasonal trends; such as warmer temperatures in summer and cooler temperatures in winter. There is also some annual variability but no consistent trend is apparent.

When the daily variability is smoothed by using running means general trends can be identified, but these are neither strong nor consistent. For example, maximum daily temperatures tended to drop by about 0.5°C during the 1980s but are now about 0.5°C higher than the long term average (Figure 5.8). Minimum daily temperatures, however, appear to have dropped almost 1°C over the length of record (Figure 5.9).

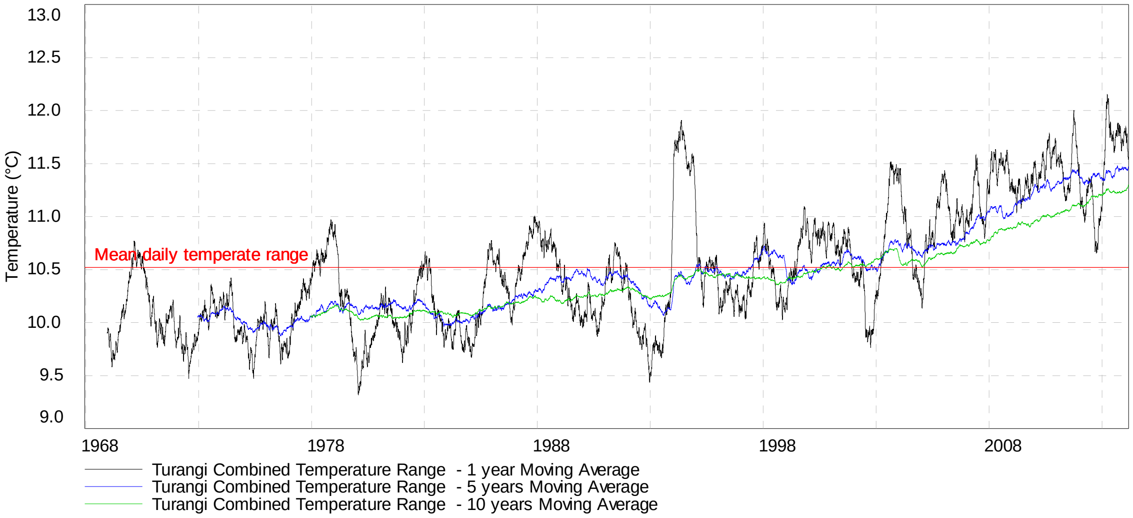


Figure 5.11: Variation in daily temperature range recorded at Turangi.

Since the mean daily temperature is simply the average of the maximum and minimum temperatures it varies in response to changes in either of these two parameters. Over the length of record the mean daily temperature at Turangi shows cyclic behaviour (Figure 5.10). It was initially higher than the long term average but then decreased before rising again. At present the mean daily temperature is very similar to the long term average. There is certainly no consistent trend of increasing mean daily temperature apparent over the past 47-years.

The slight increase in maximum temperatures and decrease in minimum temperatures has led to a consequential increase in the daily range of temperatures (Figure 5.11).

A strong seasonal tend is apparent in mean daily temperature although there is also a high degree of variability (Figure 5.12).

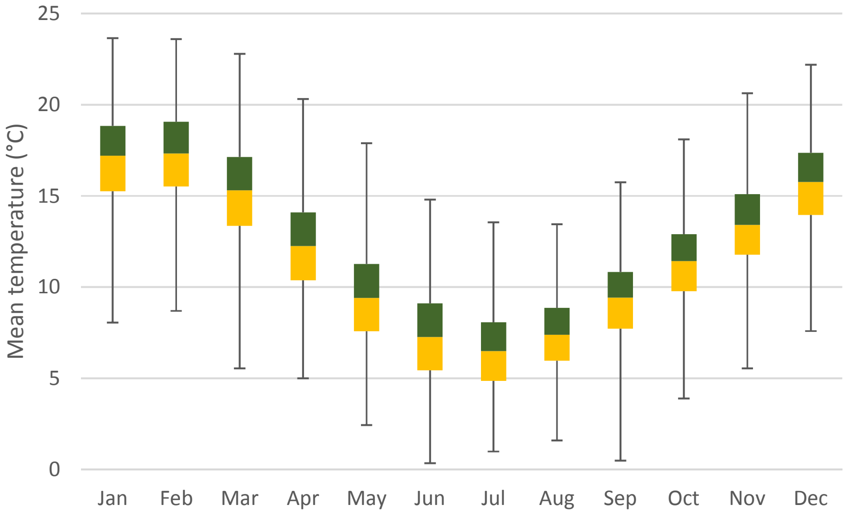


Figure 5.12: Monthly variation in mean temperature.

The temperature data available for the Tongariro catchment shows no consistent trend in mean daily temperature, or any of the temperature parameters reviewed, other than daily range. The range of daily temperatures appears to have increased since 2000. It should be noted, however, that since the daily mean temperature is the average of the daily maximum and minimum temperature a change in either of these parameters will affect the daily average. For example, a rise in the minimum temperature causes a consequential rise in the mean daily temperature. It is possible therefore for the average daily temperature to rise without any increase in the daily maximum temperature. This means that storm rainfall may not increase in the manner which has been predicted; assuming that there is a positive relationship between an increase in temperature and rainfall. This has significant implications for the estimation of the magnitude of various design flood events based on the predicted effects of global warming. An increase in average temperature may not have a significant effect on the magnitude of design floods, although the incorporation of such an assumption means that estimates of the magnitudes of design floods will be conservative.

It is important to recognise that the climate stations at Turangi are at low elevation relative to the topography of much of the Tongariro catchment. Whether the same trends in temperature discussed with respect to the record from Turangi exist in the headwaters is unknown because of the lack of data from higher elevations. The trends may not persist at the higher elevations because of the influence of topography on the climate and general weather patterns.

5.4 Inter-decadal Pacific Oscillation

The Inter-decadal Pacific Oscillation (IPO) is a climatic fluctuation in atmospheric and sea surface temperatures (SST) in the Pacific Basin that operates over a time scale of decades. Studies have shown that in some areas of New Zealand there is a strong correlation between heavy rainfall and flooding, and the IPO phases. This results in successive 'benign' and 'active' phases in flooding that occur in conjunction with negative and positive phases of the IPO respectively. A positive IPO phase persisted from 1922-1945, and again from 1977-1999; while from 1946-1976 the IPO was in a negative phase. The IPO is currently in a negative phase, and so the incidence of heavy rainfall is likely to be less than the long-term average (Figure 5.13). Shifts in the IPO modulate the frequency of occurrence and intensity of El Niño and La Niña phases of the ENSO. The positive phase is most commonly associated with higher frequency and intensity of El Niño-like conditions, while the negative phase is associated with a prevalence of La Niña patterns. For example, more El Niño episodes occurred from 1978 to 1999 than the previous three decades which saw more La Niña (McKerchar & Henderson, 2003). El Niño episodes tend to give more rain in the south and west of the country, and drier conditions in the northeast. La Niña episodes tend to give less rain in the south and east, and more rain in the northeast.

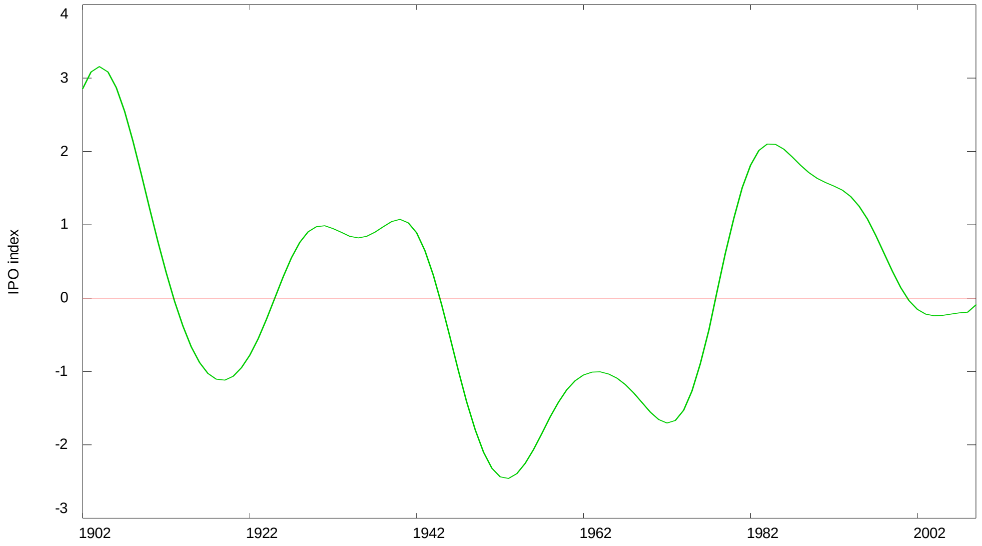


Figure 5.13: Variation in the IPO phase which has been related to changes in the rainfall regime. (Source: www.iges.org/c20c/IPO_v2.doc)

Recent climatological studies have demonstrated that the assumption of stationarity (i.e., that all data are drawn from the same continuous population) may not be valid; at least for annual rainfall in New Zealand. Compared with the period 1947-1977, consistent rainfall decreases of up to 8% occurred for the period of 1978-1999 in the north and east of the North Island, and increases of up to 8% occurred in the west and south of the South Island. These changes are attributed to shifts in the phase of the IPO.

The variability in maximum and minimum daily temperature discussed with respect to Turangi appears to be related, at least qualitatively, to Interdecadal Pacific Oscillation index (IPO). The IPO is often recognised as a significant 'driver' of climate variability in New Zealand (Figure 5.14 and Figure 5.15).

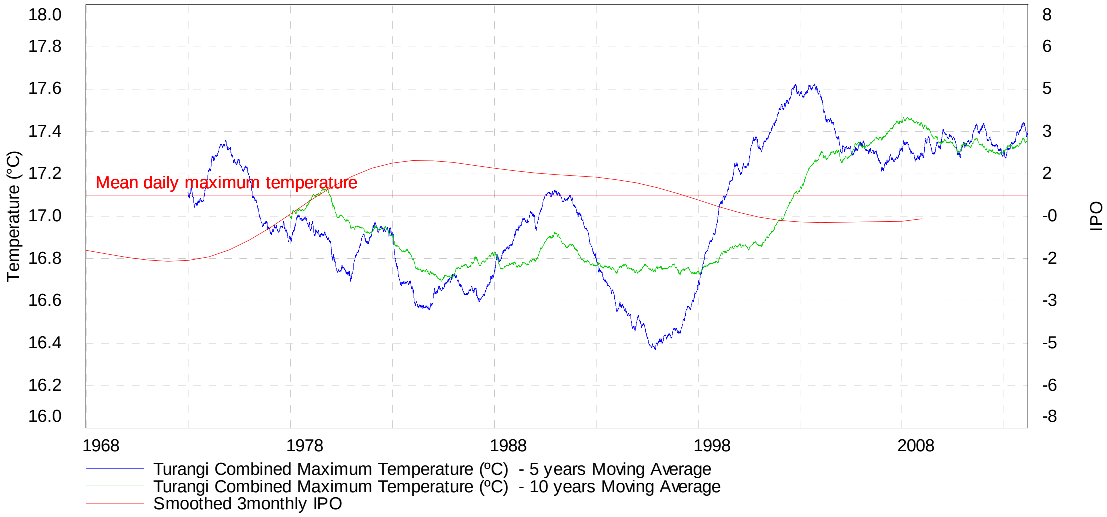


Figure 5.14: Variation in the maximum daily temperature at Turangi and the IPO index.

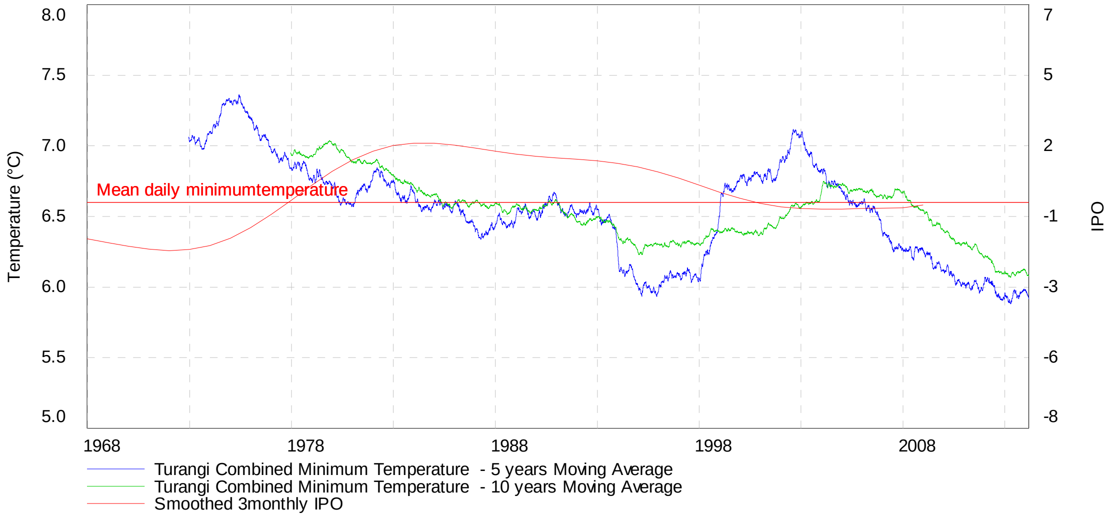


Figure 5.15: Variation in the minimum daily temperature at Turangi and the IPO index.

When the IPO index is positive daily temperatures recorded at Turangi tend to be lower than average. When the IPO is negative the daily temperatures tend to be higher than average.

5.5 Summary

The results of this review of the available flood maxima series and temperature data for the Tongariro River and Turangi has a number of implications for flood hazard assessment at Lake Taupō:

- While average daily temperatures recorded at Turangi over the past 46-years exhibit some cyclic behaviour there has been no consistent trend of increasing temperature;
- Whether any trend in temperature has occurred in the headwaters of the Tongariro catchment cannot be confirmed since there are no long term temperature data from higher elevations;
- The 57-year flow record from the Tongariro River shows no increase in the magnitude or frequency of flooding over time. There has been no increase in flood activity, and no increase in the magnitude and frequency of 'large' flood events;
- Flood activity in the Tongariro River, and by inference the other rivers and streams draining to Lake Taupō, tends to be seasonal. The passage of weather systems, antecedent conditions, and topography are also significant controls on flood activity;
- Despite there being no quantifiable relationship between flood magnitude and temperature (other than apparently at a seasonal level), certainly for larger flood events, and no consistent rise in temperatures within the Tongariro catchment, the magnitudes of various design flood events for the rivers and streams draining to Lake Taupō have been increased to allow for the predicted effects of increased temperatures; and
- Using a predicted increase in average temperature and increase in storm rainfall will likely be conservative for flood hazard assessment; yielding higher potential runoff rates, with larger flood peaks and volumes, and consequently higher lake levels.

Therefore, despite uncertainty over the link between average temperature and flood activity within the catchments draining to Lake Taupō, the magnitudes of the various design events have been increased to allow for the predicted effects of global warming. The effect of this, in the absence of a strong causal link between temperature and flood magnitude other than at the seasonal level, is that some conservatism is added to the results of any flood hazard assessment.

6 Tectonics

6.1 Introduction

The risk of flooding and inundation around Lake Taupō is not a simple function of the amount of water in the lake. This is because the Lake Taupō basin is not stable. Some areas are rising, while others are subsiding. The movement of the land means that for a fixed volume of water areas that are subsiding are exposed to greater risk while those that are rising are at less risk (Figure 6.1 & Figure 6.2). This relative movement of the land has the potential to have a significant effect on the flood risk and depth of inundation over the longer term.

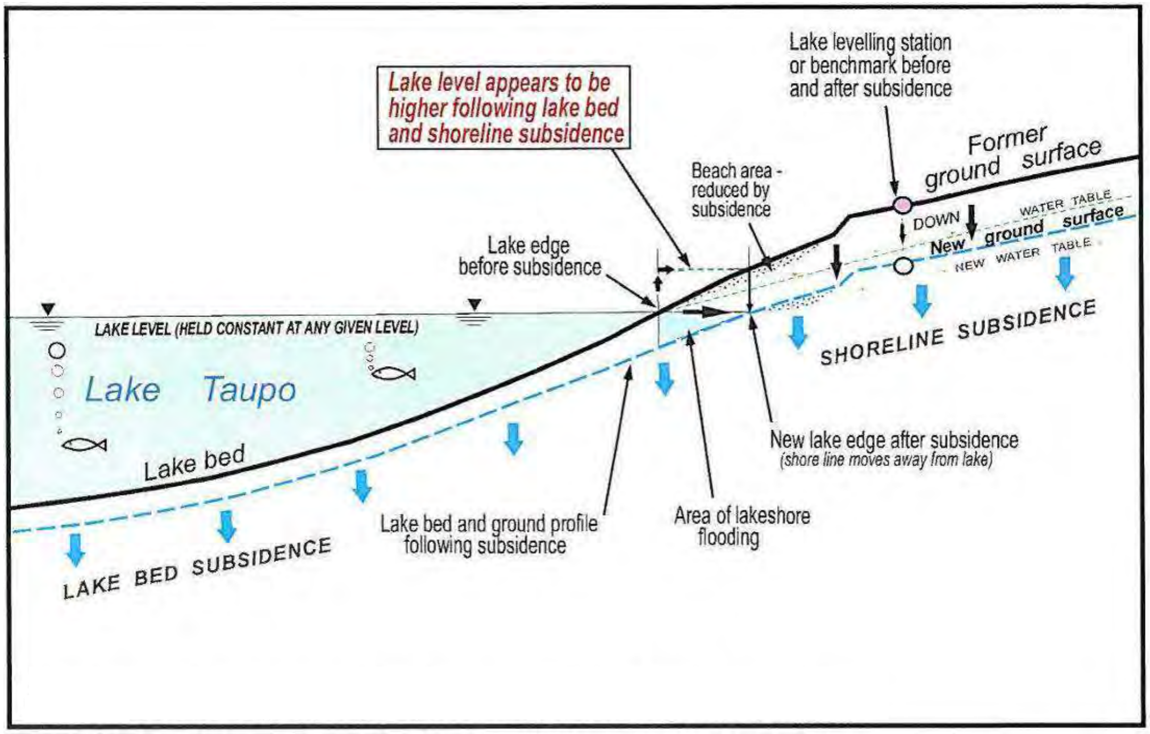


Figure 6.1: Effect of ground level subsidence on relative lake levels (Hancox, 2002).

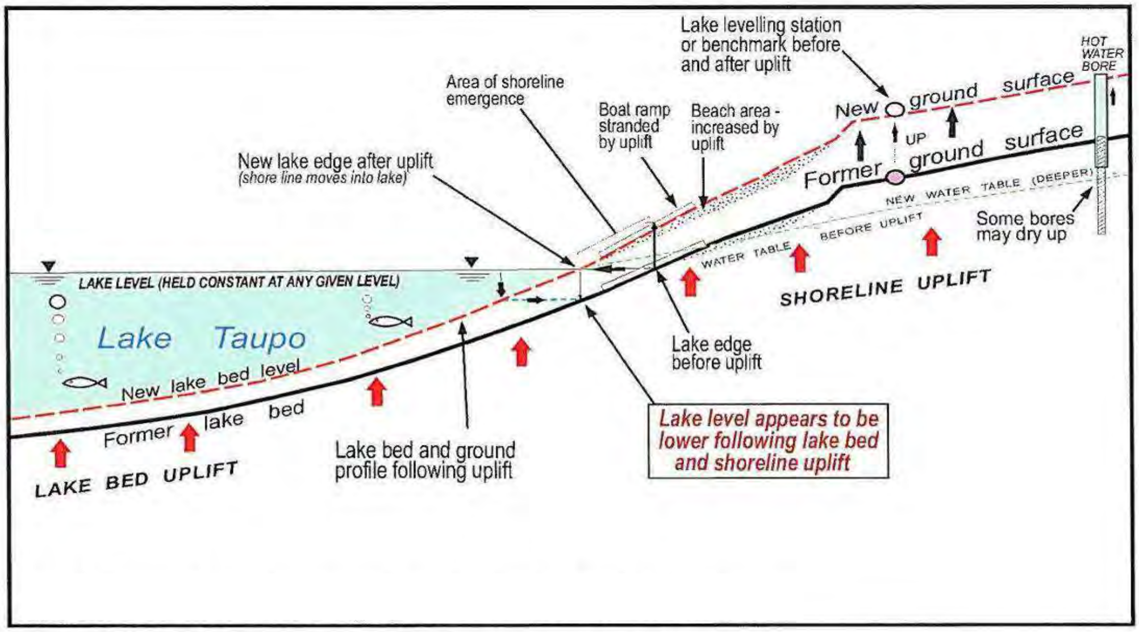


Figure 6.2: Effect of ground level uplift on relative lake levels (Hancox, 2002).

6.2 Tectonic situation

The triangle formed by Moturiki Island, Mt Ruapehu and White Island forms the Taupō Volcanic Zone. This volcanic area extends in a northwest direction to the Bay of Plenty, forming the southern end of the Tonga-Kermadec volcanic arc (Manville and Wilson, 2003). This volcanic zone marks the plate boundary between the subducting Pacific Plate and the Indo-Australian Plate. The Taupō Volcanic Zone encompasses the three active volcanoes of Mts Ruapehu, Ngauruhoe and Tongariro, as well as Lake Taupō. The zone is approximately 50km wide and 300km long.

The combination of volcanism and faulting in the Taupō Volcanic Zone has created an active landscape that includes calderas, horsts, grabens, tilting, uplift and subsidence (Manville and Wilson, 2003; Otway *et al.*, 2002). A series of faults run through this area on a northeast-southwest alignment. These faults make up the Taupō Fault Belt (Figure 6.3)

Gravitational slumping may also be a cause of subsidence, particularly at the southern end of the lake (Hancox, 2002). Deformation surrounding Lake Taupō is therefore the result of both local and long-term regional movement.

6.3 Deformation around Lake Taupō

Tectonic movement in the vicinity of Lake Taupō is complex because of the range of processes operating and number of faults involved.

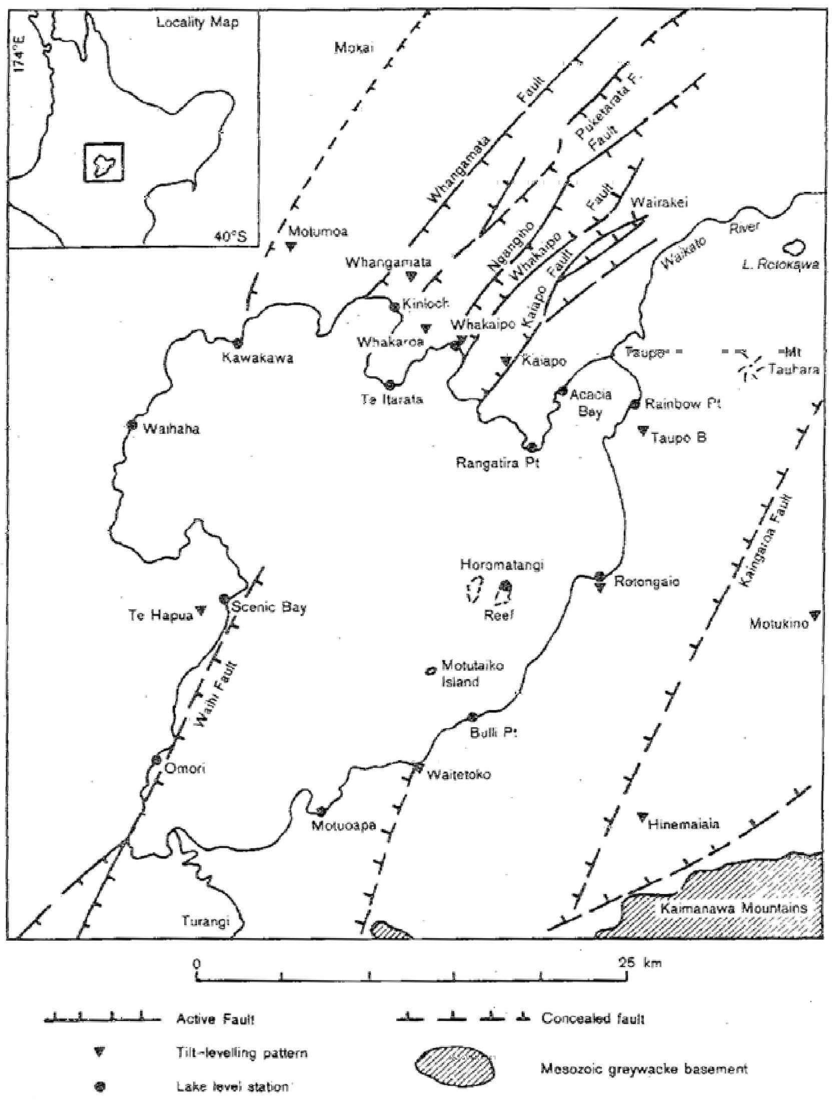


Figure 6.3: **Tectonic setting, Lake Taupō** (Otway, 1986).

Long term deformation

The Taupō eruption in 181AD ejected ~35km^3 of ash and pumiceous pyroclastic material; depositing the Taupō Pumice Ignimbrite over an area of about 20,000km^2. After the eruption Lake Taupō refilled to ~34m above its present level as a result of the large amount of material blocking the lake outlet. Immediately following the eruption the lake spilled through Waihora towards Mangakino before the outlet became re-established in the vicinity of Taupō Township. Sediment erosion and deposition while the lake was at this higher level created a distinctive horizontal terrace which now forms a prominent geomorphic feature around the shoreline of Lake Taupō.

Over the past 1800 years this originally horizontal surface has been affected by tectonic movement and warping. The relative displacement of this terrace now provides a record of the cumulative movement over the past 1800 years (Figure 6.4). Terrace surveying indicates a long term differential deformation rate of 6-9mm/yr. Maximum uplift of ~7-9m (4-5mm/yr) has occurred across the centre and north-eastern end of Lake Taupō, and appears as a broad ridge of uplift between Acacia Bay and Te Hapua Bay. Subsidence has been greatest along the southern portion of the lake. The Turangi-Tongariro delta area has gone down 1.8-3.6m in the last 1800 years, with up to 2.3mm/yr of subsidence near Turangi. A pattern of long-term subsidence is also evident at the southern end of Western Bay (down 3.6m in the last 1800 years) and at Kinloch (down 0.54m in 1800 years (Otway *et al.*, 2002; Hancox, 2002)).

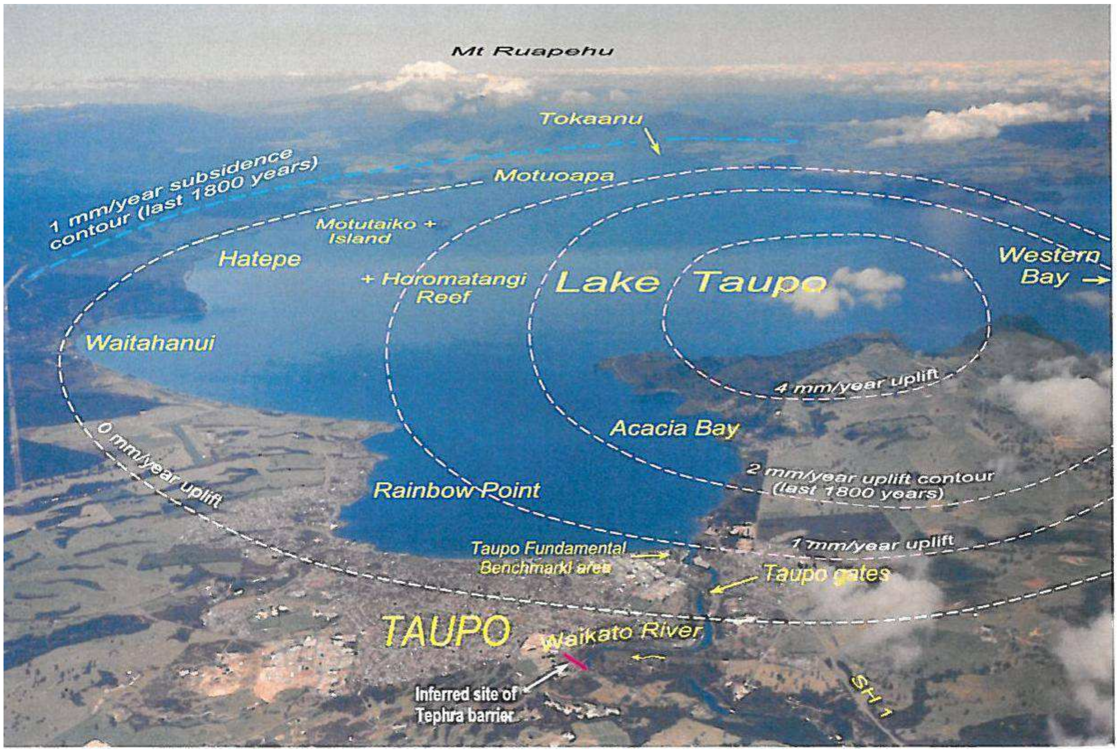


Figure 6.4: Long-term vertical ground deformation since 181 AD (Hancox, 2002).

Short term deformation

Studies have documented current movement patterns around the lake, with a particular focus on the deformation that has occurred over the last 46 years (1956-2002). The short-term deformation rate is similar to the long term rate, with the overall difference between uplifted and subsiding areas ranging from 6-9mm/yr (Figure 6.5). However, this is an average rate, and as might be expected, there are differences as to which areas went up and down, when, and by now much (Hancox, 2002).

Maximum uplift is occurring at the north-eastern end of Lake Taupō, forming a broad ridge of uplift of up to ~ 1-2mm/yr across the centre of the lake. The pattern of uplift in this area has generally been consistent over the last 23 years, although some areas rose faster and more than others. The area from Horomatangi Reef to Rangatira Point was uplifted most (up to 70mm) while the Acacia Bay, Te Hapua Bay, and Waitahanui areas rose about half of this amount (Hancox, 2002).

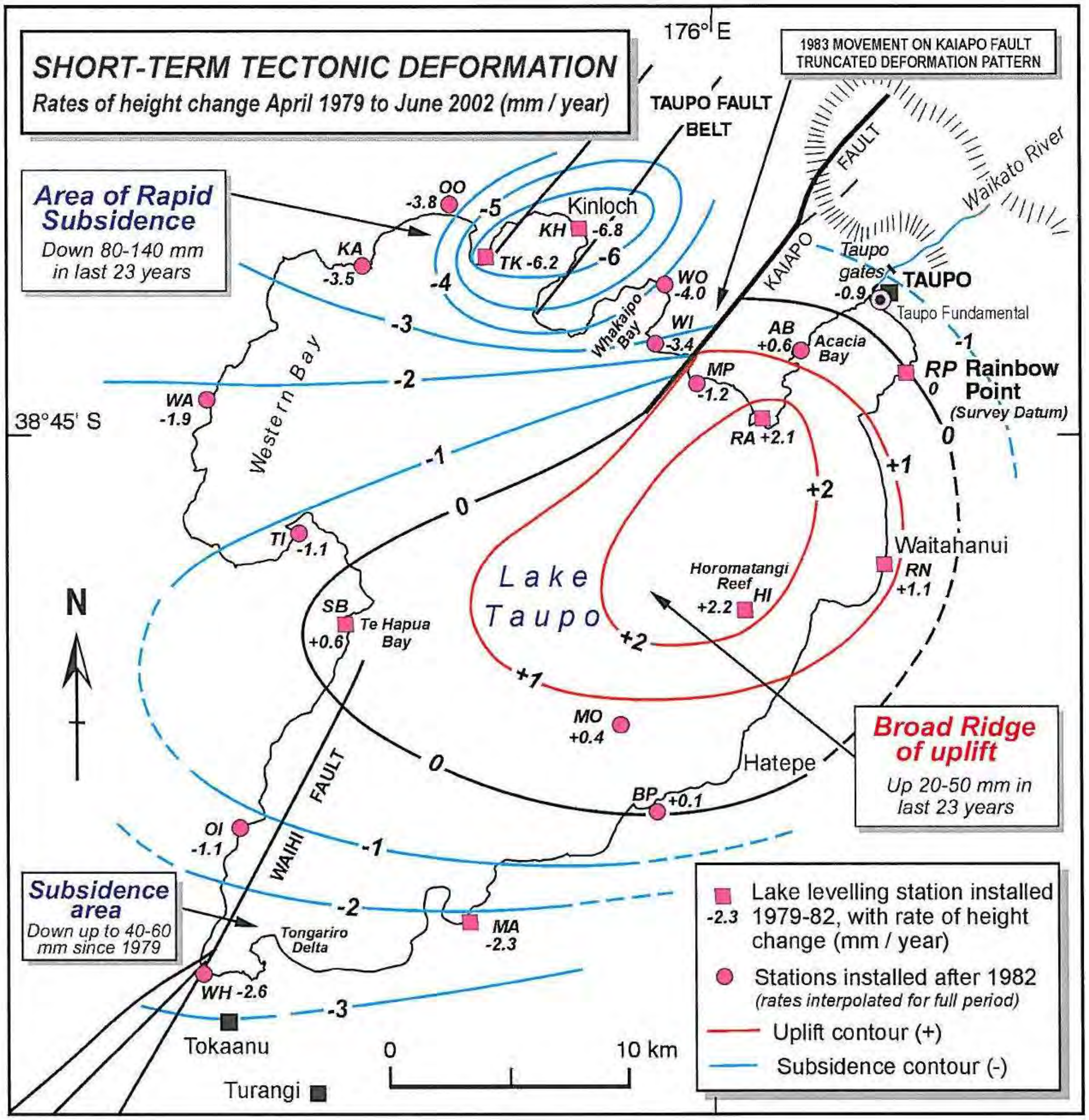


Figure 6.5: Tectonic deformation between 1979 and 2002 (Hancox, 2002).

Rapid subsidence of 6-7mm/yr was recorded at Kinloch but this rate then decreases across the lake towards Western Bay. Significant subsidence (2-3mm/yr) also occurred at the southern end of Lake Taupō from Motuoapa across to Waihi.

Over the last ~80 years tectonic deformation at Lake Taupō has not been constant. It has varied over time, especially during some seismic events. However, most of the ongoing recent tectonic deformation has been aseismic i.e., occurring without obvious earthquake activity (Hancox, 2002). This component of deformation is reasonably predictable.

Local subsidence and uplift

Localised uplift and subsidence has also been recorded around Lake Taupō, often in association with specific seismic events. For example, Whakaipo Bay subsided 3-4m as a result of the 1922 earthquake swarm. Subsidence appears to have affected the entire headland at Te Itarata. This subsidence does not show up in the surveys of the post-Taupō eruption lake terrace, however, as there are no measurement points in the affected area. It could also indicate that slow uplift of a similar amount may have occurred before 1922, and that this was cancelled out during the earthquakes. Local gravitational slumping of the beach in the area may also have occurred. Other historical examples of shoreline subsidence around Lake Taupō affected only the immediate lakeshore areas. They are likely to be the result of gravitational slumping (Hancox, 2002).

Because these localised and site-specific deformation events are essentially random in both time and place they have not been included in the analysis of shoreline deformation and how it affects the flood hazard.

6.4 Ongoing deformation

Ground elevations have been surveyed repeatedly at 22 sites around Lake Taupō between 1979 and 2013 (Figure 6.6). Both the time period over which a particular site has been surveyed, and the inter-survey interval, vary around the lake shore. Despite this, the survey data allow trends in ground movement over time to be identified and quantified.

The survey data prior to 2001 was collected by GNS Science using public good science funds through its volcano monitoring function. Since 2001 the data have been collected as part of the New Zealand GeoNet project and its sponsors EQC, GNS Science, and LINZ. The support of these organisations for allowing the use of these data for this project is gratefully acknowledged.

The average trends over the period 1979-2000 were discussed in Hancox (2002), and their implications to flood risk evaluated in Opus (2008). This discussion therefore examines the more recent data (2000-2013) in relation to those previous conclusions, and establishes whether the historic trends have continued in both direction and magnitude. This review also assesses the implications of the longer-term trends for the flood risk to land adjacent to Lake Taupō.

Data analysis

Survey data quantifying vertical ground deformation between 2002 and 2013 was reviewed in relation to longer term patterns to see whether the extrapolation of historic trends provides a reliable model of future behaviour.

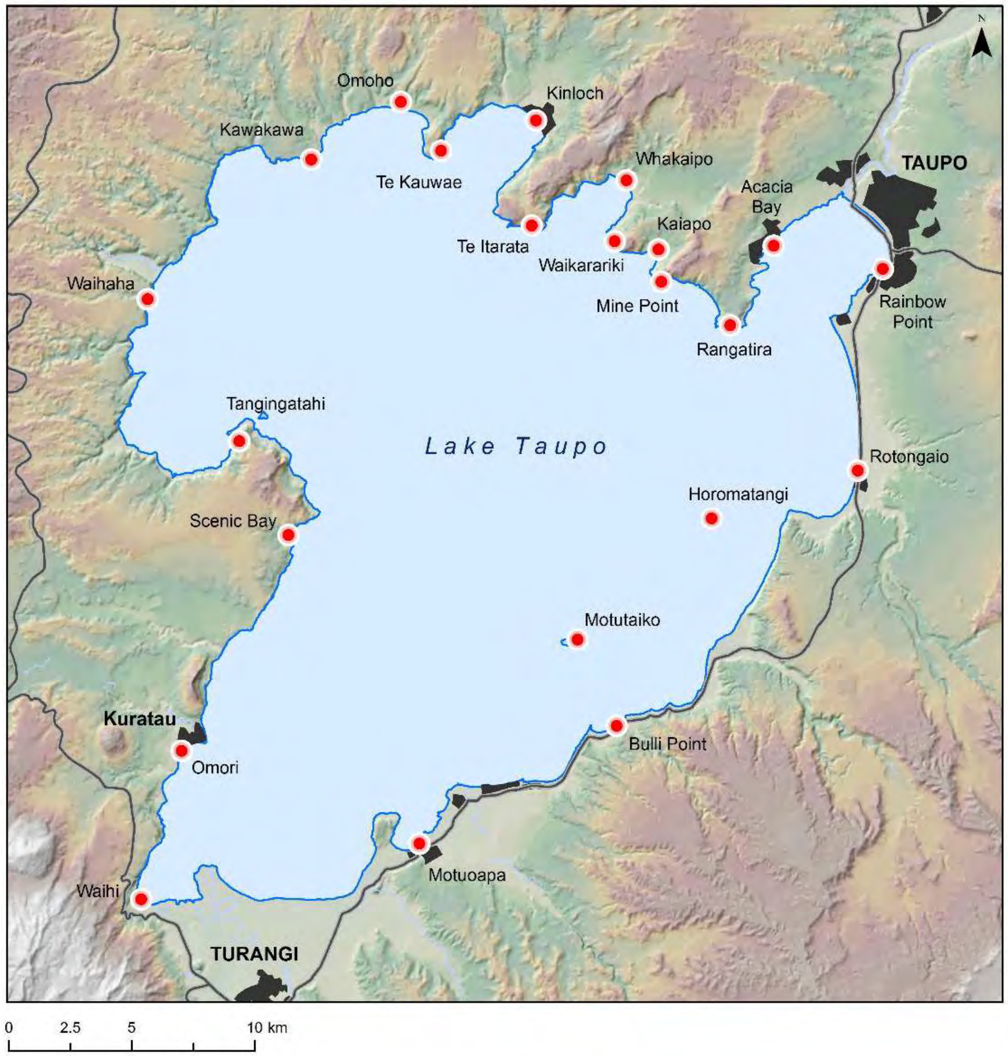


Figure 6.6: Survey locations around Lake Taupō.

To compare trends across the different time periods it was necessary to use a consistent method of deriving mean annual rates of change. Ground movement is expressed relative to the elevation of Rainbow Point (the lake levelling survey datum). Rates of change were calculated for each site over the following time periods:

- 1979 – 2013 (full survey period)
- 1979 – 2002 (period covered by Hancox, 2002 and Opus, 2008)
- 2002 – 2013 (most recent survey period)

For each period, a deformation rate was calculated so that ground movement at each site could be compared over different time periods. Rates were calculated by:

$$Rate\ of\ change\ (mm/y) = \left(\frac{Elevation\ at\ end\ of\ period\ (m) - Elevation\ at\ start\ of\ period\ (m)}{Time\ at\ end\ of\ period\ (y) - Time\ at\ end\ of\ period\ (y)}\right) * 1000$$

This approach assumes constant linear movement and change over each time period. A deformation rate determined in this manner may therefore not necessarily reflect the significant variability and fluctuations in ground levels that can occur over short periods. For example, Acacia Bay (AB) showed a 14mm drop over 3 months (December 2012-March 2013), and Rangatira (RA) showed seismically-induced uplift of 51mm over 17 months (August 1982-January 1984).

Short-term rates of deformation

Mean Annual Rates of Change

Recent deformation shows a similar pattern to the longer-term trend, albeit at a different rate. Mean rates of ground movement over the 2002-2013 period range from 6.4mm/y of subsidence to 2.7mm/y of uplift. i.e., a maximum difference of approximately 9mm/y across all sites. This period shows a narrower range of movement than the earlier 1979-2002 period over which a maximum difference of approximately 11mm/y was calculated. These, however, are average rates and considerable variability exists in the data, both across survey periods and between different survey points.

Variability in Deformation Patterns

The rate of tectonic deformation has not been constant over the entire survey period. Strong variability exists in the direction and magnitude of ground movement over the different time periods and around Lake Taupō. The spatial variability in deformation is summarised in Figure 6.7, while the ground elevations at each site during each survey are shown in Figure 6.8.

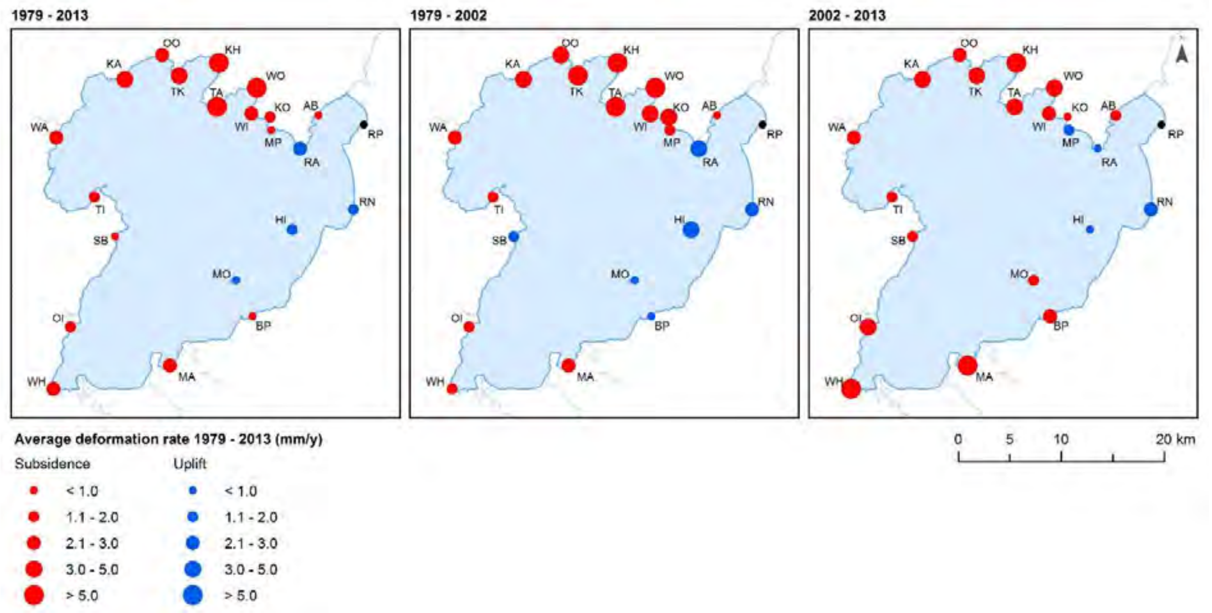


Figure 6.7: Spatial variation in rates of ground deformation around Lake Taupō.

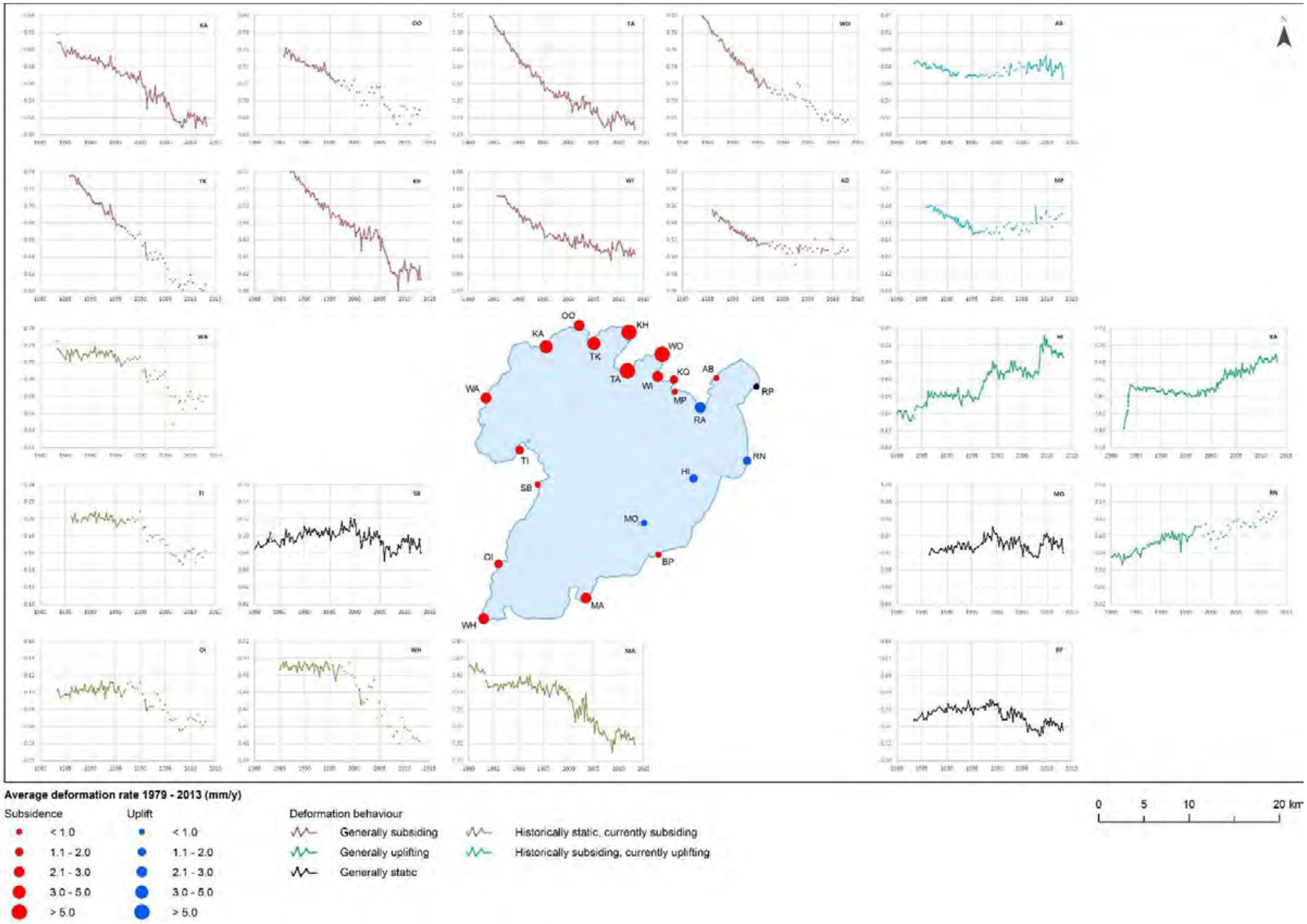


Figure 6.8: Ground elevation and annual rates of change for survey sites around Lake Taupō (1979-2013).

The various survey data allow the different sites and areas of the lake shore to be categorised by their "deformation behaviour". Five broad behaviour types are apparent in the data. These include areas which are:

- Generally subsiding;
- Generally uplifting;
- Generally static;
- Historically static, currently subsiding; and
- Historically subsiding, currently uplifting.

A consistent pattern of subsidence is apparent along the northern lakeshore across the full survey period (1979-2013). This rate, however, appears to have slowed since about 2005 at all of the northern sites. This reduction in the rate of subsidence is reflected in the general flattening of the curves in Figure 6.8. Subsidence is also occurring around the southern lake shore. Subsidence across this area, however, has been at a greater rate since about 2000; following a relatively stable phase over the earlier part of the survey period (Figure 6.8).

A general pattern of uplift is evident across the north-eastern part of the lake (Figure 6.7), albeit at a variable rate (Figure 6.8). The full names of the various site and explicit deformation rates over various time periods are given in Table 6.1.

Only three sites show consistent uplift across all survey periods (Figure 6.9).

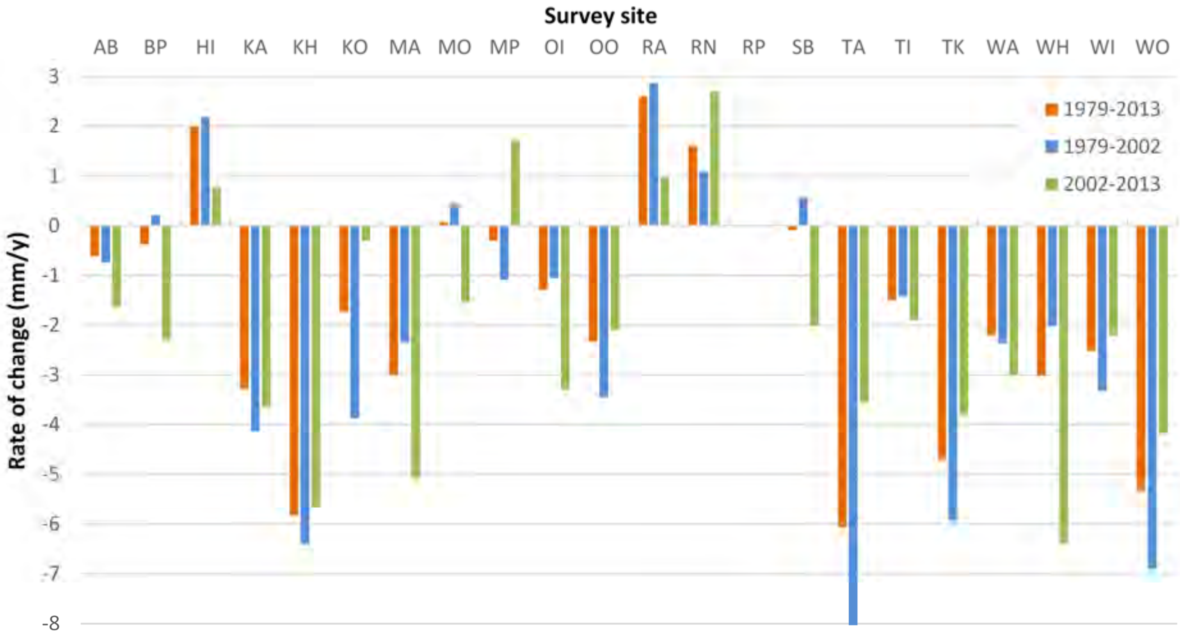


Figure 6.9: Rates of ground deformation around Lake Taupō over different survey periods.

The magnitude of the ground deformation in some locations around Lake Taupō is therefore sufficient that it should be considered when evaluating the longer-term flood risk. The variability inherent in the deformation data, however, is problematic. Despite this it is considered that the longer term trend does provide a realistic basis from which to assess the likely effect of deformation on the flood risk. To provide the most robust index, which includes the greatest amount of natural variability, use of the average trend over the entire period for which data are available is recommended (i.e. 1979-2013 in Table 6.1). Since these data express deformation as a rate per year, the total amount of deformation over a particular planning period must be derived.

Table 6.1: Rates of ground deformation by survey period.

Name	Code	Mean annual rate of change (mm/yr)		
		1979-2013	1979-2002	2002-2013
Acacia Bay	AB	-0.6	-0.7	-1.6
Bulli Point	BP	-0.4	0.2	-2.3
Horomatangi	HI	2.0	2.2	0.8
Kaiapo	KO	-1.7	-3.9	-0.3
Kawakawa	KA	-3.3	-4.1	-3.6
Kinloch	KH	-5.8	-6.4	-5.7
Mine Point	MP	-0.3	-1.1	1.7
Motuoapa	MA	-3.0	-2.4	-5.1
Motutaiko	MO	0.1	0.4	-1.5
Omoho	OO	-2.3	-3.4	-2.1
Omori	OI	-1.3	-1.1	-3.3
Rainbow Point	RP	0.0	0.0	0.0
Rangatira	RA	2.6	2.9	1.0
Rotongaio	RN	1.6	1.1	2.7
Scenic Bay	SB	-0.1	0.6	-2.0
Tangingatahi	TI	-1.5	-1.4	-1.9
Te Itarata	TA	-6.1	-8.0	-3.5
Te Kauwae	TK	-4.7	-5.9	-3.8
Waihaha	WA	-2.2	-2.4	-3.0
Waihi	WH	-3.0	-2.0	-6.4
Waikarariki	WI	-2.5	-3.3	-2.2
Whakaipo	WO	-5.3	-6.9	-4.2

Since the rate of deformation is highly site specific no single value can be used for the entire shoreline of Lake Taupō. Rather the deformation rate measured at particular points must be applied to a zone; centred on the survey location and extending in both directions to half the distance to the next survey location (Figure 6.10).

The fact that the deformation is so site specific, and so variable, means that any interpolation of the data to provide detailed information for points which have not been surveyed specifically could lead to misleading results and conclusions.

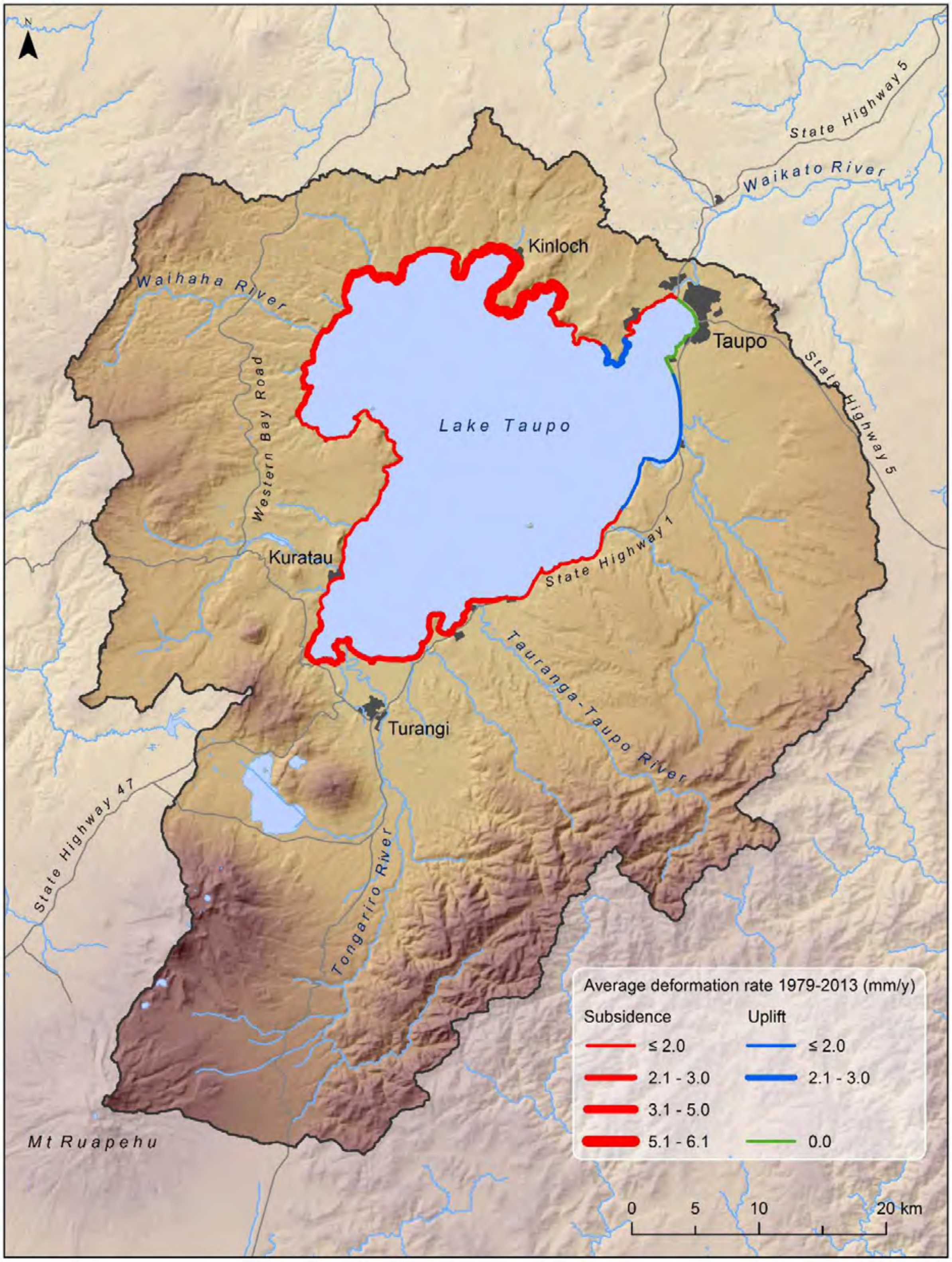


Figure 6.10: Deformation of the land adjacent to Lake Taupō.

Summary and recommendation

Surface deformation is likely to be a combination of tectonic stresses, subsidence caused by the extraction of geothermal steam to the north-east of the lake, and sediment consolidation in the vicinity of the Tongariro River delta. The northern and southern shorelines tend to be subsiding relative to the central Horomatangi Reef which is rising. This deformation is likely to continue but the rates and direction are variable and site specific. In addition to this 'continual' deformation, earthquakes may cause instantaneous vertical movement of the land.

Because of its magnitude, and potential impact on water levels, this tectonic deformation needs to be built into projections of future lake levels, and consequently the flood hazard model.

The available data relating to deformation around Lake Taupō show a consistent pattern of subsidence around the northern edge of the lake; centred roughly on Kinloch. Continued subsidence is also apparent around the southern shoreline; although at a slightly lower rate. This subsidence will effectively increase water levels in these areas over time; potentially exacerbating the flood risk.

Measurements show that the magnitude, and even direction, of deformation are highly variable. Different periods within the full survey period often yield quite different rates of deformation. Consequently, there is some uncertainty regarding the potential amount of deformation, and its effect on the flood risk, over the longer term.

While rates of subsidence appear to have slowed around the more populated northern areas in recent years, the inherent variability in ground movement and its potential effect on water levels still need to be considered when assessing the risk posed to the community by higher effective water levels.

In areas that are subsiding, the total amount of ground surface lowering over various time periods need to be considered. This provides a measure of the potential reduction in ground surface, and as a consequence, the effective increase in water level in this vicinity. Where areas are rising it is likely that over time uplift will provide an additional 'freeboard' or buffer against the effect of flooding. However, since high lake levels and wave events can occur at any time (even tomorrow) this uplift has not been included in the flood model. The effect of this is that over time these areas will have a greater margin of safety. However, to build the effect of future uplift into the present day situation would be to effectively increase the risk for current day activities.

7 Seiching

7.1 Background

Large lakes such as Taupō exhibit seiching. Seiching is the free oscillation of a body of water as it 'slops' back and forth in an enclosed, or partially enclosed, basin. This produces standing waves that result from the interaction of incident waves and their reflections. These waves have nodes and antinodes; points of zero and maximum vertical motion respectively. This can alter the effective height of the water surface by either increasing or decreasing the elevation of the surface depending on the conditions within the wave form. The frequency of the wave oscillation depends on the size and shape of the basin, its depth and bathymetry, and the temperature of the water. Deep lakes such as Taupō are particularly prone to seiching as the effect of bottom friction is relatively small.

Seiching is initiated when the lake surface becomes 'tilted'. Several environmental conditions can cause tilting of the lake surface, most commonly wind stress and barometric pressure differences. Less common causes include: heavy rain over a portion of a lake; flood discharges from rivers at one end of the lake; and seismic activity. The fundamental (or first) mode of seiche, which is the easiest to excite, in most instances has the greatest amplitude, and is therefore often the greatest source of error in equilibrium lake level measurements (Carter & Lane, 1996).

Gilmour and Heath (1989) investigated the seiche effect within Lake Taupō. They identified an internal seiche (baroclinic long wave) with a period of between 16 and 19 hours. This period is close to the inertial period (19.12 hours) and therefore the flow is strongly influenced by the Coriolis force. They also identified the 7 longest-period barotropic long wave periods which ranged from 35 to 11 minutes. The lowest-frequency barotropic modes of the lake have periods of about 35 minutes (up and down the lake) and 30 minutes (across the top of the lake). The strongest mode present in their water level records was the second one (30 mins) but this may have been influenced by the location of the water level recorder used in the study. The shape of the lake is such that the north-south oscillation has peak amplitudes at the south end of the lake whereas the east-west oscillation has peak amplitudes in the northern region. Within individual bays, localised shorter period seiche can occur (Hicks *et al.,* 2000).

Wind setup is the static tilting of the lake surface caused by a steady wind stress. Commonly, temporal variations in wind initiate seiche. The amplitude of the wind setup is controlled by the lake basin geometry (length downwind and depth) and the wind speed. Assuming an average depth of 100m for Lake Taupō, the maximum expected wind setup caused by a 10m/s wind along the long-axis of the lake would be approximately 4mm and for a 21m/s wind 20mm. These wind setup values are small compared with the run-up associated with waves breaking against the shore e.g., the 2% exceedance run-up at Taupō foreshore for 10 and 20m/s winds are 1.3m and 2.7m respectively (Hicks *et al.,* 2000).

When a barometric pressure gradient lies over a lake, the difference in pressure causes a tilting of the lake surface as the portion of the surface under the higher pressure is forced down. In a static situation, each hectopascal (i.e. hPa) of pressure difference causes an elevation difference of 10mm. This is known as the inverted barometer effect. For data that are available, the maximum pressure difference across the lake is 6.7hPa. This indicates a difference in levels of about 26mm; equivalent to a 13mm decrease at one end of the lake and a 13mm increase at the other (Hicks *et al.,* 2000)

7.2 Measured seiche effect

Lake levels are measured at both Acacia Bay and Tokaanu; with the data being recorded every 5 minutes (Figure 7.1 & Figure 7.2). Since the seiche period in Lake Taupō is approximately 30 minutes all the effects described above are present in these lake level records. The effects of waves are minimised because the recorders are in stilling wells. However, because the lake levels discussed earlier are 3-hourly averages these effects have been largely smoothed from those data and they must be added back to determine the actual short-term water level.

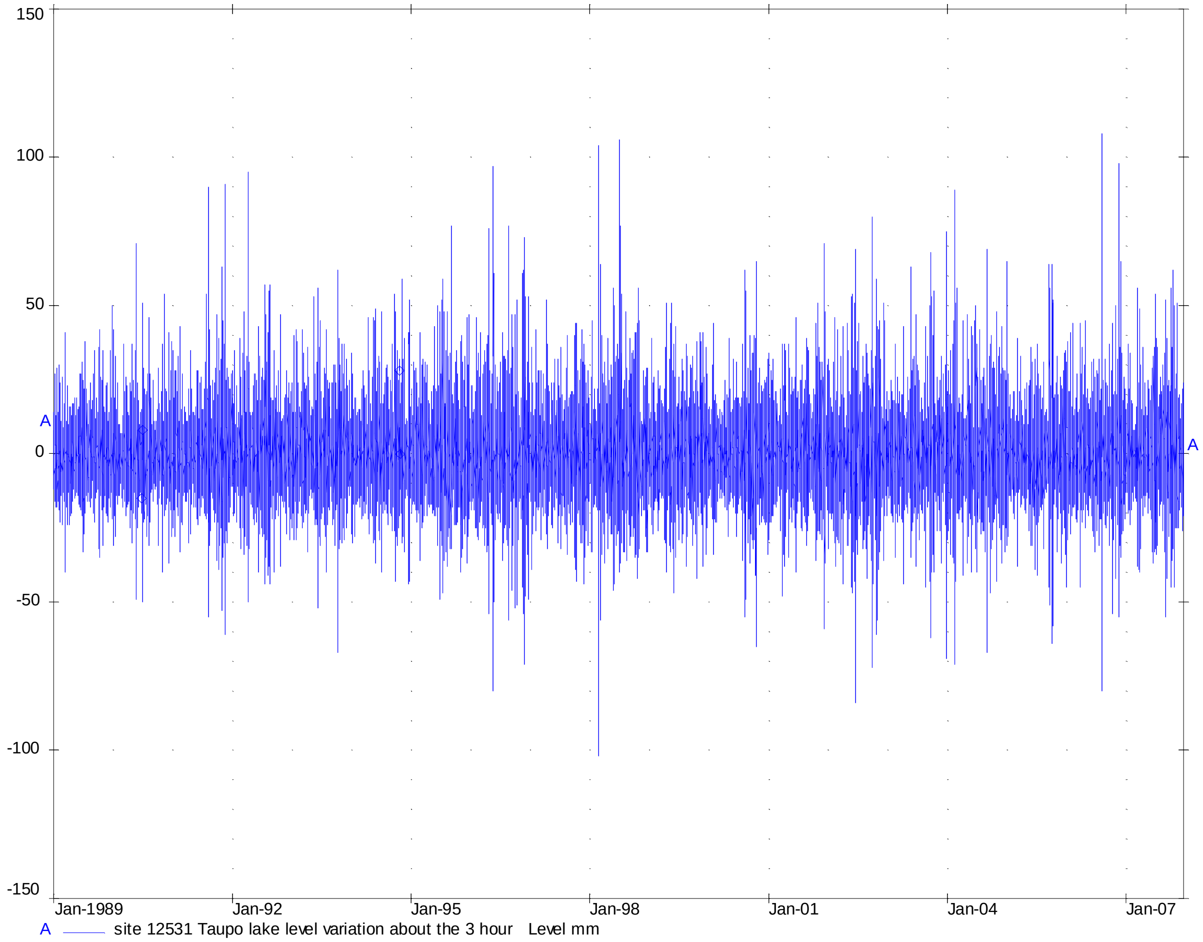


Figure 7.1: The seiche effect in the 5-minute lake level data at Acacia Bay.

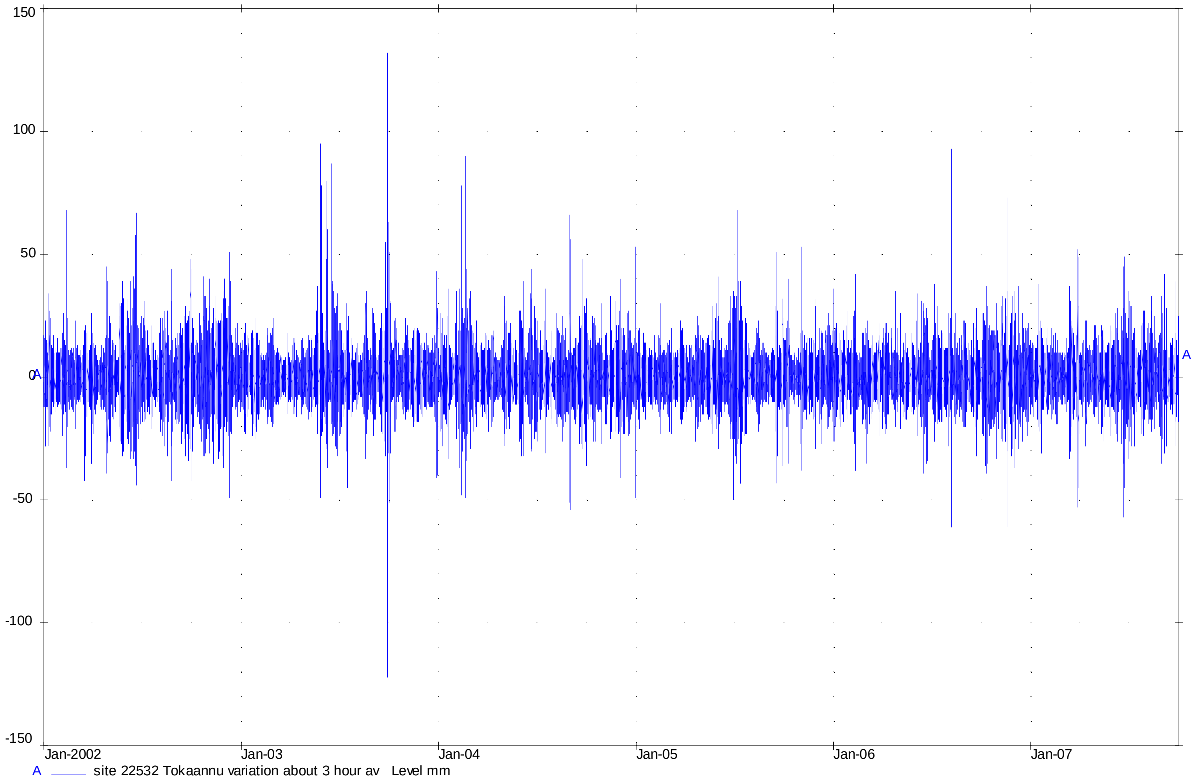


Figure 7.2: The seiche effect in the 5-minute lake level data at Tokaanu.

To quantify the seiche effect at both Acacia Bay and Tokaanu the variability of the 5 minute data from the 3-hourly average at each site was determined. Both sites show similar maximum variability (approximately ±100mm). However, in general Acacia Bay has a higher level of 'average' variability (the thicker blue zone) and greater variability on more occasions (more large peaks). This is consistent with the expected effect of the shape of Lake Taupō on the seiche.

The effect of this seiche on the height of the effective water surface is only the amplitude, or positive, increase in water level above the 3-hourly average. A frequency analysis of the variability of the Acacia Bay record was undertaken to assess the likely magnitude of the seiche effect that must be included in the flood hazard analysis. While the median increase in effective water level is only 3mm, 10% of the variability is greater than 10mm (Figure 7.3). A PE3 distribution fits the annual maximum seiche series best, although the seiche amplitude appears to become constant at 110mm after a return period of approximately 50 years. This is to be expected given the physical nature of those factors that generate and affect the seiche within Lake Taupō.

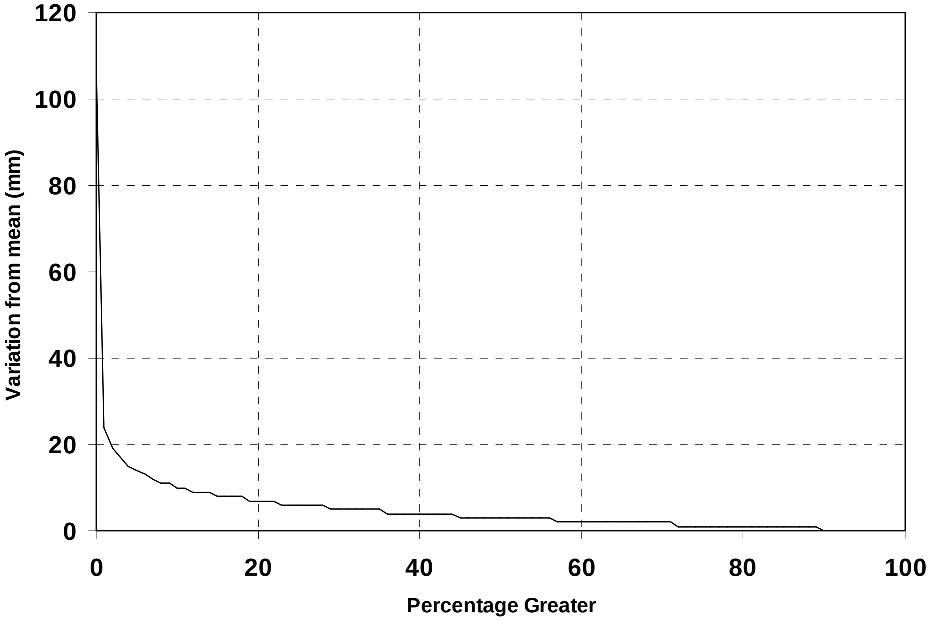


Figure 7.3: Distribution of the magnitude of the seiche effect above the 3-hourly static lake level at Acacia Bay (1989-2007).

7.3 Seismic-induced seiching

The location of Lake Taupō within the Taupō Volcanic Zone means that there is also a risk of seismically-induced seiching. The magnitude and frequency of such seiching is impossible to predict accurately. However, it has been suggested that large earthquakes, resulting from either tectonic or volcanic activity, could generate a seiche that may include waves up to 5m high that would travel across the lake (Froggatt, 2008).

Despite the potential size of such a seiche, and its possible affect, it has not been considered further in the analysis of flood risk. In addition to the unpredictable nature of such events, it is considered that should such an event occur, other environmental and economic effects are likely to be so high that the additional 'cost' associated with the seismic seiche-induced flooding is likely to be relatively minor.

7.4 Summary and recommendation

The seiche effect must be added to the 3-hourly static lake level data so as to more accurately reflect the potential elevation of the effective water surface. The magnitude of the seiche effect for different return periods (Table 7.1) must added to the lake level to indicate the potential static water level.

Table 7.1: Expected magnitude of the seiche effect on water levels.

Return Period	Seiche effect (mm)
2.33	76
5	90
10	101
20	108
50	110
100	110
200	110
500	110
Maximum Recorded	*108*

8 Land Use Impact

8.1 Background

A number of studies have investigated the link between land use and runoff in pumice catchments (Environment Waikato, 2006). Previous work (Hamilton, 2001) indicated that:

- Changing land use from forest cover to intensive pasture increases the rate and total volume of storm runoff;
- Such land use change results in higher flood peaks, and greater fluctuations in flow;
- Foliage intercepts rainfall and, as it evaporates faster from forests than from pasture, less rainfall arrives at the ground surface under forest;
- Tree roots promote good infiltration and trees can also obtain soil moisture from a greater depth than pasture;
- Interception losses and transpiration of soil moisture from a greater depth under forest affect storm antecedent conditions. Generally there is greater soil moisture storage that must be filled before runoff occurs;
- Stock trampling and vehicle use on pasture can compact the soil and reduce infiltration capacity;
- Flood producing surface runoff and overland flow are therefore less under forest than pasture;
- Pumice soils in a dry condition initially repel water until they have ‘wetted up’. Therefore, infiltration at the start of a storm is often negligible but after wetting it increases substantially; and

- This effect is more common for pasture than forest, for the reasons listed above, and this contributes to making runoff from pumice soils very sensitive to land use change.

Notwithstanding the above, most of the studies from which these conclusions have been drawn were undertaken in small catchments. The response of larger catchments to land use changes is more complex. Most of these studies have also not focused on pumice soils which are known to respond atypically to heavy rainfall, and to be more sensitive to land use changes than conventional soils.

Only two studies have specifically investigated land use-related effects on runoff on pumice soils. An almost sevenfold increase in runoff with a land use change from scrub to pasture was found in the central North Island. In intense storms, the percentage of runoff increased by a factor of up to 10. Data also indicated that, because of the high infiltration capacities, total runoff volumes from pumice soils are low when compared to other soil types regardless of vegetation cover (Selby, 1972). In the Purukohukohu catchments near Reporoa smaller flood peaks approximately doubled; and larger peaks increased by an order of magnitude when forest was converted to pasture (Rowe, 2003). The findings of these two studies are therefore consistent. However, these results differ from those in non-pumice catchments where it has been found that as flood magnitude increases the relative difference in flood peaks between pasture and forest catchments decreases.

These small-catchment studies do not account for the attenuation effects of surface and channel storage on runoff. These effects may be expected to reduce the absolute differences in runoff between land uses for flood peaks in larger catchments. As mentioned previously, pumice soils are particularly sensitive to short-duration high-intensity storms. This is likely to have a more significant effect in small catchments which have short times of concentration; such as the study areas discussed above. This would tend to bias the results, particularly when applying them to larger catchments.

An analysis of these findings, together with detailed hydrologic modelling of the potential effect of large scale conversion of forestry to pasture on a catchment's flood regime, has helped quantify the specific effects of land use change (Environment Waikato, 2006). The basic conclusions are summarised in Table 8.1.

8.2 Forest conversion

There has been a significant change in the land cover of the Lake Taupō catchment in the past. Between 1840 and 2000 the area under indigenous forest was reduced by 14%, and tussock by 90%. The areas under planted forestry, scrubland and pasture had all increased (Figure 8.1). Much of this change has occurred since the inflow and water level of Lake Taupō have been recorded (i.e., 1906) and therefore the effect of this 'past' change has been included in the previous analysis of lake levels.

Table 8.1: Estimated increase in flood peak discharge and volumes with a change in land use from forest to pasture.

Average recurrence interval	Increase in flood peak discharge (m^3/s)			Change in flood runoff volume (m^3)	
	Regional frequency analysis method (m^3/s)	*Unit hydrograph method (m^3/s)*	*Average increase per km^2 of forest converted*	*SCS method (m^3X10^6)*	*Average increase per km^2 of forest converted*
2	23.9	55.4	0.18	4.2	0.019
10	77.7	102.4	0.40	7.5	0.033
20	109.8	131.4	0.54	9.4	0.042
50	165.9	184.1	0.78	12.8	0.057
100	222.5	239.3	1.03	16.2	0.072

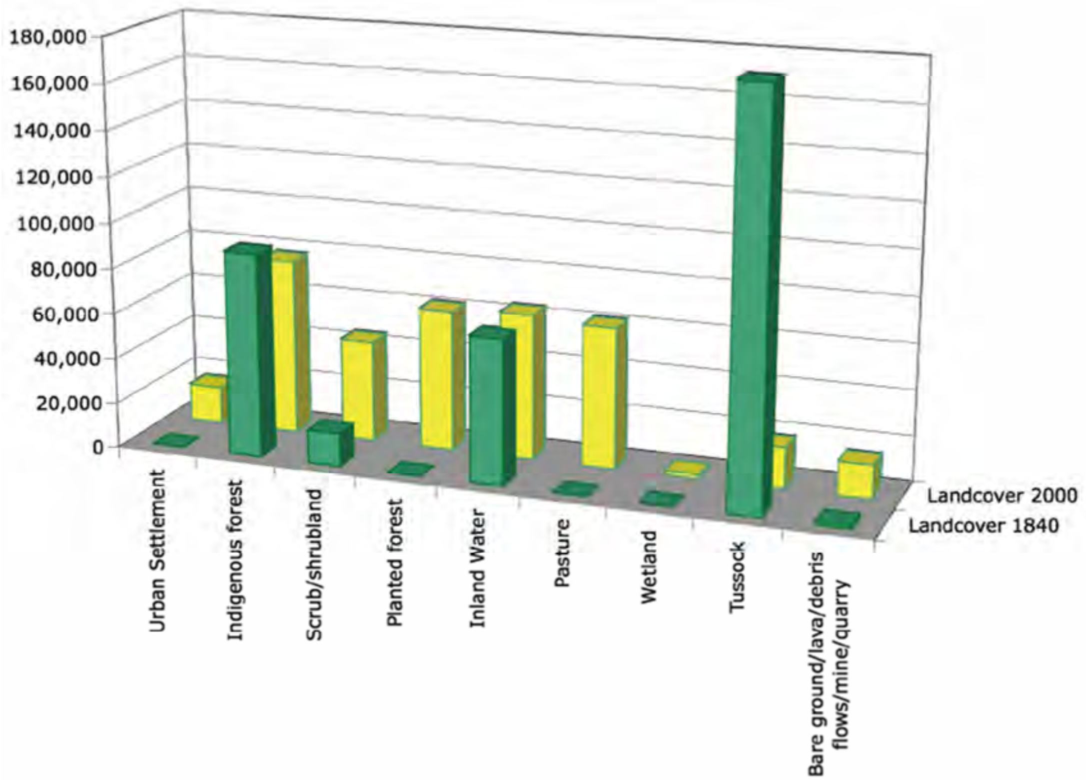


Figure 8.1: Land use changes between 1840 and 2000, Lake Taupō catchment (Hamilton, 2005).

Figure 8.2 shows the land cover surrounding Lake Taupō in 2000. Much of the catchment is under forestry (38% in indigenous and planted forest) and scrubland (12%). The majority of this is also under some 'reserve' status. Therefore, land use within the catchment is unlikely to change in the foreseeable future. There is a relatively small area of urban settlement (5%) which would have a greater effect on the runoff regime but even this land use tends to be dispersed around the shores of the lake (Figure 8.3)

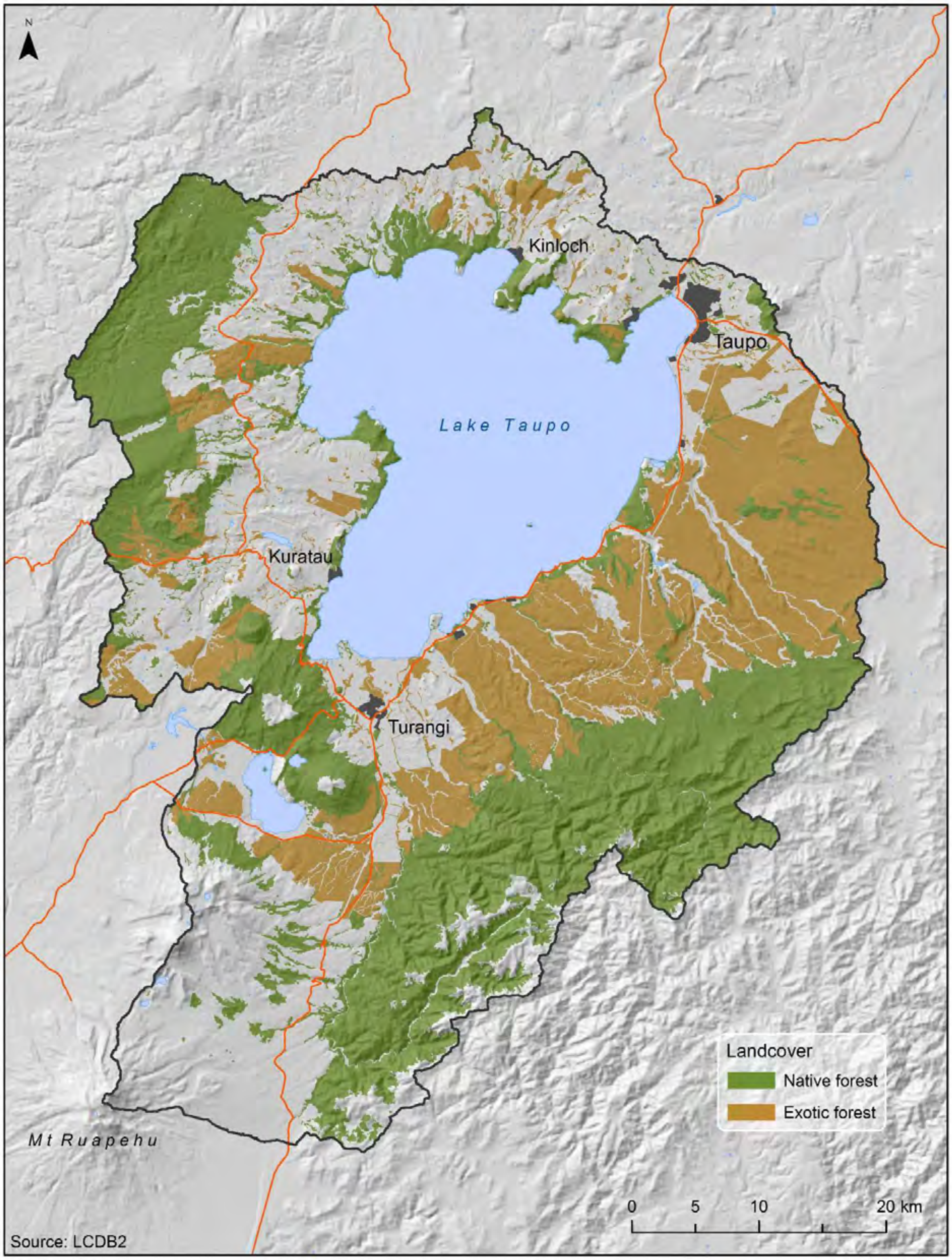


Figure 8.2: Land Cover in the Taupō catchment (Source: LCDB2-2004).

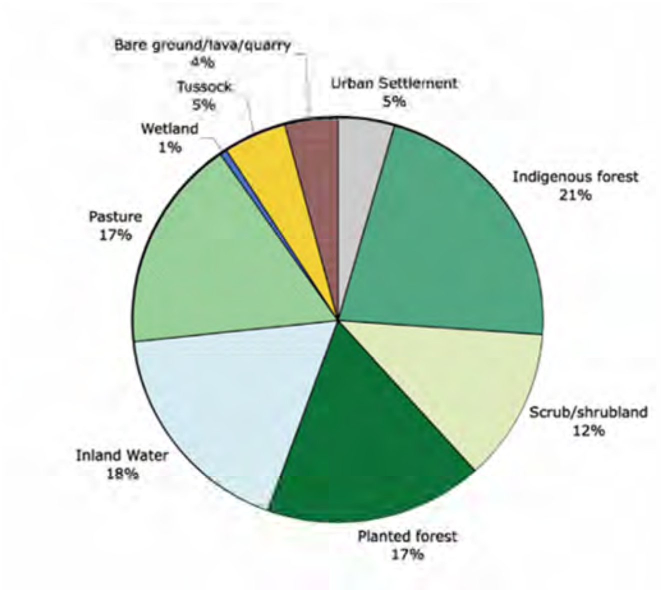


Figure 8.3: Land use Taupō catchment, in 2000 (Hamilton, 2005).

8.3 Impact on flood risk

The recent trend has been for an increase in the area under forestry within the Lake Taupō catchment. This is different to the Waikato River below the Taupō Gates where there has been a shift to the conversion of land under forestry to pasture; recently for dairy farms. Since such a shift is perhaps the land use change most likely to effect the Taupō catchment, the potential effects of such a change were modelled.

At present there are approximately 493km^2 under either open or closed forestry within the catchment. Another 135km^2 had been recently harvested (LCDB2-2004). The most dramatic, although highly unlikely, land use change that could affect the hydrologic regime and lake levels would be the conversion of all these forestry lands to pasture. This would see 628km^2 of land currently under forest converted to pasture. Using the information presented in Table 8.1, this would have the potential effects summarised in Table 8.2.

8.4 Effect of land use change

Some change to the rainfall–runoff relationship might be expected within the catchment as a result of a change in land use. However, in the context of changing the lake levels this is likely to be minor. There are a number of reasons for this:

- Much of the catchment is mantled with porous and permeable volcanic material. This has been shown to be the major control on the runoff regime of the Lake Taupō catchment rather than vegetation type (Fahey and Rowe, 1992);

Table 8.2: Potential effect on the hydrologic regime if all 628km^2 of forest lands within the Lake Taupō catchment were converted to pasture.

	Average increase in peak discharge per km^2 converted (m^3/s)	Increase in peak discharge if all converted (m^3/s)	Average increase in flood runoff volume per km^2 converted (m^3)	Increase in flood runoff volume if all converted (m^3 X 10^6)	Potential increase in lake level as a result of land conversion (mm)
2	0.18	113	0.019	12	20
10	0.40	251	0.033	21	33
20	0.54	339	0.042	26	41
50	0.78	490	0.057	36	57
100	1.03	647	0.072	45	72

- Those areas where land use change has a greater potential to affect the runoff regime (i.e., areas underlain by greywacke) are generally in the surrounding hill country. These areas are likely to remain under protection or production forest;

- Any significant land use change is likely to affect only small areas of particular sub-catchments. Any effects will be smoothed and attenuated further down the catchment. Since the levels in Lake Taupō reflect the net effect of all changes and processes occurring in all sub-catchments any change would not be discernible in lake levels;

- The majority of inflow to Lake Taupō comes via the Tongariro River. Much of this flow comes from within the National Park or Waiouru Army lands. Significant land use change is unlikely in either of these areas;

- Should there be any changes to the net inflow to Lake Taupō these are likely to be managed and compensated for in the manner in which the Taupō Gates are operated;

- The effect of land use change on the hydrologic regime of Lake Taupō since 1906 are already included in the flow and level records used in analysis. It might be argued that any changes over that period are likely to be significantly greater than those in the future;

- The general trend has been for an increase in forestry throughout the catchment; and

- Even if all the area currently under forestry was converted to pasture, an extremely unlikely scenario, this would increase the lake level caused by a 100-year event by only 72mm.

Summary and recommendation

As a result of the lack of information regarding potential changes to future land use, and the relatively small impact of converting all existing forestry lands to pasture (considered highly unlikely), the effects of land use change on future lake levels has not been considered further in this study.

9 Static Water Level

9.1 Summary

The risk of flooding, and potential depth of any inundation, to land adjacent to Lake Taupō are primarily controlled by the static water level in the lake. The static water level is a function of the lake level and the seiche; which must be added as it is removed when processing the lake level data to 3-hourly averages, the form in which it is held in the Power Archive. Over time it is possible that global warming and climate change may result in increases in lake level under particular conditions. These effects must also be added to the static water level. The effect of relative tectonic warping of the landscape is likely to be significant over longer time periods. In areas subject to subsidence the effect of this on water levels also needs to be considered.

The static water level for any specific return period is therefore equal to the sum of the estimates of the lake level together with the appropriate seiche, climate change, and deformation components. The static water level can therefore be determined by adding the appropriate values from Table 3.6, Table 4.8, and Table 7.1 (Table 9.1). To this must be added the 'site specific' effect of tectonic deformation over the particular return period chosen. The rate of tectonic deformation were summarised in Table 6.1 and Figure 6.10.

Table 9.1: Expected static water level for different return period events excluding deformation.

Return Period	Lake Level (m)	Climate Change 2090s (m)	Seiche Effect (m)	STATIC WATER LEVEL
2.33	357.18	0.06	0.08	357.32
5	357.28	0.09	0.09	357.46
10	357.35	0.11	0.10	357.56
20	357.40	0.13	0.11	357.64
50	357.45	0.16	0.11	357.72
100	357.49	0.19	0.11	357.79

10 Wind Waves

10.1 Introduction

Although waves do not affect the static water level they can increase the effects of high lake levels, and consequently worsen inundation, through wave run-up. Wave height, and therefore energy, is primarily controlled by wind speed, wind duration, and fetch.

As a wave breaks at the shore, swash of the wave runs up the beach increasing the active area at threat to flooding beyond the still water level of the lake. Waves are a function of the wind speed, water depth and fetch (the unobstructed distance travelled by waves). The height of run-up is primarily a function of wave height, wave period and beach slope. Many other factors can also influence wave run-up including permeability (rate of flow through the porous beach material), vegetation, porosity (the percentage of the beach material that consists of open spaces), roughness, and wave reflection. Figure 10.1 highlights the difference between wave height and wave run-up.

Figure 10.1: Waves running up the beach at Waitahanui. Blue dashed line shows still lake level, pink line shows wave run-up caused by wind (Hicks *et al.*, 2002).

10.2 Wind environment

The prevailing winds across Lake Taupō are from the west and south-west. Strong winds are caused by either: major storms moving in from the south-west that tend to last several days; or, northerly winds associated with tropical depressions (Riggs *et al.*, 2001). Assuming that fetch is the limiting factor in wave formation, areas most vulnerable to wave run-up are on the northern and eastern shores of Lake Taupō. The southern end of the lake is generally sheltered from the dominant wind direction, as are enclosed areas such as Acacia Bay.

Wind data are recorded at two stations around Lake Taupō: the Taupō Airport, and the Turangi Meteorological Service Station. Results from these stations show the northern end of Lake Taupō is windier than the southern end. Turangi in the south also has a greater number of calm days (39) compared to Taupō (26) (Macky and Bowler, 1998).

The strength and frequency of winds can also vary with long-term trends and climatic cycles; for example, the different phases of the Southern Oscillation Index. These trends and patterns may influence shoreline inundation and flooding but little detail is available on how these trends impact the wind regime of Lake Taupō (Hicks *et al.,* 2002).

10.3 Wind regimes

The most appropriate data available for modelling the wave regime of Lake Taupō is that recorded at Taupō Airport AWS. The available wind record runs from November 1991 until the December 2013. The data from 1991-1994 were recorded as 3-hourly averages, and those since 1995 as hourly averages. The anemometer has been in the same position, and had the same exposure, over the entire period of record. Any changes in the wind regime are therefore likely to reflect real changes rather than instrumental error or site effects.

Analysis was undertaken on the 3-hourly averages over full years only, i.e., from 1992 to 2013. Wind data for 2013 was obtained from Taupō District Council since data from Taupō Airport AWS are no longer available directly. A comparison of the data from these two sources, on an overlapping period of record during 2012, showed that both data sets were consistent; although not identical (Figure 10.2 and Table 10.1). It is unknown why the same data obtained from two separate sources appears to be different.

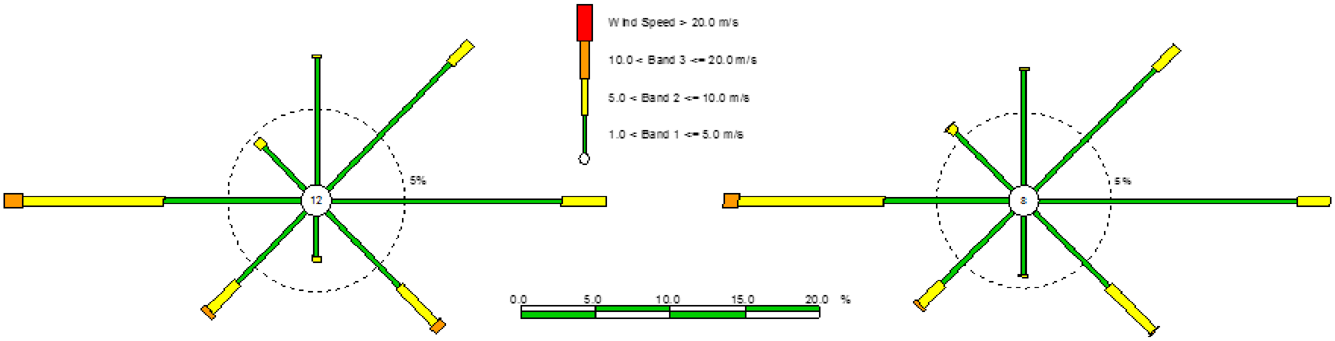


Figure 10.2: Comparative wind roses of 3-hour average Taupō AWS (left) and Taupō DC supplied data (right) for the overlapping period from 1-Jan-2012 to 1-Jan-2013.

Table 10.1 Distribution (percentage time in each octant) of 3-hour average Taupō AWS and Taupō DC supplied wind data for the overlapping period 1-Jan-2012 to 1-Jan-2013.

	1-5 m/s		5-10 m/s		10-20 m/s		Total	
	Taupō AWS	Taupō	Taupō AWS	Taupō	Taupō AWS	Taupō	Taupō AWS	Taupō
N	8.2	7.9	0.3	0.2	0.0	0.0	8.5	8.1
NE	11.7	11.7	1.9	2.1	0.0	0.0	13.6	13.8
E	15.4	17.7	3.0	2.3	0.0	0.0	18.4	20.0
SE	6.8	7.2	3.4	4.3	0.5	0.1	10.8	11.6
SE	2.5	4.0	0.4	0.2	0.0	0.0	2.9	4.1
SW	6.4	6.9	2.6	2.0	0.4	0.2	9.4	9.1
W	9.2	8.6	9.5	10.0	1.2	1.0	19.9	19.5

NW	4.0	5.5	0.6	0.6	0.0	0.1	4.6	6.2
Calm							11.9	7.5

The two data sets were subsequently joined to form a single Taupō wind series from 1992 until the end of 2013 which was used for analysis.

A 3-hour average wind speed was chosen for analysis. This is the approximate time required to generate a 'fully-arisen-sea' state over the broader fetches of Lake Taupō under strong wind conditions. Since the necessary wind data are only available since 1992, it was not possible to investigate the likely wave regime prior to this date. While there are some wind data for earlier periods these are generally of poor quality, low resolution, and the records contain many periods of missing data. To ensure consistency of analysis only those data since 1992 were therefore used in this analysis.

The Taupō airport wind record was assumed to be representative of the whole lake. In fact, the short wind record from Turangi shows that the southern shore experiences more calm periods, and its extremes are less severe than at Taupō Airport (Macky & Bowler, 1998). Given this, the wind-wave modelling results presented in the following sections may over-predict the wave energy around the southern shore; although the relative magnitude/frequency estimates will still be realistic (Mack *et al.*, 2006).

The dominate winds at Lake Taupō are westerlies which occur almost 30% of the time (Figure 10.3). Winds from the northwest, east and southwest are also fairly common (Table 10.2). Strong winds i.e. those >10m/s occur from the west approximately 1% of the time; this is higher than the percentage of strong winds from all other directions combined. As a result of the stronger westerly winds, the waves breaking on the eastern shores of Lake Taupō are likely to be larger, more frequent, and contain more energy.

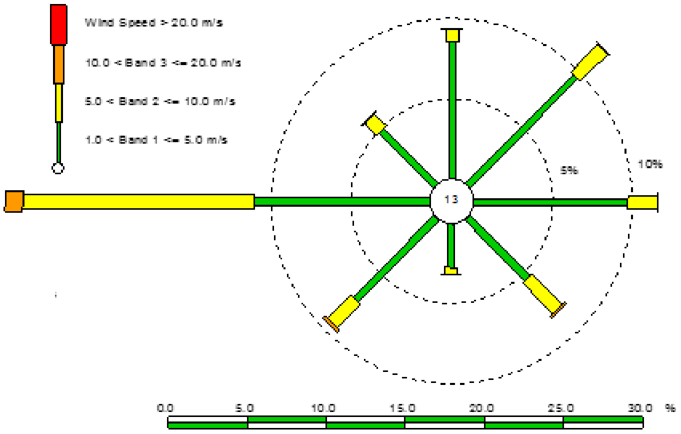


Figure 10.3 3-hour average wind rose of the combined Taupō wind record for the period 1992-2013.

Table 10.2 Wind regimes (percentage time in each octant) for the combined 3-hour average Taupō wind record during the period 1992-2013.

	1-5 m/s	5-10 m/s	10-20 m/s	Total
N	8.5	0.8	0.0	9.3
NE	9.6	2.4	0.1	12.1
E	9.7	1.9	0.0	11.6
SE	5.3	2.7	0.2	8.2
S	2.7	0.4	0.0	3.1
SW	7.2	2.1	0.2	9.5
W	11.0	14.6	1.1	26.7
NW	4.9	1.1	0.0	6.0
Calm				13.5

10.4 Wave run-up modelling

The most detailed and extensive coverage of wave information for Lake Taupō is contained in Hicks *et al.* (2000). That analysis used 27 years of 3-hour average wind speed and direction data from Taupō Airport. The dataset, despite a number of gaps and various recording resolutions, provided a record long enough to characterise the wind-wave climate. It also allowed the identification of inter-annual variability, and any correlation between the wind-wave record, lake level, and the Southern Oscillation Index.

Some earlier work relating to waves on Lake Taupō was undertaken by Macky & Bowler (1998). That study, however, focused on only a few locations and investigated wave height rather than wave run-up. Although there is a relationship between wave height and wave run-up it was decided to use Hicks *et al.* (2002) holistic approach to lakeshore wave run-up for the current study. This is because Hicks *et al.* (2002) derived data for the entire lake shore; calculated wave run-up rather than just wave height; and their approach has become the 'standard' when analysing wave data relating to Lake Taupō.

Lakewave model

Wave run-up around Lake Taupō was estimated by Hicks *et al.* (2000) using the hindcast model *"Lakewave"*. The model used the daily 3-hour maximum recorded wind at the Taupō Airport between 1979 and 2006. Wave generation is based on the NARFET (NARrow FETch) model. NARFET was designed for restricted, narrow fetch situations and allows wave generation in off-wind directions. For wide fetches it gives essentially the same results as the straight-line fetch method given in the Shore Protection Manual (CERC, 1984).

The *Lakewave* model is based on several assumptions but provides an indication of wave run-up around the shoreline of Lake Taupō. The model assumptions, as detailed in Hicks *et al.* (2000), are that:

- Waves are locally generated and fetch limited;
- The enclosed water body is 'deep' (i.e., the depth is greater than half the wavelength of the peak-energy frequency, except near shore);
- The wind field is uniform, and is represented by records from a single station;
- The wind conditions are steady, equalling the average condition between records; and
- The waves are not diffracted or refracted, apart from simple refraction of shoaling waves approaching a shore defined by smooth, parallel contours (where radiation stress is conserved).

As discussed previously, wind data for this study were 3-hourly averages obtained from Taupō AWS for the period 1992-2013. The use of this wind record, which includes any variability in the wind regime over the past 22 years, may result in some relatively minor differences when compared to the results of Hicks et al. (2000). However, restricting the analysis to use only wind data since 1992 ensures the use of a consistent, high quality, wind record.

Model output

Lakewave produces estimates for a range of variables, but of most interest to the current study is wave run-up. It is important to recognise that a particular set of wind conditions does not produce a wave train of uniform and identical waves. Rather it produces a variety of waves that vary in their characteristics. This distribution of waves is usually assumed to approximate a Rayleigh distribution. The Rayleigh distribution, unlike a normal distribution, still has an average value but the majority of values are clustered towards the lower end of the distribution (i.e. lower wind speeds or wave heights) with only a few large values. That is, the distribution is not symmetric about the mean. Many studies, including the current one, highlight the importance of knowing the height (and subsequently run-up) of the largest wave that can be expected. Since the Rayleigh distribution actually goes to infinity to the right of its peak it is necessary to define the 'significant wave height'.

While a range of definitions exist for the significant wave height, one of the more common, and that used in *Lakewave,* is the 2% exceedance run-up height. This is the wave run-up height that is exceeded 2% of the time under the prevailing wind conditions.

Model accuracy

A qualitative assessment of the accuracy of the model was undertaken in Hicks *et al.* (2000) using an analysis of the wave regimes shown in oblique photographs. Under brisk south-westerly conditions the average wind recorded at Taupō airport was 6.8m/s from 250 degrees. *Lakewave* predicted 3.9s deep-water waves (wavelength equal to 23.7m) at Wharewaka Point. In comparison, the deep-water wavelength scaled off the photographs of Wharewaka Point at the time was 20m. This agreement is quite reasonable. At a broader scale, it was also found that there was qualitative agreement between the modelled run-up height, and the amount of surf on photographs. It was concluded that *Lakewave* functions acceptably at a broad scale, although it is limited in small embayments where wave conditions are strongly affected by refractions and diffraction (Hicks *et al.,* 2000).

Model output analysis

Lakewave and the available wind data were used to produce estimates of the 2% exceedance run-up at 937 locations around Lake Taupō (Figure 10.4). The model initially used a standard beach slope of 7 degrees and a sediment size of 2mm. As a result, this output is perhaps more indicative of potential rather than actual wave run-up. However, the model does indicate the variability of wave run-up around Lake Taupō. Greatest wave run-up is apparent around the NE shore of the lake, particularly along Taupō Foreshore and south along Five Mile Beach as far as Waitahanui. Acacia Bay is particularly well sheltered and as a result the wave run-up is very low.

The fact that there is considerable variability in the wave run-up environment means that a single value cannot be used in any flood hazard analysis. The complexity of the system, and constraints of this project, also meant that individual site analysis was impractical. Therefore, the wave run-up data presented in Figure 10.4 were used to divide the shoreline of Lake Taupō into 10 distinct wave run-up environments, within which similar wave run-up behaviour can be expected. These 10 distinct environments are shown in Figure 10.5. The wave environment of the Taupō Zone is similar to that at Kaiapo Bay, but distinctly different to that of Acacia Bay. Likewise, the wave run-up environment at Kuratau is similar to that at Waihaha but distinctly different to Whanganui Bay.

For each of these 10 wave environments a detailed analysis of wave run-up behaviour was undertaken using site-specific values of beach slope, sediment size and density, porosity etc.

The effect of site exposure and site characteristics on the wave run-up regime is clearly shown in Figure 10.6. Acacia Bay is sheltered from most wind directions and has very limited fetch. Hence the wave run-up regime is dominated by small run-ups. The maximum modelled 2% exceedance wave run-up was only 0.44m. Taupō Foreshore on the other hand is exposed to stronger winds and has the longest fetch. Consequently it has a maximum wave run-up of 1.50m (Table 10.3).

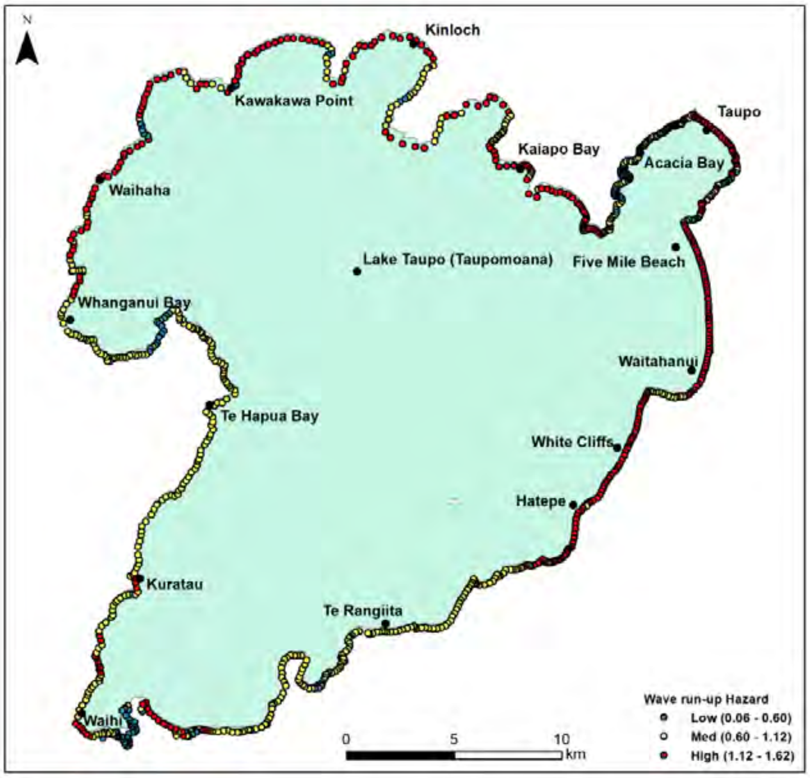


Figure 10.4: Wave run-up (2% exceedance) around the shore of Lake Taupō.

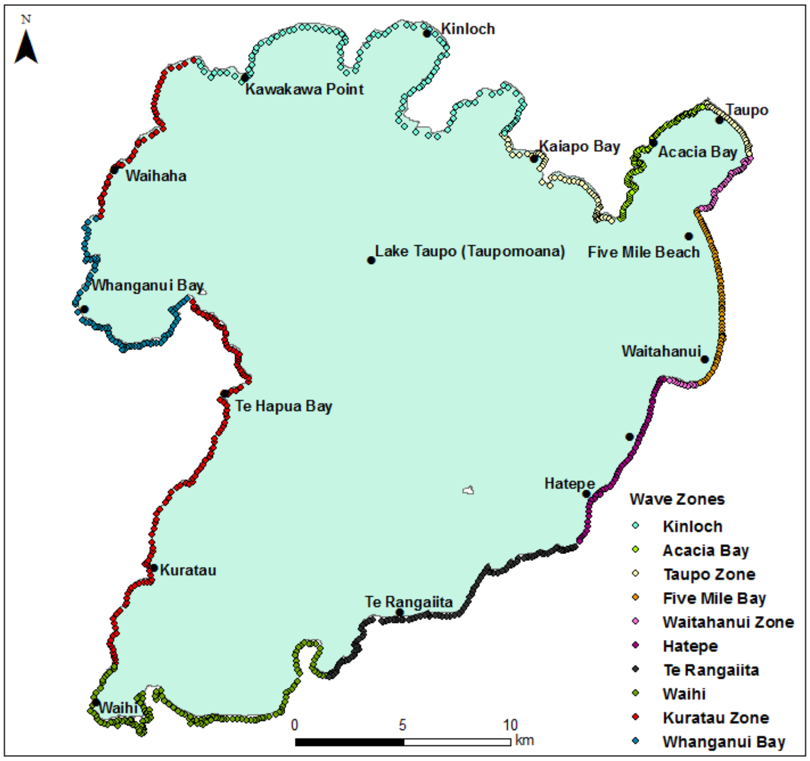


Figure 10.5: Wave run-up environments around the shore of Lake Taupō.

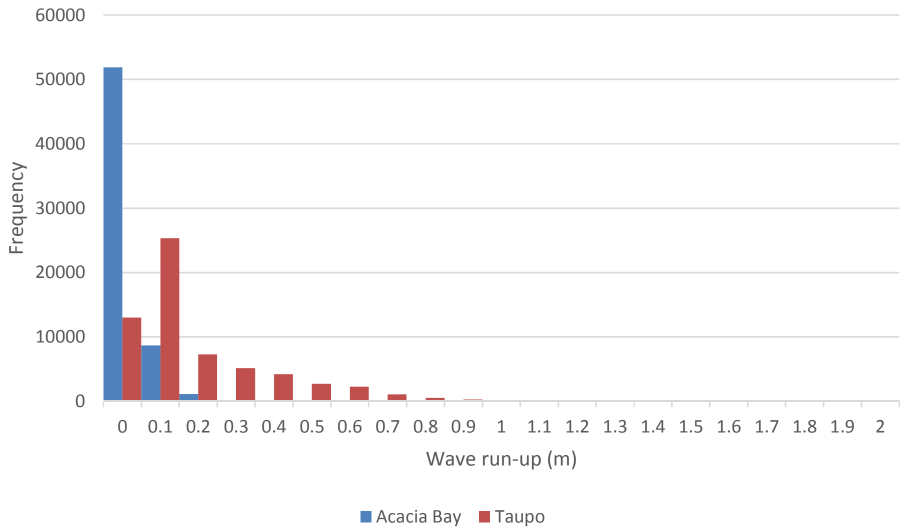


Figure 10.6: Wave run-up regimes (determined from the 3-hourly wind data) at Acacia Bay and on the Taupō township foreshore.

Frequency distributions for the 2% exceedance wave run-up for each of the wave environments confirms the fact that different sections of the shoreline respond to the wind regime in a characteristic manner (Figure 10.7).

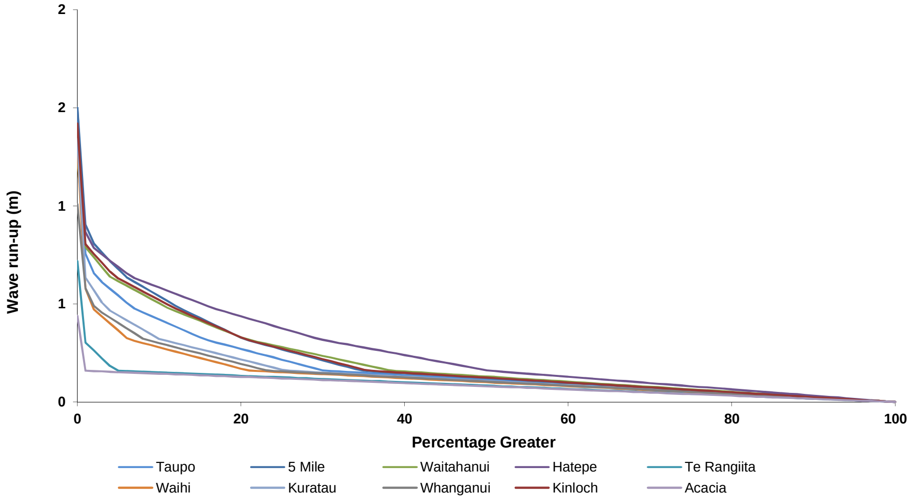


Figure 10.7: Different wave run-up environments around the Lake Taupō.

A frequency analysis was undertaken of the wave run-up data for each of the 10 distinct wave environments. While a Gumbel statistical distribution was most appropriate for six of the sites, a PE3 distribution was better for the other four sites. The appropriate statistical distributions fit the data well providing good estimates of the magnitude of wave run-up events for particular return periods (Table 10.4). Table 10.5 presents a statistical summary of the variability in wave run-up across all 10 wave environments analysed. This table reinforces the fact that a single value of wave run-up should not be applied to the entire lakeshore, and that specific values are appropriate to particular zones.

Figure 10.8 shows how the magnitude of the wave run-up changes with increasing return period. What is significant about this figure is that it clearly shows that the most rapid increase in wave run-up occurs out to a return period of about 20 years. After, this the increase is significantly more gradual.

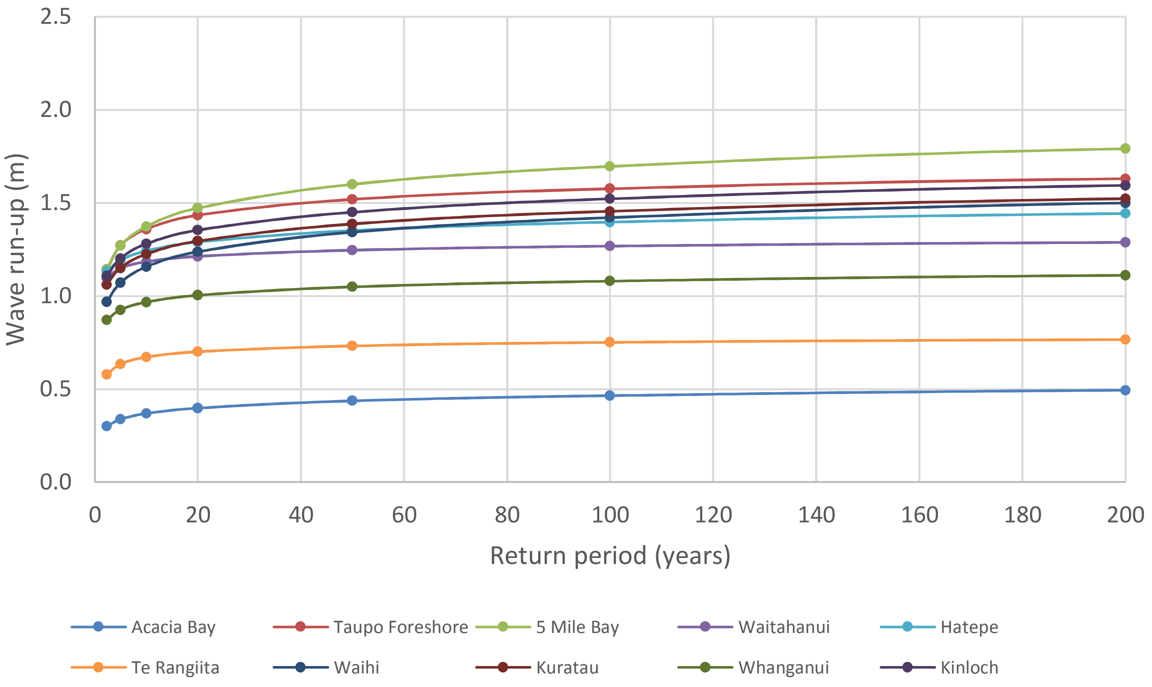


Figure 10.8: Wave run-up for the different environments at different return periods.

The rate of change in wave run-up varies with frequency or return period. At sites subject to strong winds the wave regime has a greater potential effect on effective water levels than simply the static water level of the lake. It can also be seen that as the return period of a particular event increases, out past 20 years, the significance of changes caused by wave run-up on the effective water level decrease in importance.

Table 10.3: Statistics of 2% exceedance run-up within the 10 different wave environments (1992-2013).

	Acacia Bay	Taupō Foreshore	5 Mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	0.01	0.14	0.18	0.18	0.24	0.03	0.10	0.11	0.10	0.17
Maximum	0.44	1.50	1.50	1.24	1.35	0.72	1.29	1.34	1.01	1.42
Lower quartile	0.01	0.01	0.03	0.02	0.06	0.01	0.02	0.01	0.01	0.01
Median	0.01	0.06	0.09	0.11	0.16	0.01	0.06	0.06	0.06	0.07
Upper quartile	0.01	0.20	0.25	0.26	0.37	0.04	0.14	0.16	0.15	0.26
98th percentile	0.157	0.658	0.809	0.740	0.786	0.263	0.472	0.571	0.490	0.756

Table 10.4: Frequency and magnitude of the estimated 2% exceedance run-up within the 10 different wave environments.

	Acacia Bay	Taupō Foreshore	5 Mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
Best-fit Distribution	*Gumbel*	*PE3*	*Gumbel*	*PE3*	*Gumbel*	*PE3*	*Gumbel*	*Gumbel*	*PE3*	*Gumbel*
Return Period										
2.33	0.300	1.141	1.144	1.097	1.132	0.578	0.969	1.061	0.871	1.107
5	0.338	1.271	1.270	1.149	1.193	0.634	1.072	1.151	0.926	1.202
10	0.369	1.359	1.373	1.184	1.242	0.672	1.157	1.225	0.967	1.280
20	0.398	1.434	1.472	1.213	1.290	0.701	1.238	1.295	1.004	1.354
50	0.437	1.519	1.600	1.246	1.351	0.732	1.343	1.387	1.049	1.450
100	0.465	1.576	1.696	1.268	1.397	0.751	1.421	1.455	1.080	1.522

Table 10.5: Estimated average 2% exceedance wave run-up across all 10 different wave environments.

Return Period	Minimum	Mean	Maximum	Range	Lower quartile	Median	Upper quartile
2.33	0.300	0.940	1.144	0.844	0.896	1.079	1.107
5	0.338	1.021	1.271	0.933	0.963	1.150	1.193
10	0.369	1.083	1.373	1.004	1.015	1.205	1.242
20	0.398	1.140	1.472	1.074	1.056	1.264	1.295
50	0.437	1.211	1.600	1.163	1.098	1.347	1.387
100	0.465	1.263	1.696	1.231	1.127	1.409	1.455

10.5 Coincidence of high lake levels and strong winds

Background

Of particular concern with regard to the extent and level of flooding around Lake Taupō is the potential coincidence of high lake levels and large wave run-up. This is particularly important if the two parameters are linked. Considerable work has been done on the coincidence of high lake and run-up levels by Hicks *et al.* (2000) and Beca (2006).

The wind climate at Taupō Airport shows a seasonal pattern. The spring months are the windiest, and the autumn and winter months the calmest. Westerly quarter winds prevail in all seasons. Diurnal variability tends to be greatest in summer, with stronger westerly lake breezes during the day, and often offshore breezes at night. The southern lakeshore experiences more calm periods and its extremes are less severe than at Taupō Airport (Hicks *et al.,* 2000).

Following the installation of the Taupō Gates there has been a reduction in the incidence of exceptionally high and low lake levels. Control of the lake level has caused some changes in the distributions of levels in particular months, but the natural seasonal pattern of low levels in April-June, and high levels in September-November, has been maintained (Opus, 2012).

The natural lake levels in spring tend to be higher in years when the El Niño Southern Oscillation (ENSO) phenomenon is in the La Niña phase. This occurs because natural inflows to the lake, mainly in winter and spring, are increased during La Niña seasons. No evidence was found that seasonal wind strength is affected by prevailing ENSO conditions, although wave run-up and the ENSO index are weakly correlated. Run-up on the north-eastern lakeshore tends to be higher during El Niño phases and higher on the south-western shore during La Niña phases (Hicks *et al.,* 2000).

Analysis

The modelled daily maximum 2% wave run-ups were graphed against daily mean lake levels for the period 1992-2013 for the ten different wave environments (Figure 10.9 to Figure 10.18). It would appear, as expected, that the two variables (i.e. lake level and wave run-up) are independent of each other. Maximum lake levels are generally associated with low wave run-ups, while the maximum run-ups are all associated with ‘average’ lake levels. This is because ‘average’ lake levels occur more often and therefore there is a greater chance of such conditions coinciding with periods of large wave run-ups.

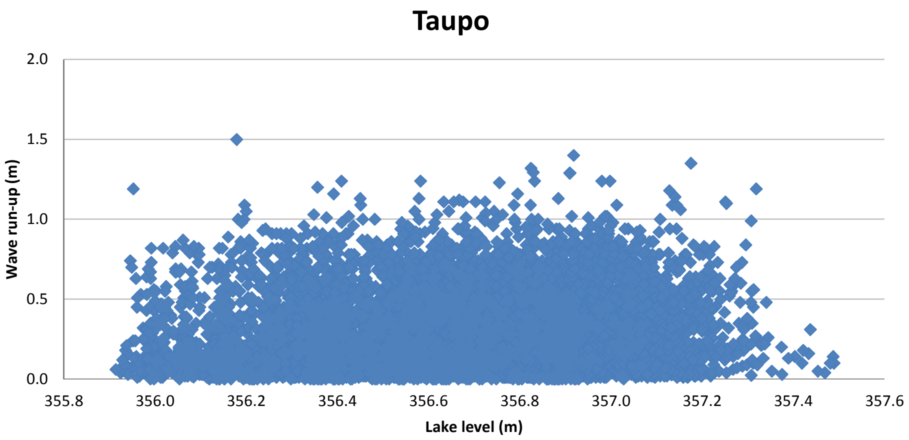


Figure 10.9 Variation in daily wave run-up on Taupō Foreshore and the corresponding lake level (1992-2013).

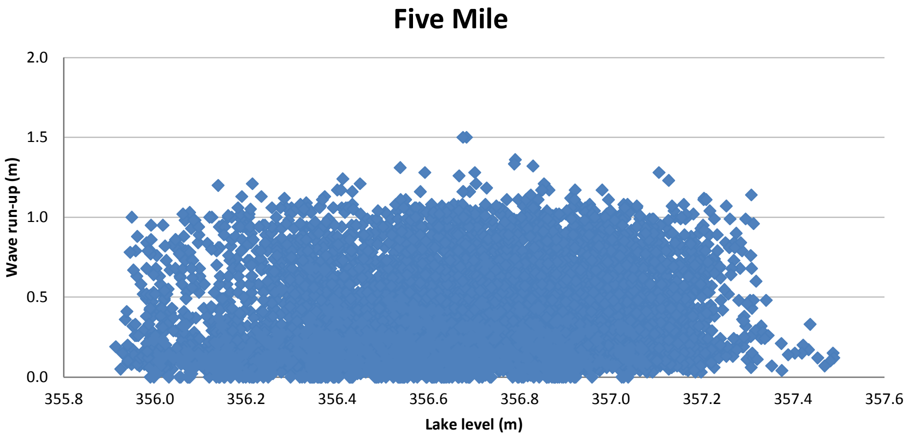


Figure 10.10 Variation in daily wave run-up on Five Mile Beach and the corresponding lake level (1992-2013).

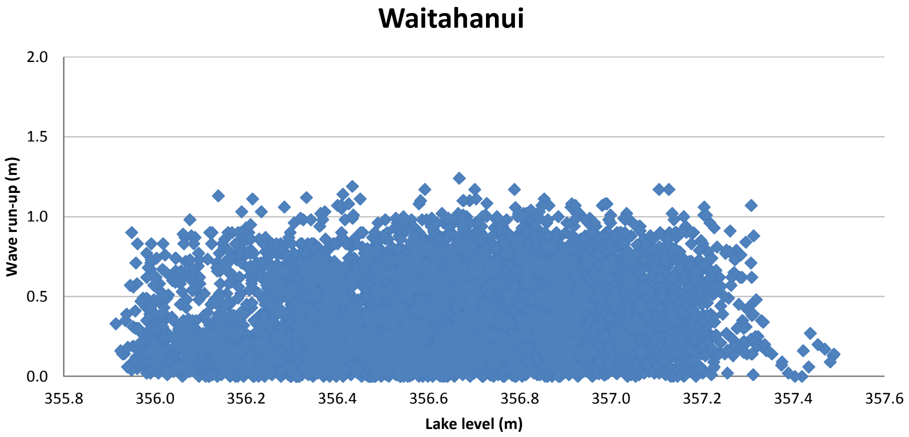


Figure 10.11 Variation in daily wave run-up on Waitahanui Beach and the corresponding lake level (1992-2013).

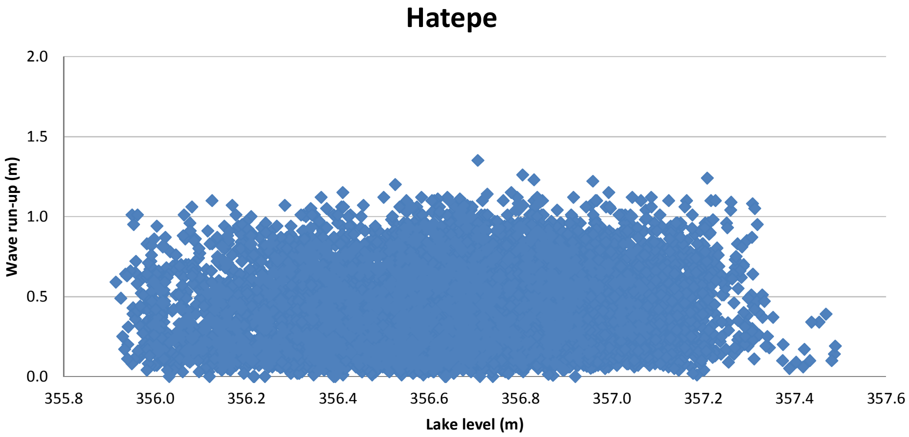


Figure 10.12 Variation in daily wave run-up on Hatepe Beach and the corresponding lake level (1992-2013).

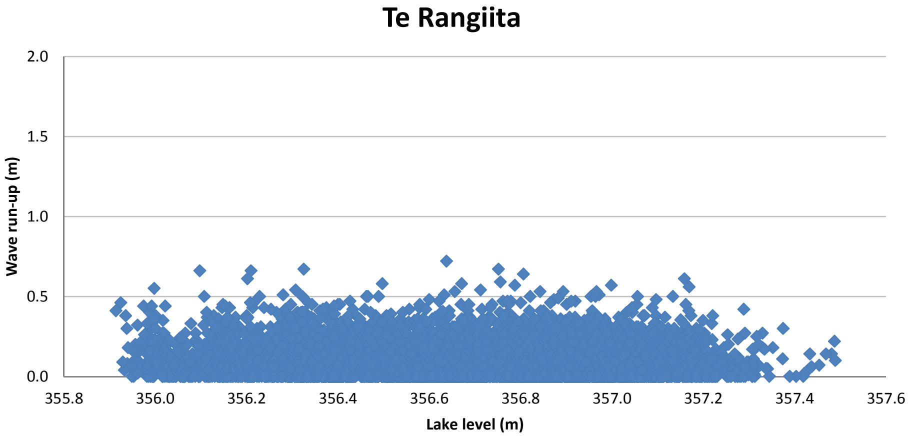


Figure 10.13 Variation in daily wave run-up on Te Rangiita and the corresponding lake level (1992-2013).

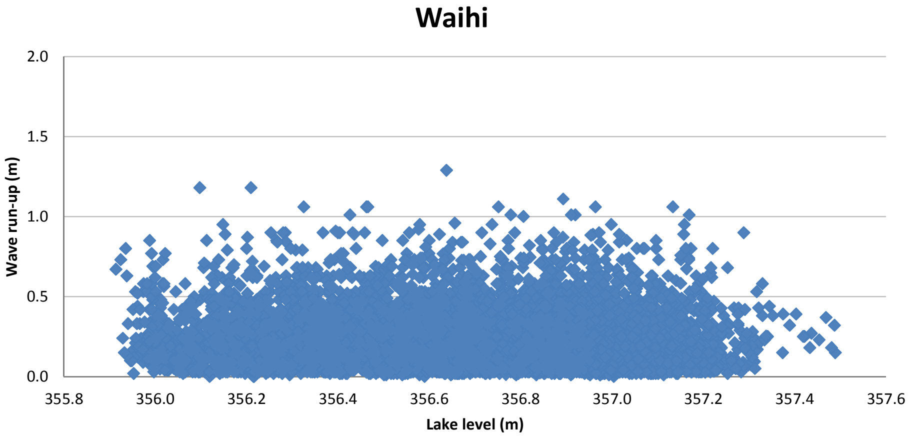


Figure 10.14 Variation in daily wave run-up on Waihi Beach and the corresponding lake level (1992-2013).

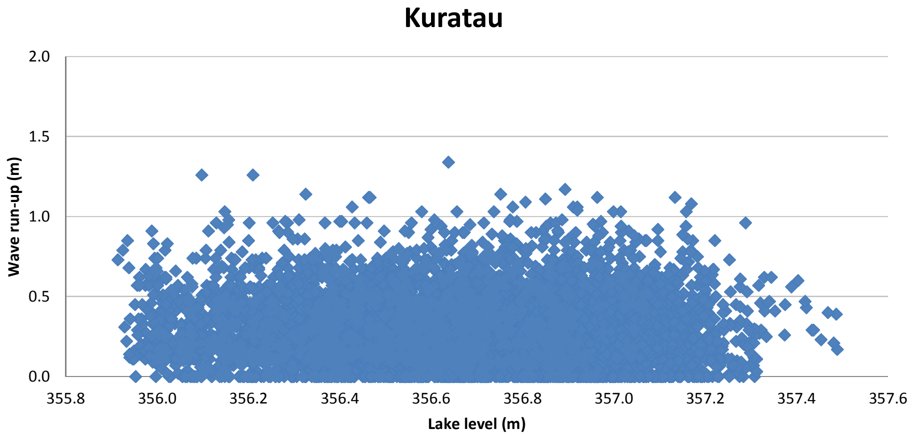


Figure 10.15 Variation in daily wave run-up on Kuratau Beach and the corresponding lake level (1992-2013).

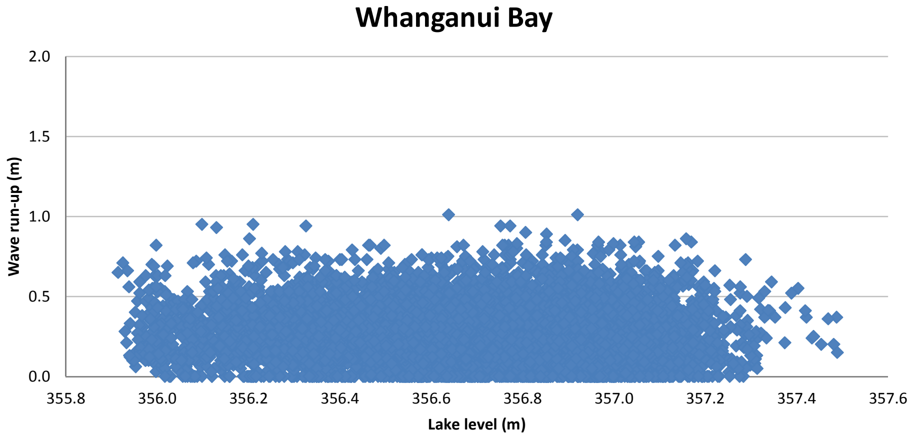


Figure 10.16 Variation in daily wave run-up on Whanganui Bay and the corresponding lake level (1992-2013).

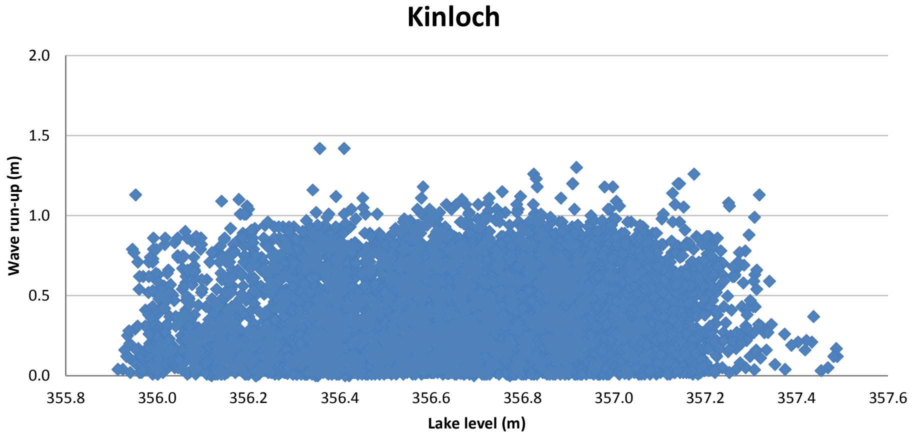


Figure 10.17 Variation in daily wave run-up on Kinloch Beach and the corresponding lake level (1992-2013).

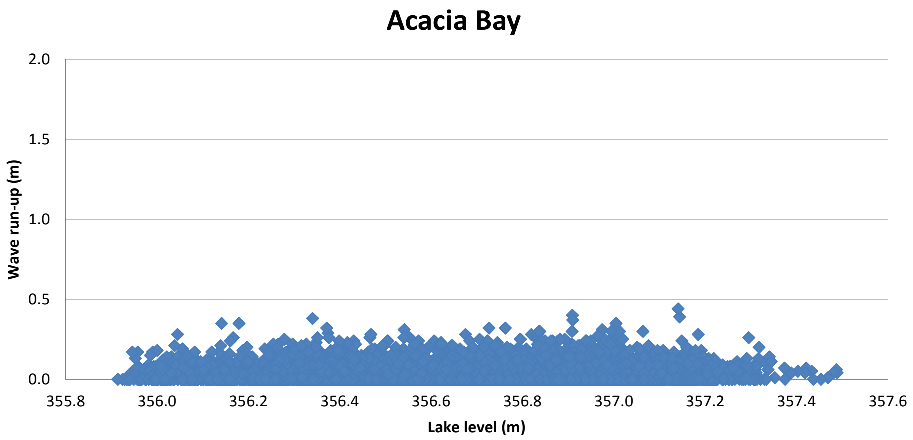


Figure 10.18 Variation in daily wave run-up on Acacia Bay and the corresponding lake level (1992-2013).

To assess whether any pattern exists within the distribution of lake levels and wave run-up only the annual maxima were plotted (Figure 10.19). Again, there is considerable scatter but no trend of greater run-ups at higher lake levels. This lack of clear pattern between the lake level and wave run-up data is not surprising. Therefore, wave run-up and lake level can be considered two independent variables for Lake Taupō.

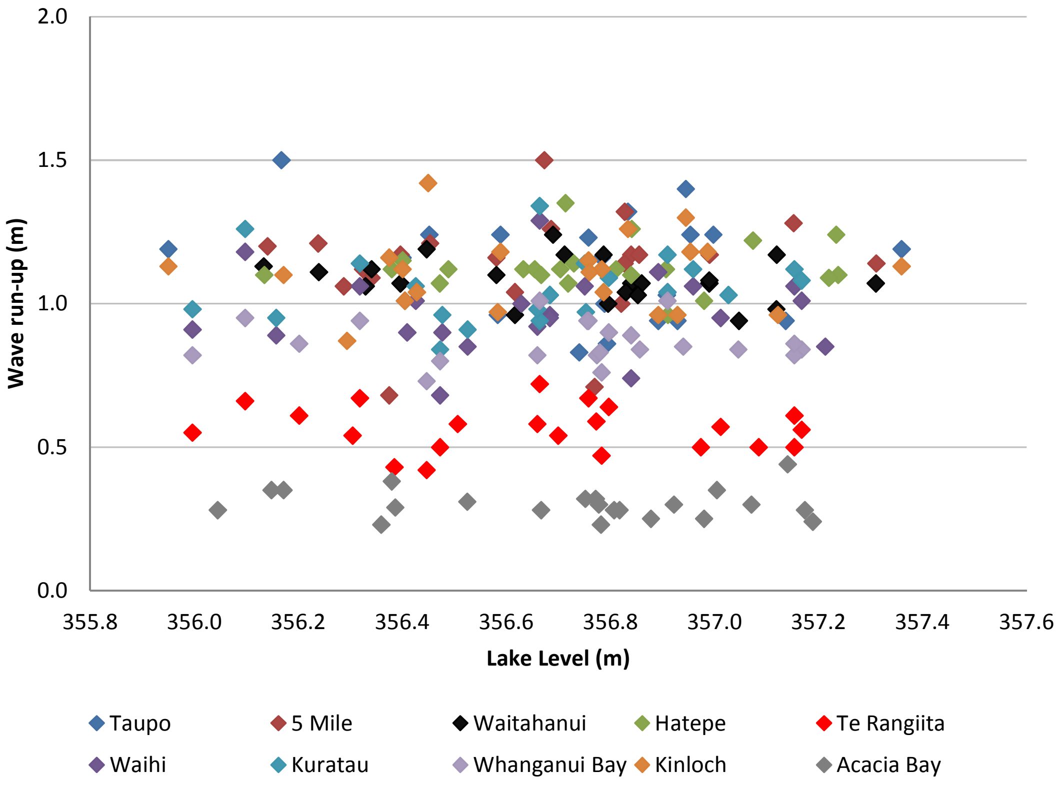


Figure 10.19 Variation in the annual maxima of daily run-up within various wave environments around Lake Taupō and corresponding lake level (1992-2013).

To confirm the lack of any relationship between lake level and wave run-up the two variables within each of the ten wave environments were correlated (Table 10.6). In no case did the resulting coefficient of determination (i.e. r^2) indicate any relationship between lake level and wave run-up. The gradient of the various 'best-fit' line at each location was essentially zero. Therefore, the 'relationship' is a horizontal line through what can be considered random scatter i.e. wave run-up and lake level are two independent variables.

Table 10.6: Relationships between maximum annual modelled wave run-up and lake level within various wave environments around Lake Taupō.

Site	Regression Model	R^2
Taupō Foreshore	y = 0.009x + 0.7877	0.11
Five Mile	y = 0.0008x + 1.4023	0.07
Waitahanui	y = -0.0707x + 26.305	0.08
Hatepe	y = 0.0201x – 6.0477	0.00
Te Rangiita	y = -0.0234x + 8.895	0.01
Waihi	y = -0.0163x – 4.829	0.00
Kuratau	y = 0.0548x – 18.507	0.02
Whanganui Bay	y = -0.0087x + 3.9672	0.00
Kinloch	y = 0.0144x – 4.0364	0.00
Acacia Bay	y = -0.0126x + 5.1582	0.01

The same random pattern and lack of any relationship is also apparent when wave run-up is correlated with 'natural' lake levels (Figure 10.20)

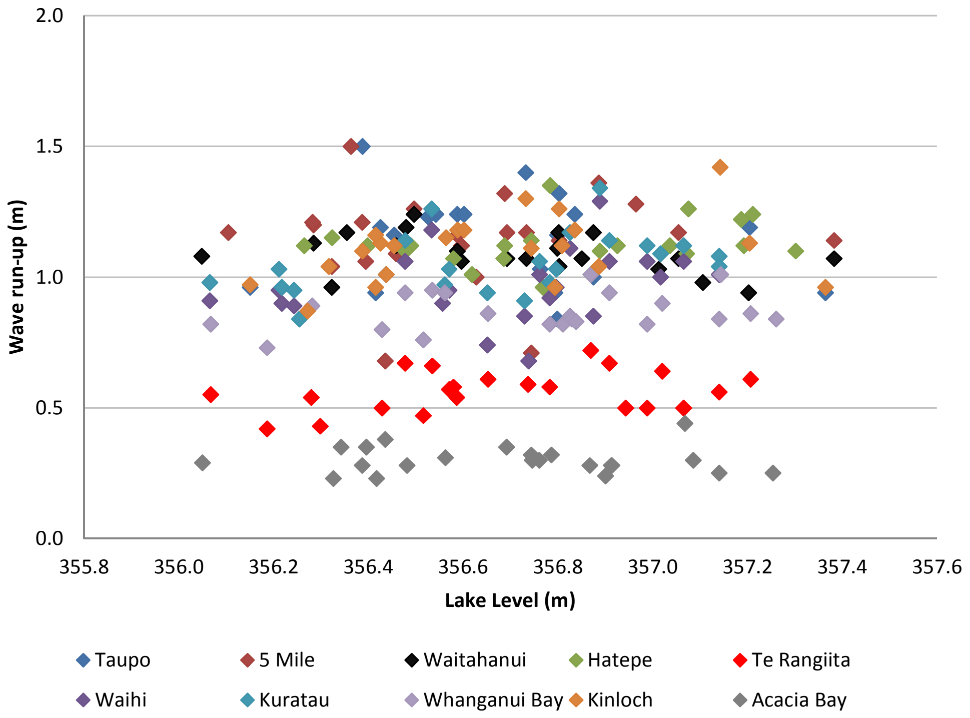


Figure 10.20: Variation in annual maxima of modelled daily run-up within various wave environments around Lake Taupō and what would have been the natural lake level (1992-2013).

There is therefore no indication that high lake levels are associated with large wave run-up. It should be noted that longer periods of higher lake level increase the chance of these levels coinciding with a strong wind (i.e. large wave run-up) event. However, longer periods of lower lake level also increase the chance that these will also coincide with a strong wind event. Therefore while higher lake levels may increase the potential risk, lower lake levels reduce the risk. Since the periods of 'reduced' lake level tend to coincide with periods of stronger winds, the net effect of lake management has been to reduce the overall risk of the coincidence of high lake levels with large wave run-up.

11 Combined Risk

11.1 Conceptual issues

Of particular concern with respect to flooding around Lake Taupō is the coincidence of high lake levels and large wave run-up. As discussed, although the two variables are essentially independent they can still occur concurrently. This coincidence of occurrence compounds the effect of each variable when considered alone.

Assessing how the two parameters, lake level and wave run-up, can be combined to provide a measure of the total 'risk' is particularly problematic. Simply multiplying the two independent risks presents two issues:

- Different combinations of events do not have unique probabilities; and
- The actual probability may be significantly less than the simple multiple of the two independent risks. This is because the maximum risk only occurs when the two events occur at a specific time, and not just in the same year. Hence the actual risk could be as low as 1/365th of the simple multiple of the two independent risks calculated from the annual maxima series.

Lake level and wave run-up can also be combined to form different magnitude effective water level (i.e. EWL) events with the same return period; and the same magnitude event can occur with different likelihoods. For joint ARIs (i.e. average recurrence interval) of between 100 and 1000-years, the variability caused by how the two factors are combined is approximately 25% of the total range. Considering the 100-year ARI combined event, the change in effective water level ranges from 0.28m (50-year RP lake level with a 2.33-year RP wave run-up) to 0.38m (10-year RP lake level with a 10-year RP wave run-up).

11.2 Occurrence of high effective water levels

To avoid the difficulties discussed above, an alternative approach to assessing the combined risk of high lake levels and large wave run-up was adopted. This involved adding the actual maximum daily lake level to the modelled maximum daily wave run-up in the ten wave environments.

A frequency analysis was then undertaken on each of the 10 wave environments to produce estimates of the effective water level for different frequency events. In most cases a GEV statistical distribution provided the 'best-fit' to the data. The 'goodness of fit' of the statistical distributions suggests that confidence can be placed in the estimates of the effective water level for the various return periods.

Differences in site exposure relative to the prevailing and dominant winds across Lake Taupō and shoreline characteristics result in significant variations in the estimated effective water levels in the 10 wave environments (Table 11.1).

The maximum measured lake level experienced over this period of record was 357.49m and it occurred during the 1998 flood. This lake level had an estimated return period of approximately 117-years which is consistent with the data in Table 11.1.

With regard to the combined effective water levels, the maximum effective water levels so far experienced have ARIs that vary around the lake. In Acacia Bay, the highest estimated effective water level had a return period of approximately 15-years. On the Taupō Foreshore the largest event had a return period in excess of 20-years. This emphasises the importance of using values that are specific to particular wave environments. This pattern, however, may also reflect the effect of some of the limitations of *Lakewave* discussed previously and any error inherent in the distribution fitting.

For comparison, the estimated maximum effective water levels in each of the 10 wave environments during the July 1998 flood were also obtained (Table 11.2). For the west facing beaches and Taupō Foreshore the highest effective water levels occurred on the 15 July 1998. This corresponded with the period of greatest erosion of these beaches. This provides an independent measure of the validity of the estimated water levels.

Since the 'height' to which the effective water level may rise within each wave environment is controlled by both the lake level and wave run-up, the effects of either high lake levels or large wave run-up were compared.

The five highest lake levels, selecting only one in any year, were identified in the 'actual' lake level record. It should be noted that these high lake levels occurred when inflows exceeded the maximum possible outflow through the control gates; a significantly higher flow than possible through the original natural channel, for a considerable period of time. Recognising that lake level varies relatively slowly, the highest modelled wave run-up during the week centred on the maximum lake level was identified. This was then used to estimate the maximum effective water level attained during each 'flood' period. These periods, and the estimated maximum effective water levels, are ranked on the basis of the measured lake level in Table 11.3.

The highest estimated effective water levels have ARIs ranging from about 5 to 50-years depending on the particular wave environment. The large range in ARIs is an artefact of the independence of the wave and lake level records and the directional variability of the waves.

It should be noted that the return periods of these estimated effective water levels during these highest lake level events tend to be low relative to those in Table 11.1. This is because the main criterion for selecting the events was simply a high lake level. It is likely that no large run-up event occurred during this period, although larger run-ups may have occurred at slightly lower lake levels. This would have given a greater combined effective water level.

It should also be noted that although the events are arranged in order of lake level, the effective water levels do not have the same rankings. The highest effective water levels occurred during: 2010 for 5 Mile Bay, Waitahanui and Hatepe; but during 2004 for Taupō Foreshore, Acacia Bay and Kuratau; 1998 for Kinloch; 2008 for Te Rangiita; both 2004 and 1996 for Waihi and Kuratau and both 2008 and 1996 for Whanganui Bay. While the highest lake level was recorded in 1998, this coincided with the highest effective water level at only one location i.e. Kinloch. The same lake level therefore does not result in the same effective water level at all locations because of the variability in the wind and therefore wave run-up around Lake Taupō.

A similar analysis was undertaken but using the five maximum modelled run-up events. The estimated effective water levels at the time of these large run-up events are listed in Table 11.4.

It should be noted that the events listed in Table 11.4 are often different to those in Table 11.3. In four cases, Taupō Foreshore, Hatepe, Waihi and Acacia Bay, the effective water levels were the same as Table 11.3 but in the other six cases; 5 Mile Bay, Waitahanui, Te Rangiita, Kuratau, Whanganui Bay and Kinloch, the effective water levels were smaller.

The highest estimated effective water levels have ARIs ranging from about 2.3-years to in excess of 50-years depending on the wave environment. Six of the seven wave environments had effective water levels in excess of a 50-year ARI. Again, the return periods (i.e. ARIs) of the estimated effective water levels based on high modelled wave run-up are relatively low. This is because of the use of a single criterion for selecting the 'extreme' events. It is likely that the large run-up events occurred during periods of relatively low lake level and therefore the effective water level was not as high as if the run-up had occurred at a higher lake level. Overall, however, the effective water level or maximum extent of wave run-up is more sensitive to the size of the wave run-up and the wave environment than to lake level.

The relationship between lake level and wave run-up is therefore not simple. While both lake level and wave run-up effect the maximum extent of wave run-up, and therefore potentially erosion at a particular location, the wave environment actually has the greater control irrespective of lake level. This is because in general lake level changes relatively slowly, especially when compared to the wave regime, and the total lake level range is small compared to the variability of wave run-up.

Table 11.1: Estimates of the effective water level for the different wave environments during events with different frequencies (1992-2013).

Return Period	Actual Lake Level	Taupō Foreshore	5 Mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui Bay	Kinloch	Acacia Bay
	PE3	*PE3*	*PE3*	*PE3*	*GEV*	*GEV*	*GEV*	*GEV*	*GEV*	*GEV*	*GEV*
2.33	357.18	358.02	358.16	358.03	358.07	357.49	357.83	357.92	357.79	358.04	357.33
5	357.28	358.21	358.29	358.17	358.21	357.62	358.00	358.08	357.91	358.21	357.45
10	357.35	358.36	358.35	358.26	358.32	357.71	358.13	358.20	357.99	358.33	357.52
20	357.40	358.50	358.38	358.32	358.41	357.77	358.24	358.29	358.06	358.43	357.58
50	357.45	358.67	358.41	358.40	358.52	357.85	358.38	358.40	358.13	358.54	357.63
100	357.49	358.67	358.42	358.45	358.95	357.89	358.47	358.47	358.17	358.61	357.66
Estimated maximum	*357.49*	*358.53*	*358.45*	*358.38*	*358.45*	*357.77*	*358.19*	*358.25*	*358.02*	*358.45*	*357.58*
Date of maximum	*17 July 1998*	*24 Feb 2004*	*22 Sep 2010*	*22 Sep 2010*	*17 Sep 2010*	*23 Aug 2008*	*27 Feb 2004*	*27 Feb 2004*	*23 Aug 2008*	*14Jul 1998*	*30 Jun 2004*

Note: The Actual lake level data are physically measured. The other columns show the estimated effective water level (i.e. EWL) which is based on the measured lake level combined with the modelled wave run-up.

Table 11.2: Effective water levels during the July 1998 flood.

	Actual Lake Level	Taupō Foreshore	5 Mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui Bay	Kinloch	Acacia Bay
Estimated maximum	*357.49*	*358.51*	*357.92*	*357.80*	*358.27*	*357.71*	*358.00*	*358.06*	*358.00*	*358.45*	*357.55*
Date of maximum	*17 July 1998*	*15 July 1998*	*15 Jul 1998*	*15 Jul 1998*	*15 Jul 1998*	*18 Jul 1998*	*9 Jul 1998*	*9 Jul 1998*	*26 Jul 1998*	*15 Jul 1998*	*18 Jul 1998*

Table 11.3: Maximum estimated effective water levels (i.e. EWL) for the five periods of highest lake level (1992-2013)*. Note: The table is ordered on lake level not EWL.*

Lake Taupō		Taupō Foreshore		5 Mile Bay		Waitahanui		Hatepe	
Lake Level	Date	EWL	Date	EWL	Date	EWL	Date	EWL	Date
357.49	17-Jul-1998	358.51	15-Jul-1998	358.45	23-Sep-2010	358.38	23-Sep-2010	358.45	18-Sep-2010
357.35	3-Mar-2004	358.53	25-Feb-2004	358.36	14-Feb-2004	358.30	14-Feb-2004	358.35	31-Jan-2011
357.33	31-Oct-1998	358.36	22-Oct-1998	358.39	22-Jun-2004	358.18	21-Oct-1998	358.32	21-Oct-1998
357.32	23-Sep-1998	358.35	29-Jan-2011	358.32	16-Nov-1994	358.28	22-Jun-2004	358.27	15-Jul-1998
357.31	15-Sep-1996	358.32	6-Jun-2004	358.32	29-Jan-2011	258.26	16-Nov-1994	358.26	10-Oct-1994

Te Rangiita		Waihi		Kuratau		Whanganui Bay		Kinloch		Acacia Bay	
EWL	Date	EWL	Date	EWL	Date	EWL	Date	EWL	Date	EWL	Date
357.77	24-Aug-2008	358.11	24-Aug-2008	358.19	24-Aug-2008	358.02	24-Aug-2008	358.34	30-Jun-2004	357.58	30-Jun-2004
357.63	28-Feb-2004	358.19	28-Feb-2004	358.25	28-Feb-2004	357.95	28-Feb-2004	358.44	25-Feb-2004	357.48	3-Mar-2004
357.71	18-Jul-1998	358.05	27-Jun-2004	358.10	27-Jun-2004	357.95	26-Jul-1998	358.33	22-Oct-1998	357.46	14-Jul-2002
357.73	4-Oct-1994	358.18	4-Oct-1994	358.24	4-Oct-1994	358.01	4-Oct-1994	358.45	15-Jul-1998	357.55	18-Jul-1998
357.71	14-Sep-1996	358.19	14-Sep-1996	358.25	14-Sep-1996	358.02	14-Sep-1996	358.31	29-Jan-2011	357.56	22-Sep-2010

Table 11.4: Maximum effective water levels for the five periods of highest modelled wave run-up. *Note: The table is ordered on EWL not lake level.*

Taupō Foreshore		5 Mile Bay		Waitahanui		Hatepe		Te Rangiita	
EWL	Date	EWL	Date	EWL	EWL	EWL	Date	EWL	Date
357.68	6-May-1999	358.18	6-Jun-2002	357.91	14-Mar-2007	358.06	25-Aug-2002	357.36	23-Oct-1992
358.32	6-Jun-2004	358.18	18-Nov-2000	357.62	24-Feb-1998	358.07	19-Nov-1996	357.42	2-Jul-1995
358.53	25-Feb-2004	358.15	12-Jun-2006	358.30	14-Feb-2004	358.45	18-Sep-2010	357.00	29-Jun-2000
358.15	25-Nov-2011	357.85	17-Oct-2002	357.87	26-May-2002	358.06	12-Jun-2006	356.87	8-Jul-1992
358.20	18-Aug-2004	357.98	26-May-2002	357.96	19-Nov-2000	358.18	8-Nov-1994	356.76	5-Sep-2001

Waihi		Kuratau		Whanganui Bay		Kinloch		Acacia Bay	
EWL	Date	EWL	Date	EWL	Date	EWL	Date	EWL	Date
357.93	23-Oct-1992	357.98	23-Oct-1992	357.65	23-Oct-1992	357.83	23-Jul-1992	357.58	1-Jul-2004
357.39	8-Jul-1992	357.47	8-Jul-1992	357.93	22-Jul-2011	358.22	6-Jun-2004	357.31	17-Aug-2004
357.28	5-Sep-2001	357.31	5-Sep-2001	357.16	8-Jul-1992	358.44	25-Feb-2004	356.72	21-Jun-2013
358.00	9-Jul-1998	358.06	9-Jul-1998	357.05	5-Sep-2001	357.64	25-Nov-2011	356.49	9-May-1992
358.19	28-Feb-2004	357.89	2-Jul-1995	357.69	2-Jul-1995	358.11	18-Aug-2004	356.53	6-May-1999

11.3 Estimated effective water levels

Analysis of the measured lake levels combined with the modelled wave run-up involves only a single probability. However, because these data are based on daily values from 1992-2013 various adjustments for seiche, climate change, and site-specific tectonic deformation need to be added to provide an estimate of the effective water level necessary for planning and policy decisions. The adjustments for seiche and climate change are listed in Table 11.5.

Table 11.5: Adjustments for seiche and climate change effects on lake level

Return Period	Climate Change 2090s (m)	Seiche Effect (m)	Total Increase in Static Water Level (m)
2.33	0.06	0.08	0.14
5	0.09	0.09	0.18
10	0.11	0.10	0.21
20	0.13	0.11	0.24
50	0.16	0.11	0.27
100	0.19	0.11	0.30

The estimated effective water levels derived from the existing hydrometric data were adjusted for seiche and the potential effects of climate change by adding the values in Table 11.5 to the site-specific data in Table 11.1. These adjusted effective water levels are listed in Table 11.6.

Table 11.6: Estimates of the effective water level within the different wave environments, adjusted for climate change and seiche, for events with different frequencies (1992-2013).

Return Period	Acacia Bay	Taupō Foreshore	5 Mile Bay	Waitahanui	Hatepe
	GEV	*PE3*	*GEV*	*GEV*	*GEV*
2.33	357.47	358.16	358.30	358.17	358.21
5	357.63	358.39	358.47	358.35	358.39
10	357.73	358.57	358.56	358.47	358.53
20	357.82	358.74	358.62	358.56	358.65
50	357.90	358.94	358.68	358.67	358.79
100	357.96	358.97	358.72	358.75	359.25

Return Period	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
	GEV	*GEV*	*PE3*	*GEV*	*GEV*
2.33	357.63	357.97	358.06	357.93	358.18
5	357.8	358.18	358.26	358.09	358.39
10	357.92	358.34	358.41	358.2	358.54
20	358.01	358.48	358.53	358.3	358.67
50	358.12	358.65	358.67	358.4	358.81
100	358.19	358.77	358.77	358.47	358.91

Comparison to other indices

A range of possible indices of the potential flood risk posed by high static water levels and wave run-up at 10 locations around the Lake Taupō shoreline are summarised in Table 11.7. These indices were chosen to reflect a range of ways in which lake levels and wave run-up can be combined.

Table 11.7: Effective water levels defined using different measures.

	Acacia Bay	Taupō foreshore	5-mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
10-yr LL X 10-yr run-up	357.72	358.71	358.72	358.53	358.59	358.02	358.51	358.58	358.32	358.63
100-yr recorded EWL	357.66	358.67	358.42	358.45	358.95	357.89	358.47	358.47	358.17	358.61
100-yr + median run-up	357.50	357.55	357.58	357.60	357.65	357.50	357.55	357.55	357.55	357.56
Maximum estimated *	357.58	358.53	358.45	358.38	358.45	357.77	358.19	358.25	358.02	358.45

Within each of the 10 wave environments the maximum estimated effective water level, defined by combining the daily lake level with the maximum daily wave run-up, has exceeded the 1% design event defined by adding the median run-up to the 100-year lake level. Consequently, a design EWL defined in that manner is likely to under-estimate the risk of flooding.

The 100-year ARI or 1% AEP EWL design event defined using the combined daily lake level and maximum daily wave run-up is higher than the maximum estimated EWL experienced within all environments except 5-mile Bay. The differences are generally in the range of 10-30cm.

A design EWL defined by the 10-year ARI lake level combined with the 10-year ARI wave run-up is more conservative than the other measures i.e. it defines a design EWL which is higher than the other measures. The EWL defined in this manner, however, appears to be unrealistically high given the conservatism which has been incorporated when deriving this index. This index also involves consideration of combined probabilities and consequently the difficulties inherent in such an approach discussed earlier.

Summary

The use of the 100-year ARI or 1% AEP design event effective water level defined from the combined actual lake level record and the modelled wave run-up would appear to provide a robust and defensible index for use in flood risk mitigation and planning. It is suggested therefore that the effective water levels summarised in Table 11.6 be used to define a wave run-up risk zone, higher than the 100-year static water level.

To this must be added the tectonic deformation expected over the return period considered (i.e. 1% AEP) to determine the total 'freeboard' necessary to provide the designated level of protection.

The two flood and inundation zones would consequently become:

Level 1: The 100-year static lake level; adjusted for seiche, anticipated climate change, and tectonic deformation; and

Level 2: The 100-year effective water level (EWL) defined from combining the measured lake level record with the modelled wave run-up, adjusted for the effects of seiche, climate change, and tectonic deformation. This effective water level will be at a slightly higher elevation than the static lake level and will reflect the combined effect of the interaction of variations in lake level and wave run-up at the shore.

11.4 Storm surge and landslides

Storm surges and landslides can both cause wave run-up around the shores of Lake Taupō. For example, major landslides occurred in Waihi in 1846 and 1910 (Hegan *et al*. 2001). When these events have occurred since 1906 their impact has been incorporated in the lake level data. Therefore the frequency analysis undertaken above has already included these effects. Since no data exist for events greater than those since 1906, and since such events have been extremely rare (and random), their effect has not been included in this study.

12 Risk Assessment

12.1 Introduction

Just because an area is subject to flooding does not fully quantify the actual risk to life and property. The actual risk relates not just to 'getting wet' but to the depth of water, its velocity, and the duration of inundation. The Taupō flood studies was a combined project involving both the Taupō District and Waikato Regional Councils. Consequently there was a need to retain a consistency of approach when defining flood hazard. Considerable work has been done to define a flood hazard index that relates to, and combines, these various characteristics of a flood event (Environment Waikato, 2008a). A hazard matrix, and definition of various hazard categories, has subsequently been adopted following public consultation and refinement. This hazard matrix is used extensively throughout the region (Environment Waikato, 2008b).

This 'river' flood hazard classification describes the potential impact of a flood event on people and property. The classification refined by Environment Waikato was developed using the following considerations:

- *Flood waters have the potential to cause a person to become unstable and unable to manoeuvre.* International research suggests that there is a danger of being knocked over when the product of the flood depth and flood speed exceeds 0.5; with a significantly greater risk to life when the same product exceeds 1.0.

- *Flood waters have the potential to impede a person's ability to rescue themselves or others.* When the flood depth exceeds 1.0m (i.e. waist depth), a person's ability to navigate through flood waters (both on foot and using a vehicle) is restricted, therefore impeding the rescue of themselves and others.

- *Flood waters have the potential to damage buildings, both superficially and structurally.* International research suggests that structural damage is likely when the flood speed exceeds 2m/s. It is also likely that structurally weak points such as doors and windows will be damaged when the flood speed exceeds 1m/s.

These considerations have been translated into a river flood hazard classification. Distinct levels of river flood hazard have been defined by their likely impact on people and property. These levels are outlined in Table 12.1 (Environment Waikato, 2008b).

The river flood hazard is defined as a function of the product of the predicted depth and speed of the flood waters (Figure 12.1).

Table 12.1: Description of river flood hazard categories (Environment Waikato, 2008b).

Category	Impact on people	Damage to property
Low	The combined depth and speed of floodwaters are unlikely to impede the manoeuvrability or stability of the average person.	Damage to property is likely to be non-structural and mainly due to inundation and deposition of sediment.
Medium	The combined depth and speed of floodwaters are likely to start to impede the manoeuvrability or stability of the average person.	Damage to property is unlikely to be structural provided that weak points such as windows and doors are retained above flood level.
High	The combined depth and speed of floodwaters are likely to significantly impede the manoeuvrability or stability of the average person.	Damage to property is likely to be widespread and structural, including instances where buildings have been raised above the 'flood level'.
Defended	This flood hazard category identifies land that is within an identified river flood hazard area but has been subsequently included in a flood protection scheme that is managed and maintained by Environment Waikato.	

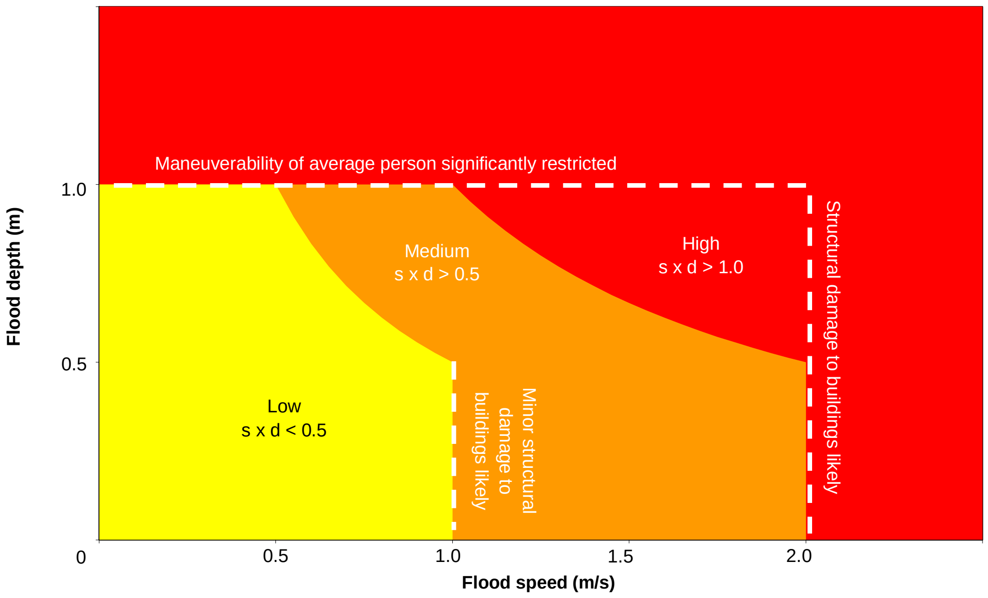


Figure 12.1: River flood hazard classification matrix (Environment Waikato, 2008b).

12.2 Application to Lake Taupō

The above risk matrices, and their various iterations, are widely used throughout New Zealand, Australia and globally. The hazard matrix, however, was defined for riverine environments where there can be a significant flow velocity component to the flood hazard. Therefore, while the hazard matrix is applicable to flood assessments of the various tributaries which drain to Lake Taupō, its relevance to a flood hazard assessment of the actual lake shore is perhaps less certain. However, there are considerable advantages to using a single flood hazard matrix throughout the Taupō District.

Since the water level of Lake Taupō is likely to rise relatively slowly, the key elements of the risk are the depth and duration of inundation. Only one of these factors is inherent in the standard matrix. However, it is recognised that a 'low hazard' defined largely on 'structural criteria' which may not recognise the economic and social costs once flood waters get above floor level. There is also an assumption that all affected persons are able bodied and mobile which may not be the case. In addition, a low hazard does not indicate no hazard which may be a possible interpretation.

In the Taupō flood studies the standard flood hazard matrix therefore needs to be modified when assessing the flood hazard as a result of high lake levels. This is because lake flooding does not generally have a velocity component and hence information exists for only one variable in the matrix i.e. water depth.

The significance of floor levels might provide one basis for subdividing the low hazard category. This could result in finer definition of the 'low hazard' zone, and a recognition of various consequences and impacts of flooding other than simply structural failure. For example, there could be a Low_1 Hazard – water depth <300mm; Low_2 Hazard – water depth 300-500mm; Medium – water depth 500mm-1m; and High – water depth >1m.

13 Conclusion

The risk of flooding, and the potential extent and depth of inundation around Lake Taupō is a multi-factor problem. Water level, and as a result the risk of flooding, is a function of the interaction of a number of factors, including: rainfall and runoff; lake level management for hydro power generation and flood mitigation; wind generated waves; seiching; climate and land use change, and tectonic deformation of the lake bed and shore.

These factors can combine to cause a particular flood level or inundation depth; but the same level can be reached by the coincidence of different factors. It is therefore possible to have the same water level with different frequencies, different water levels with the same frequency, and different water levels with different frequencies. In addition, the potential effect of a change in water level at the shore varies with topography and beach profile and material; and its potential consequences may depend on the level of capital investment and development. Each element of the shoreline therefore has a distinctive, and possibly unique, flood risk. This must be recognised within any management strategy.

The timeframe is also an important consideration. While the effect of some of these variables is likely to be relatively constant through time, others are not. For example, the lake level and wave regimes are likely to be similar for the foreseeable future. However, while the effects of climate change and tectonic deformation may be of little consequence over the short term, their potential impact may increase over time. Over 100 years their cumulative effects in some locations may be larger than the variability of lake level and wave run-up.

The various factors that affect water level fall into two groups: those that affect the static water level (e.g., lake level, seiche, climate and land use change, and tectonic deformation); and those that act upon this static water level (e.g., waves and wave run-up). The potential adverse effects of each of these groups of factors can be managed with different strategies.

13.1 100-year static water level

The static water level is a function of the combination of lake level, seiche, climate and land use change, and tectonic deformation. Land use change has been shown to have a negligible effect on the hydrologic regime and has therefore not been considered in detail. Since the effect of lake level, seiche, and climate change are consistent around the lake the use of a single value (for a particular return period event) is appropriate (Table 13.1). Tectonic deformation, however, varies significantly around the lake (Table 6.1). Where an area is subsiding, the reduction in the ground level over the period considered must be added to the other factors to produce a site-specific static water level.

Table 13.1: Expected static water level for events with different frequencies of occurrence.

Return Period	Lake Level (m)	Climate Change 2090s (m)	Seiche Effect (m)	STATIC WATER LEVEL
2.33	357.18	0.06	0.08	357.32
5	357.28	0.09	0.09	357.46
10	357.35	0.11	0.10	357.56
20	357.40	0.13	0.11	357.64
50	357.45	0.16	0.11	357.72
100	357.49	0.19	0.11	357.79

Since the impact of climate change and tectonic deformation will increase over time, their cumulative potential effect over a 100-year time frame needs to be considered when establishing the flood risk posed by the static water level.

Therefore, the static water level used for defining the flood level should include: the 100-year lake level (357.49m); the climate change effect on the 100-year event (0.18m); the 100-year seiche (0.11m); and a 100 years of accumulated tectonic deformation. This static water level therefore delineates areas where inundation might be considered inevitable within the next 100-years; or with a likelihood of 1% AEP each year. The possibility of inundation will increase over time towards the 100-year horizon as accumulated tectonic subsidence becomes more significant.

13.2 Wave run-up effect

The static water level provides the 'surface' upon which waves can form. The size of these waves is a function of the wind conditions and fetch. When the waves reach the shore they will run up the beach and affect an area above the static water level. The effect of the wave run-up, in combination with the static water level, therefore also needs to be built into the flood risk assessment.

It can be seen from Table 13.2 that the effect of wave run-up is greatest during relatively frequent events. After a return period of approximately 10-20 years the increase in wave run-up per year of 'decreased risk' is small. Therefore, the addition of a 10-20 year wave run-up event will include most of the effect of waves when combined with the static water level.

Table 13.2: Wave run-up for various locations at different return periods (m).

Return Period	Acacia Bay	Taupō foreshore	5-mile Bay	Waitahanui	Hatepe	Te Rangita	Waihi	Kuratau	Whanganui	Kinloch
2.33	0.30	1.14	1.14	1.10	1.13	0.58	0.97	1.06	0.87	1.11
5	0.34	1.27	1.27	1.15	1.19	0.63	1.07	1.15	0.93	1.20
10	0.37	1.36	1.37	1.18	1.24	0.67	1.16	1.23	0.97	1.28
20	0.40	1.43	1.47	1.21	1.29	0.70	1.24	1.30	1.00	1.35
50	0.44	1.52	1.60	1.25	1.35	0.73	1.34	1.39	1.05	1.45
100	0.47	1.58	1.70	1.27	1.40	0.75	1.42	1.46	1.08	1.52

13.3 Combined flood hazard level

The total flood hazard level is the combined effect of the static water level and the wave run-up. But static water level and wave run-up can combine in an infinite number of ways. Each combination has the potential to affect areas to a certain elevation, with a particular likelihood of occurrence. The 1% AEP level, or 1 in 100-year combined return period event, is often used in hazard planning. However, a 1% AEP combined event can be generated by a number of different combinations of static water level and wave run-up. Each of these combinations reaches a different elevation.

The use of the 100-year ARI or 1% AEP effective water level defined from the actual lake level record combined with the modelled wave run-up provides a robust and defensible second flood risk level for use in flood risk mitigation and planning. Such an approach also results in a single 'risk variable' with a single probability. However, because these data are based on daily values adjustments for seiche, climate change, and site-specific tectonic deformation are required. This effective water level (Table 13.3) is at a higher elevation than the static lake level and reflects the combined effect of the interaction of variations in lake level and wave run-up at the shore.

Table 13.3: Estimates of the effective water level for the different wave environments at various return periods (1992-2013).

Return Period	Acacia Bay	Taupō foreshore	5-mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
2.33	357.47	358.16	358.30	358.17	358.21	357.63	357.97	358.06	357.93	358.18
5	357.63	358.39	358.47	358.35	358.39	357.8	358.18	358.26	358.09	358.39
10	357.73	358.57	358.56	358.47	358.53	357.92	358.34	358.41	358.2	358.54
20	357.82	358.74	358.62	358.56	358.65	358.01	358.48	358.53	358.3	358.67
50	357.90	358.94	358.68	358.67	358.79	358.12	358.65	358.67	358.4	358.81
100	357.96	358.97	358.72	358.75	359.25	358.19	358.77	358.77	358.47	358.91

13.4 Areas affected by each condition

The risk posed by both the static water level and effective water level vary around the lake. Their position relative to the present shoreline depends on the topography of the land. These levels can be overlaid on the LiDAR-derived terrain model to determine their position around the entire lake shore. These maps can provide a basis for discussions leading to the development of sound, robust, long-term hazard management policies.

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15 Glossary

Baroclinic - a term applied to atmospheric conditions where trends in pressure (pressure surfaces) are at an angle to trends in temperature, the reverse of barotropic.

Barotropic - a term applied to atmospheric conditions where trends in pressure (pressure surfaces) align with trends in temperature, as in the ideal air mass; the reverse of baroclinic.

Coriolis force - the Coriolis effect (caused by the Coriolis force) is the apparent deflection of moving objects from a straight path. One of the most notable examples is the deflection of winds moving along the surface of the Earth to the right of the direction of travel in the Northern Hemisphere and to the left of the direction of travel in the Southern Hemisphere. This effect is caused by the rotation of the Earth and is responsible for the direction of the rotation of large cyclones: winds around the centre of a cyclone rotate counter-clockwise on the Northern Hemisphere and clockwise on the Southern Hemisphere.

Hazard – something that threatens a person's well-being.

Incident wave – wave moving landward.

Inertial period – the time between successive wave peaks where the fluid inertia is balanced purely by the Coriolis force.

Inundate – to cover usually dry land with flood waters.

LiDAR - (Light Detection and Ranging) is an optical remote sensing technology that measures properties of scattered light to find the range and/or other information i.e., elevation of a distant target. The usual method of determining distance to an object or surface is to use laser pulses.

masl – metres above sea level (amsl – height above mean sea level).

Return period (2.33-year) - a return period is also known as a recurrence interval. It is an estimate of the likelihood of an event of a certain size. It is a statistical measurement denoting the average recurrence interval over an extended period of time. The 2.33-year return period flood is often used as a measure of the mean annual flood.

Risk – The possibility of suffering harm or hurt.

Seiche - a wave that oscillates in lakes, bays, or gulfs from a few minutes to a few hours as a result of seismic or atmospheric disturbances, or variations in level.

Standing (stationary) wave - a wave characterised by lack of any apparent forward motion.

Tectonic deformation - changes in the landscape caused by tectonic (internal to the earth) stresses.

Opus International Consultants Ltd
L5, Majestic Centre, 100 Willis St
PO Box 12 003, Thorndon, Wellington 6144
New Zealand

t: +64 4 471 7000
f: +64 4 499 3699
w: www.opus.co.nz