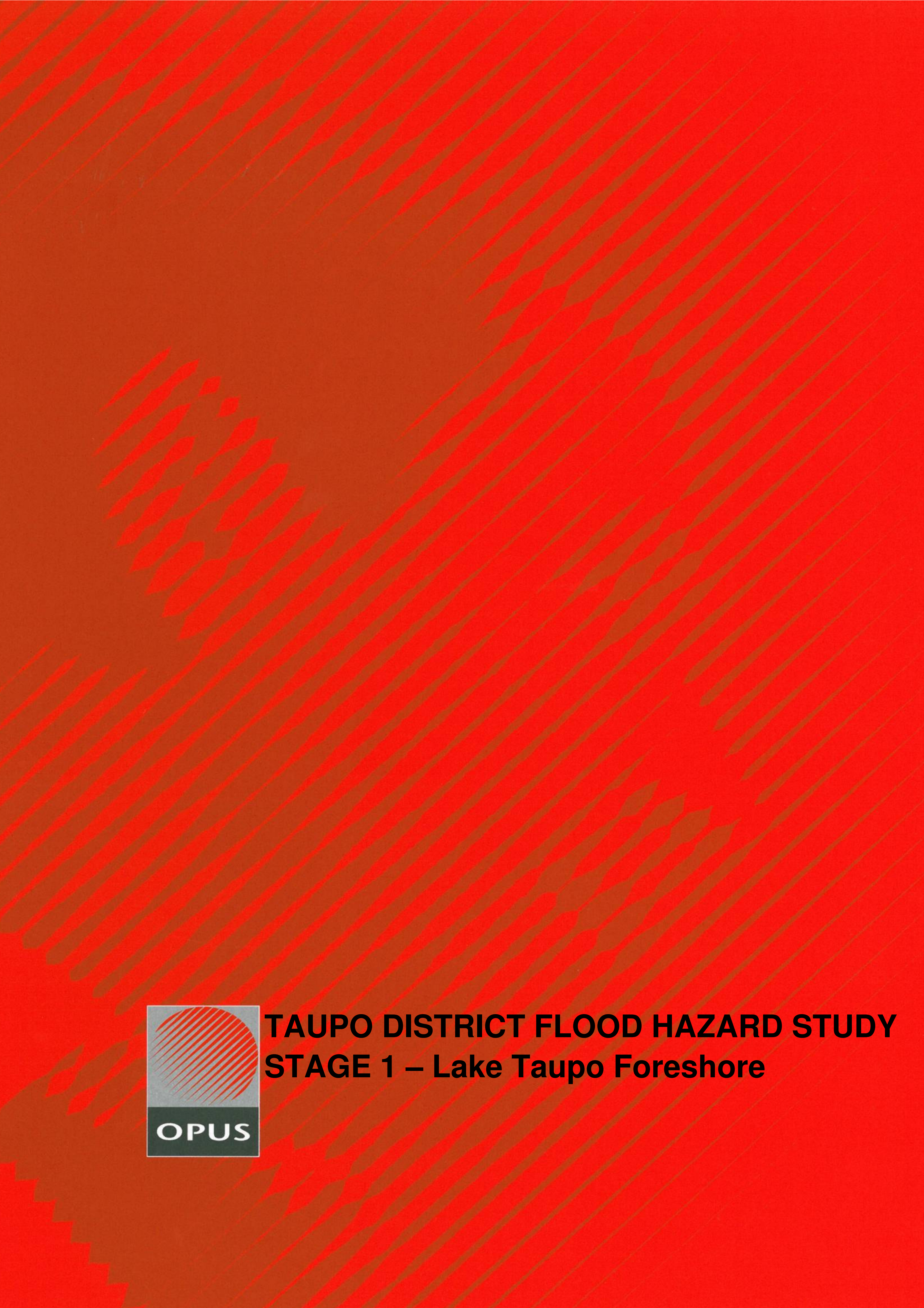

TAUPO DISTRICT FLOOD HAZARD STUDY
STAGE 1 – Lake Taupo Foreshore

OPUS

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STAGE 1 – Lake Taupo Foreshore

For: ***Environment Waikato and Taupo District Council***

March 2008

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Executive Summary

Quantifying the flood hazard of Lake Taupo involves a number of issues which are not present when establishing the flood hazard for a specific river. Water levels within Lake Taupo are not solely a 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 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.

The flood assessment involved magnitude – frequency analyses of a number of factors. Implicit in these analyses is the stationarity of data. This 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 Taupo, 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. The effect of a change in water level at the shore varies with topography, beach profile and material, and 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 adopted with each factor analysed from both a temporal (magnitude and frequency) and spatial perspective. 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 was also assessed.

The effects of higher water levels and wave run-up were overlaid on a high resolution digital terrain model (DTM) to identify which areas would be flooded by a particular combination of factors, and the depth of any inundation. As well as illustrating the overall effect of particular parameter combinations, their effect on specific sites down to 1m resolution was 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.

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, is defined using the 1 in 100 combined static water level and wave run-up event.

Contents

1 Introduction

1.1 Purpose

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 Taupo are vulnerable to flooding, particularly over the longer term, as a result of large inflows, high lake levels, big waves, 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. Environment Waikato and the Taupo 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:

- Environment Waikato and the Taupo 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;
- The need to resolve an appeal on the District Plan pertaining to the risk of inundation around the foreshore of Lake Taupo;
- Central Government's review of flood management in New Zealand; and
- Environment Waikato's Project Watershed which aims to address flood protection, soil conservation, and river management in the Waikato River catchment.

The primary objective of this *Taupo District Flood Hazard Study* is to identify the flood risk to land adjacent to Lake Taupo. 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, have been developed. These maps were analysed individually, and cumulatively, to identify those areas at greatest risk. 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 Taupo Foreshore Risk Management Strategy. The information in this report will subsequently be incorporated into Environment Waikato's regional plans and policy statements, and Taupo District Council's District Plans and land use planning.

This phase (Stage 1) of the study addresses flooding of the lake foreshore (Figure 1.1). Subsequent phases will investigate the flood risk associated with each of the major tributaries.

Figure 1.1 Location map.

1.2 The nature of the Lake Taupo flood hazard

Quantifying the flood hazard of Lake Taupo involves a number of issues which are not present when establishing the flood hazard for a specific river. Water levels within Lake Taupo that affect the flood hazard are not solely a 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; 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 shore. 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 than others on the water level, 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, 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 high 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. Each combination is associated with a particular likelihood of occurrence and 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 see how the factors interact to produce a particular flood level and extent.

1.3 Description of the Lake Taupo catchment

The Lake Taupo catchment covers an area of approximately 3289 km^2; including a lake area of 615 km^2. The elevation ranges from 2797 m at the top of Mt Ruapehu, down to approximately 356 m 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 rainfall varies from over 4000 mm on Mt Ruapehu to approximately 1000 mm at Taupo Township (Figure 1.3).

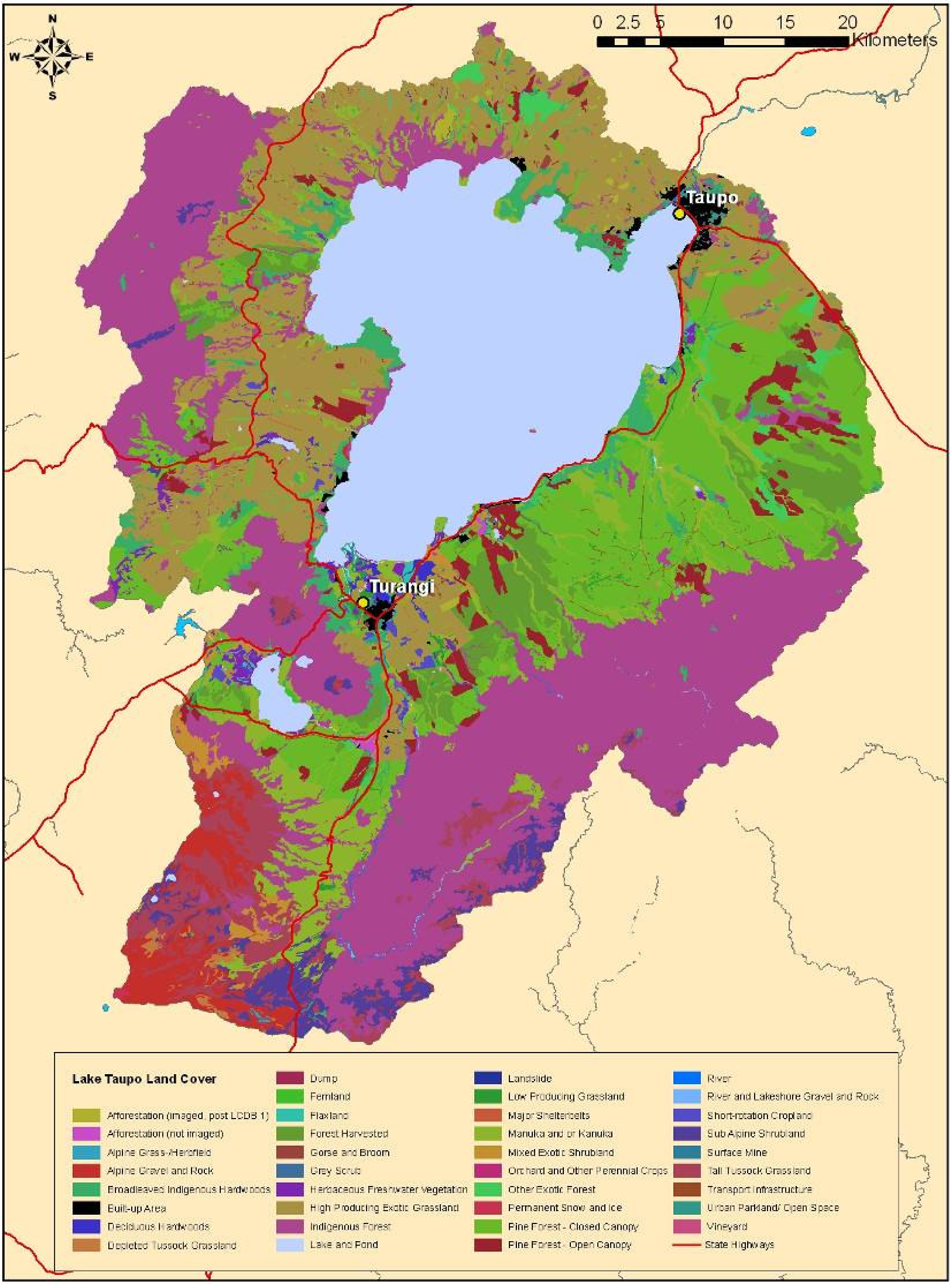


Figure 1.2 Land use around Lake Taupo (Source: LCDB2-2004).

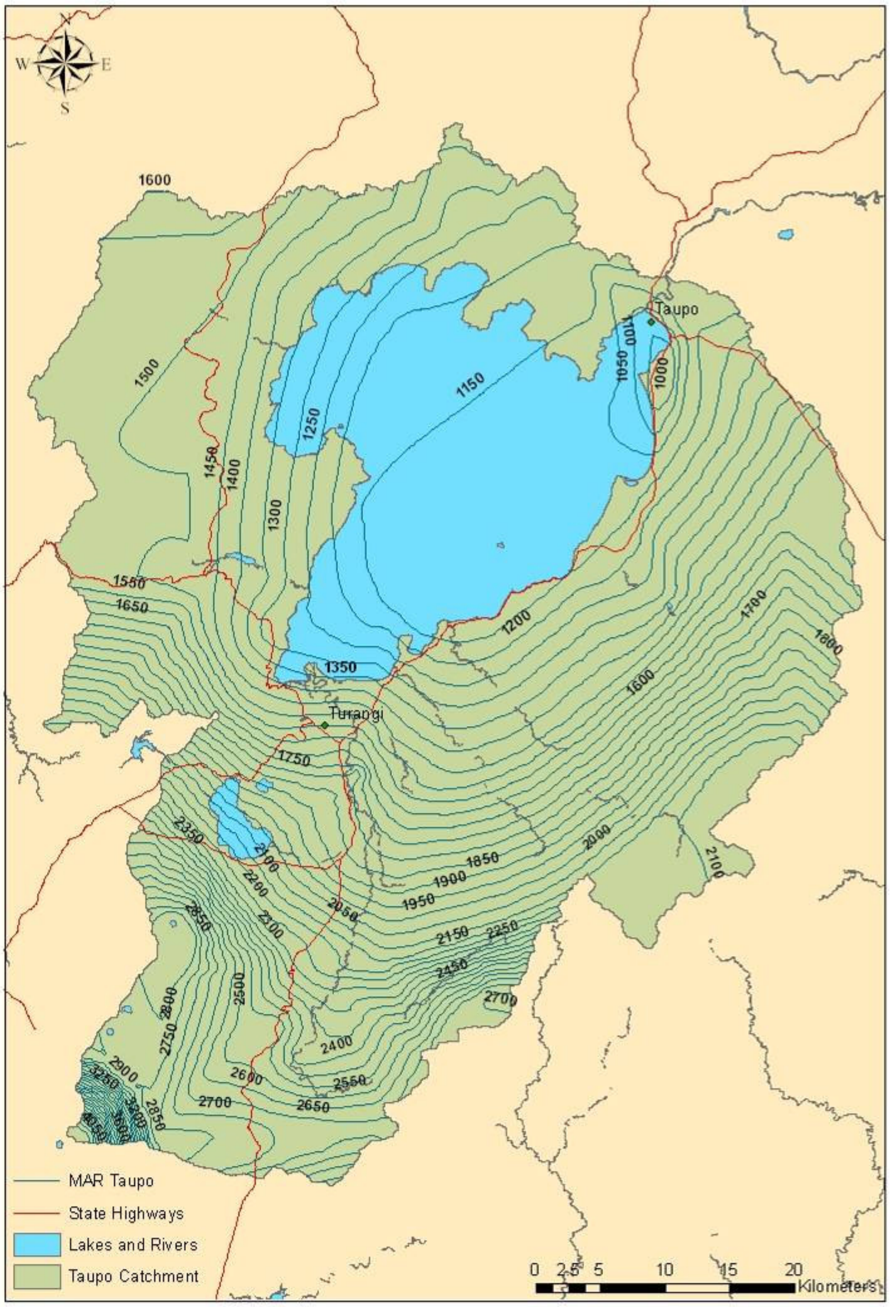


Figure 1.3 Mean annual rainfall (mm) around Lake Taupo.

The majority of the catchment is mantled by airfall or redeposited, relatively young, unconsolidated, volcanic deposits erupted from the Ruapehu, Tongariro, Taupo 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. The precipitation is then released from groundwater more slowly resulting in broad flood hydrographs, with high baseflows and low coefficients of variation.

In the south-eastern part of the catchment, the geology consists of indurated basement greywacke of the Kaimanawa Ranges. Greywacke is non-porous and relatively impermeable. Catchments within this material therefore respond more rapidly to rainfall events creating storm hydrographs with distinct and sharp flood peaks but low baseflows.

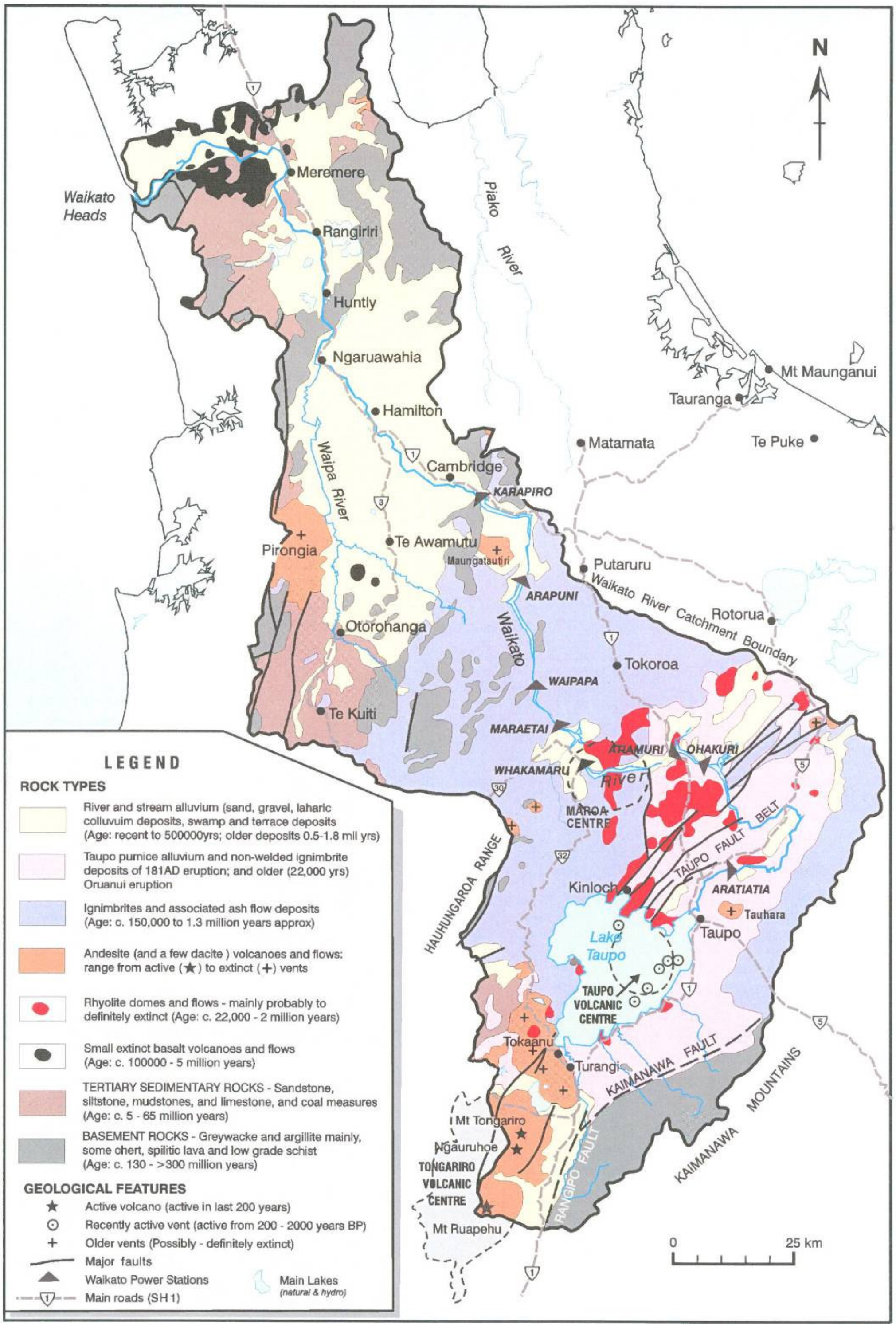


Figure 1.4 Geology of the Waikato River (Hancox, 2002).

2 Flood Modelling Approach

2.1 Introduction

As discussed above, the risk of flooding and the potential extent and depth of inundation around Lake Taupo is 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 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 potential effect of a change in water level at the shore varies with topography, beach profile and material, and 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 a temporal (magnitude and frequency) and a spatial perspective. A number of factors that affect water levels (and therefore flooding and inundation) have been investigated. These include lake level, tectonic activity, seiche, waves, 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 Taupo. All available data relating to each factor were analysed to determine the magnitude – frequency distribution 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. The 2.33-year return period event is included as it often considered to approximate the 'mean annual flood'.

A high resolution digital terrain model (DTM) of the shoreline, and extending inland for 300-400 m was constructed using LiDAR data. The model was extended for approximately 1 km along the lower reaches of the Tauranga-Taupo and Tongariro Rivers to allow consideration of the additional flood risk posed by these rivers. The spatial resolution of this model was 1 m, with elevation accuracy to ±0.1 m.

The magnitude – 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 1 m. Each 'layer' of information can be analysed independently, or in combination, and overlaid on the DTM to quantify the effect of the frequency of an event on the magnitude of its impact.

Since the water level responds to various factors, all information relating to each factor under particular return periods was added together to quantify their combined effect. Their total effect on lake level was then overlaid on the DTM to show which areas will be inundated, and to what depth, by the particular combination of factors at specific return periods. As well as illustrating the overall effect of particular parameter combinations, their effect on specific sites down to 1m resolution can be analysed.

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

All the spatial coverages produced from the factors considered in this study are contained in a data base companion to this report.

2.3 Stationarity

Stationarity is a key assumption in all frequency analysis, including those used in this study. Stationarity implies (and it is therefore assumed) that the maxima or minima used in the analysis exhibit no trends or cycles; and 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 Taupo Gates; the operating rules for the Taupo 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' in a data set. However, they increase the chance of violating the basic rule of stationarity. Longer records have the potential to be more affected by land use, climate, or other changes.

3 Lake Level

3.1 The controlled lake level

Flow down the Waikato River is controlled for power generation purposes via the Taupo Gates that were commissioned in 1941. The Taupo Gates (and modified channel) manage outflow from the lake, and consequently their operation affects the water level in Lake Taupo. In 1947 the Lake Taupo Compensation Claims Act was passed specifying the maximum working level of Lake Taupo for power generation purposes. This level stands at 357.387 m above mean sea level (relative to the Moturiki Datum, 1956). If the lake exceeds this level, then affected landowners may claim for damages. Table 3.1 shows a timeline of significant events that have influenced the operation of Lake Taupo.

In addition to 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 flows into Lake Taupo (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 Taupo is reached (357.25 masl); 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 on the lower Waikato River outflow from Lake Taupo 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 action necessary during the flood event.

Mighty River Power Ltd's resource consent conditions state that water can not be held in Lake Taupo for electricity generation purposes when the lake level is above 357.25 masl. The Lake Taupo Gates were not designed as a flood management system, and therefore Mighty River Power Ltd's ability to modify the levels of Lake Taupo is limited (Mighty River Power, 2005). Outflow can, however, be managed to some extent at the request of

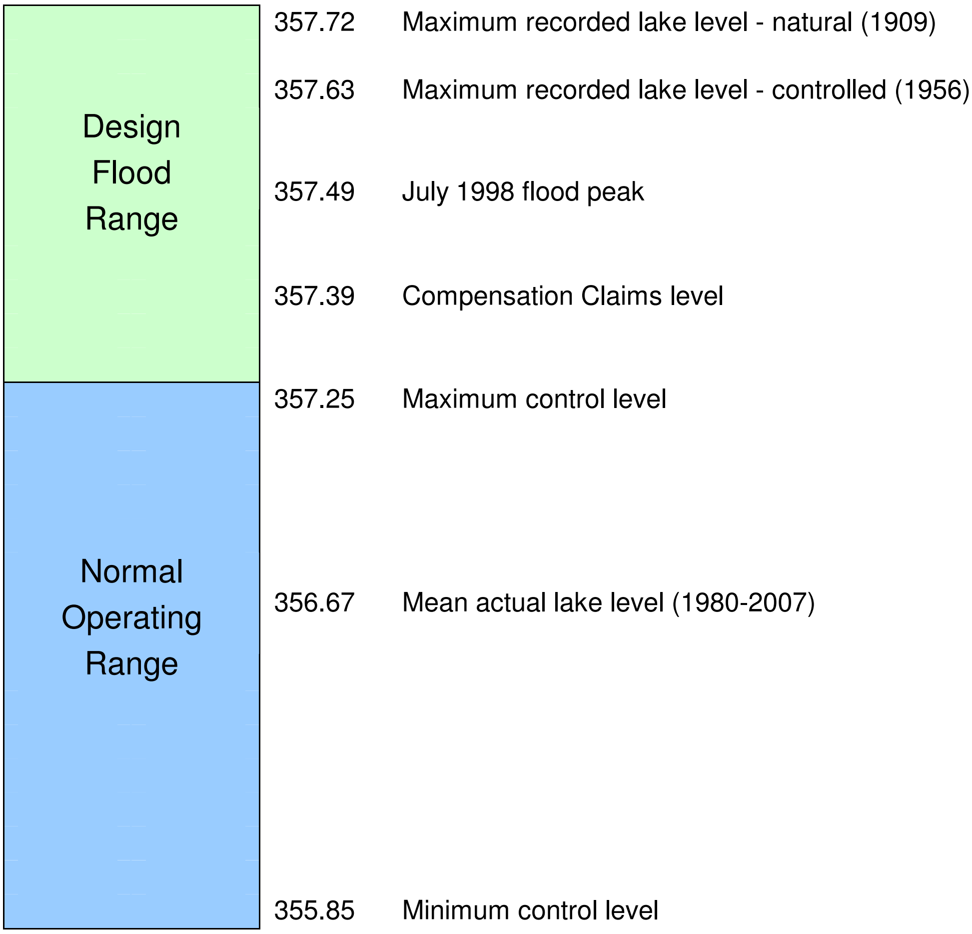
Environment Waikato, and in conjunction with the flood rules, to limit downstream flooding. This is particularly relevant if the Waipa River is also in flood so as to avoid the coincidence of flood peaks in the lower Waikato River (refer to the Flood Management Rules).

The normal operating range of Lake Taupo varies between the minimum control level of 355.85 m and the maximum control level of 357.25 m (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 357.49 m and had a PE3 distribution return period of 83 years (using the 1980-2007 record). This was less than the highest recorded lake level of 357.72 m, but that occurred in 1909 prior to commissioning of the Taupo Gates and the Waikato Hydro System.

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

Date	Event
June 1929	Arapuni Dam and power station commissioned
September 1941	Taupo Gates commissioned
1947	Lake Taupo Compensation Claims Act, maximum control level 357.387 m
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
1977	Tongariro Offset Works Agreement
October 1979	Eastern Diversion TPD commissioned
September 1992	Whanganui intake minimum flow decision came into effect. 3 m^3/s minimum flow at Whakapapa Intake
February 1993	Whanganui intake minimum flow decision came into effect. 29 m^3/s minimum flow at Whanganui River at Te Maire
August 2003	Mighty River Power resource consents granted
September 2003	Mighty River Power start operating to their resource consent conditions
December 2004	Genesis Energy resource consents granted

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



Note: All data are rounded to two decimal places

Figure 3.2 Key levels for Lake Taupo (m). Note: These are static levels using the 3-hour average lake levels (ignoring any wave effects). Elevations are relative to mean sea level using the Moturiki datum in 1956.

3.2 Taupo lake level records and frequency analysis

Opus maintains two Lake Taupo level records. The first is the actual lake level recorded relative to the Taupo Fundamental Benchmark, levelled to the Moturiki datum in 1956. The second is a synthesised ‘natural’ lake level record which assumes that Lake Taupo has no control structure; that the outflow channel was not altered; and that water is not diverted via the Tongariro Power Development Scheme. Both these records contain 3-hourly average water level data.

Since the installation of the Taupo 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 1940’s. This was prior to the passing of the Lake Taupo Compensation Claims Act (Table 3.1). Between 1980 and 2007 the actual record had a mean lake level of 356.668 m compared to what would have been a mean natural lake level of 356.659 m. That is, the mean actual lake level was only 9 mm higher than 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 2007. This is the situation since the installation of the Taupo 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 and what would have been the natural levels. Overall the lake has been kept slightly higher than natural levels, although the maximum lake levels are very similar. Slightly lower levels have also been maintained on occasion.

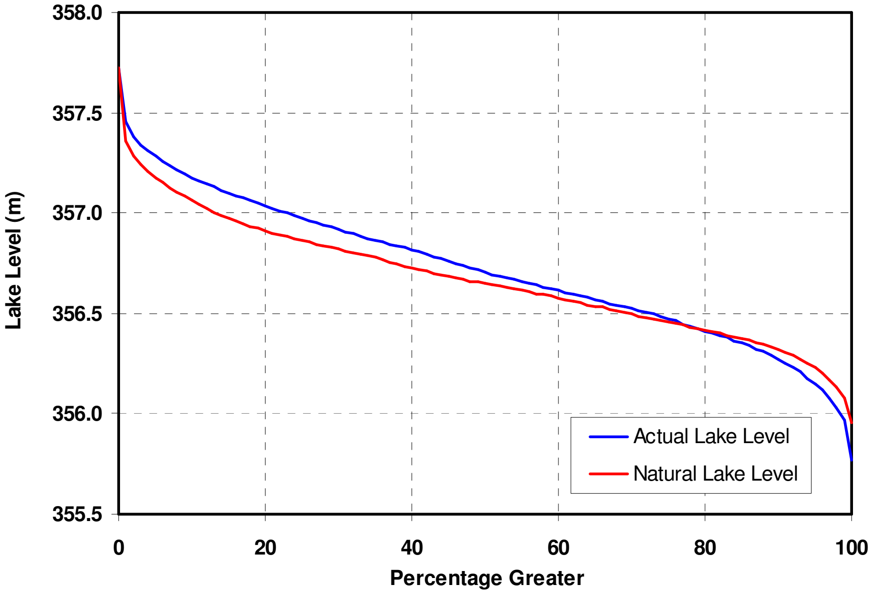


Figure 3.3 Percentage of time that lake levels were exceeded, 1941-2007.

Figure 3.4 compares the distribution of lake levels between 1980 and 2007. This is the period since the commissioning of the TPD scheme, since Mighty River Power Ltd have been operating the Waikato Hydro System, and immediately following the granting of the current consents in 2003. Under natural conditions Lake Taupo would have spent slightly more time above 357.00 m, while the actual lake level has spent more time below 356.50m.

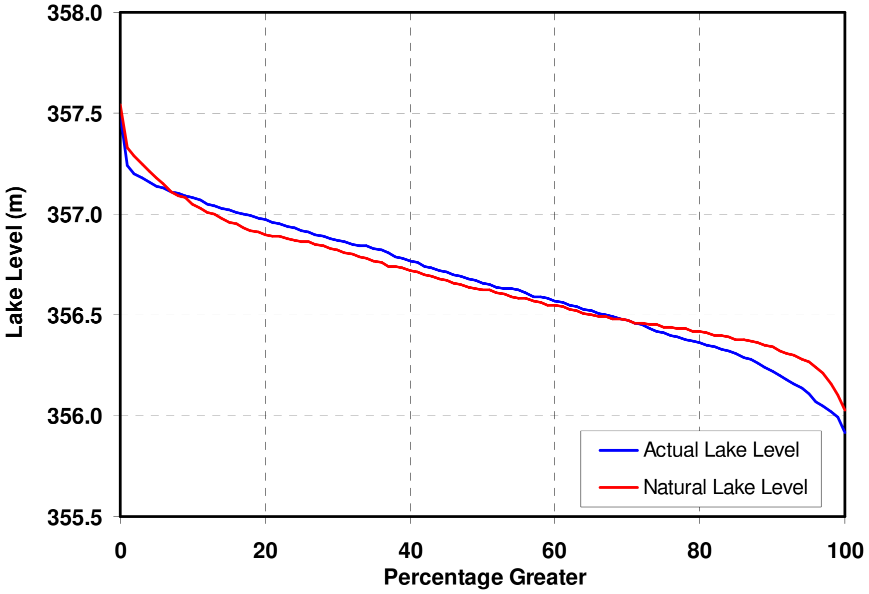


Figure 3.4 Percentage of time that lake levels were exceeded, 1980-2007.

Figure 3.5 compares the actual (managed) and what would have been the natural lake levels between 1941 and 2007. While the actual levels differ slightly over time, the seasonal and annual patterns of change in level are almost identical between 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 Taupo. The largest 10 events are highlighted. The highest lake levels occurred in the earlier half of the record, prior to the commissioning of the Taupo Gates and the Lake Taupo Compensation Claims Act (1947). 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 ceases during significant flood events.

Frequency analysis of both lake level records was conducted to estimate the lake level of the annual (2.33), 5, 10, 20, 50, 100, 200 and 500-year return period events. The entire record (1906-2007); the record for the managed operation since the commissioning of the Taupo Gates and prior to TPD (1942-1970); and the record since the commissioning of the Tongariro Power Development Scheme (1980-2007) 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, and Generalised Extreme Value distributions were all fitted to the data to check which provided the best estimate of extreme values. The Pearson 3 distributions were preferred for all three record periods Tables 3.3 to 3.5 detail the expected lake levels for eight return periods, using different periods of record, and the most appropriate frequency distribution.

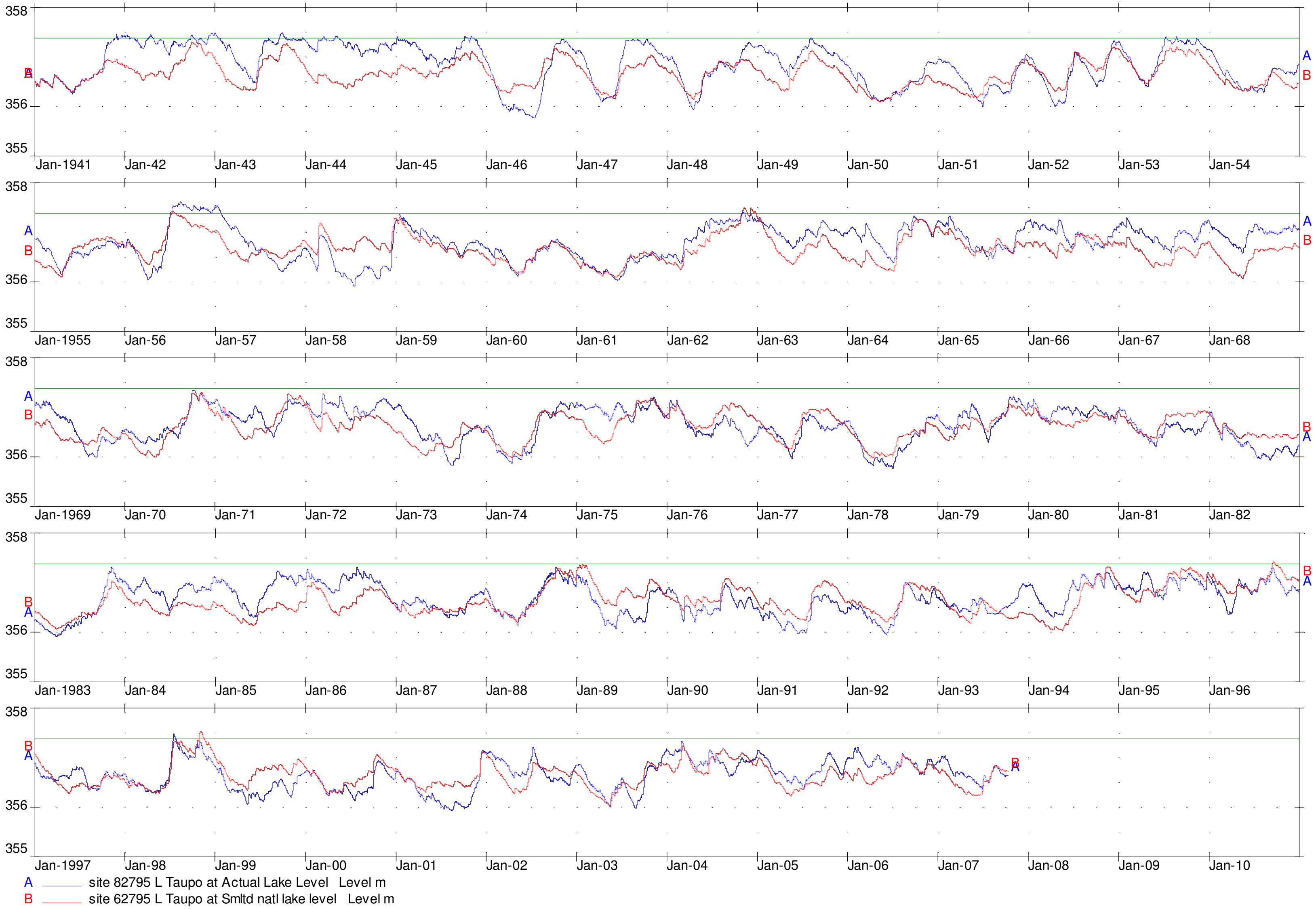


Figure 3.5 **Comparison of Taupo Actual and the Taupo Natural lake level records, 1941-2007. The Compensation Claims level of 357.387 m is marked in green.**

Table 3.2 Annual maximum recorded lake level (Actual and Natural records); outflow from; and inflow to Lake Taupo.

Year	Actual Lake Level (m)	Natural Lake Level (m)	Outflow (m^3/s)	Inflow (m^3/s)
1906	357.235	357.235	186	415
1907	357.418	**357.418**	208	**858**
1908	356.982	356.982	159	367
1909	**357.723**	**357.723**	246	446
1910	357.113	357.113	173	412
1911	356.824	356.824	141	306
1912	357.235	357.235	186	365
1913	357.052	357.052	166	321
1914	357.037	357.037	164	326
1915	357.144	357.144	176	673
1916	357.205	357.205	183	412
1917	357.235	357.235	186	336
1918	357.174	357.174	179	317
1919	357.052	357.052	166	423
1920	356.991	356.991	159	247
1921	356.930	356.930	152	316
1922	356.930	356.930	152	333
1923	356.839	356.839	143	347
1924	356.988	356.988	159	289
1925	357.296	357.296	193	665
1926	**357.631**	**357.631**	235	**802**
1927	**357.449**	**357.449**	212	467
1928	357.388	**357.388**	204	438
1929	357.116	357.116	173	339
1930	357.174	357.174	179	330
1931	356.869	356.869	146	234
1932	356.702	356.702	130	280
1933	356.748	356.748	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	356.813	140	397
1940	357.001	357.001	160	514
1941	**357.464**	356.969	176	461
1942	**357.479**	357.306	214	453
1943	**357.494**	357.278	280	532
1944	**357.433**	356.783	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	356.915	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	356.852	174	384
1955	356.885	356.915	181	411
1956	**357.634**	**357.442**	240	656
1957	**357.555**	357.058	194	360
1958	357.196	357.301	206	**1357**
1959	357.372	357.305	211	549
1960	356.863	356.837	173	495
1961	356.623	356.614	200	348
1962	357.418	**357.504**	274	696
1963	357.314	357.320	267	516
1964	357.342	357.281	266	719
1965	357.336	357.122	219	557
1966	357.266	356.999	249	629
1967	357.305	356.911	237	776
1968	357.253	356.817	215	487
1969	357.141	356.763	225	448
1970	357.348	357.309	289	487
1971	357.174	357.282	280	492
1972	357.287	357.074	**350**	620
1973	357.083	356.707	259	518
1974	357.125	356.960	**351**	483
1975	357.215	357.196	288	610
1976	357.150	357.097	282	629
1977	356.868	356.988	258	627
1978	356.863	356.709	259	655
1979	357.239	357.075	291	527
1980	357.175	357.002	289	505
1981	356.983	356.947	273	406
1982	356.914	356.892	267	664
1983	357.332	357.044	294	512
1984	357.137	356.772	285	406
1985	357.252	356.631	**296**	570
1986	357.319	357.022	**297**	689
1987	356.912	356.695	267	428
1988	357.319	357.293	**297**	670
1989	357.176	**357.381**	286	618
1990	356.997	357.099	275	718
1991	356.775	357.054	259	693
1992	357.023	357.015	277	566
1993	356.989	356.872	254	722
1994	357.233	357.340	291	**844**
1995	357.232	357.314	289	**861**
1996	357.311	**357.433**	**297**	726
1997	356.900	357.091	268	475
1998	**357.493**	**357.542**	**316**	**941**
1999	356.841	357.035	261	642
2000	356.946	357.076	277	**869**
2001	357.159	357.123	293	**961**
2002	357.223	357.088	**298**	670
2003	357.192	356.929	273	660
2004	357.348	357.249	**309**	**912**
2005	357.161	357.004	295	516
2006	357.221	357.054	**300**	659
2007	357.048	356.847	287	438

Table 3.3 Lake Taupo level frequency analyses, 1906-2007 (PE3 distribution).

Return Period	Actual Lake Level 1906-2007 (m)	Natural Lake Level 1906-2007 (m)
2.33	357.21	357.10
5	357.36	357.26
10	357.45	357.37
20	357.53	357.46
50	357.61	357.57
100	357.66	357.64
200	357.70	357.71
500	357.76	357.79
Maximum Recorded	357.72	357.72

Table 3.4 Lake Taupo 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	357.56	357.61
500	357.57	357.66
Maximum Recorded	357.63	357.50

Table 3.5 Lake Taupo level frequency analyses, 1980-2007 (PE3 distribution).

Return Period	Actual Lake Level 1980-2007 (m)	Natural Lake Level 1980-2007 (m)	Mighty River Power Ltd's consent conditions
2.33	357.17	357.09	
5	357.29	357.24	*357.25*
10	357.35	357.35	
20	357.41	357.44	*357.39*
50	357.47	357.55	
100	357.50	357.63	*357.50*
200	357.53	357.70	
500	357.57	357.78	
Maximum Recorded	357.49	357.54	

It should be noted in Table 3.5 that the 'target' exceedence levels set in Mighty River Power Ltd's consent conditions (granted in 2003) for operating the Taupo Gates are very close (exact for the higher return periods) to the levels estimated for the same return periods in this study.

3.3 Assumptions

In this study the data record from 1980 to the end of 2007, and therefore the estimates of lake level in Table 3.5, is 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 scheme, since Mighty River Power Ltd have been operating the Waikato Hydro System, and immediately following the granting of the current consents in 2003. It therefore limits the potential impact of non-stationarity of data that may be an issue if a 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 Ltds' 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 would therefore have had the potential to distort extreme lake level estimates.

3.3.1 Granting of consents

This analysis has assumed that the future operation of the Taupo Gates will result in substantially the same pattern of lake level variation as discussed above. The most recent consents to manage the lake level were granted to Mighty River Power Ltd in late 2003. It is therefore not yet possible to identify whether these have led to any significant changes in the lake level regime. Figure 3.6, however, suggests that the pattern of lake level variation in the four years up until 2008 was different to that over the previous four years.

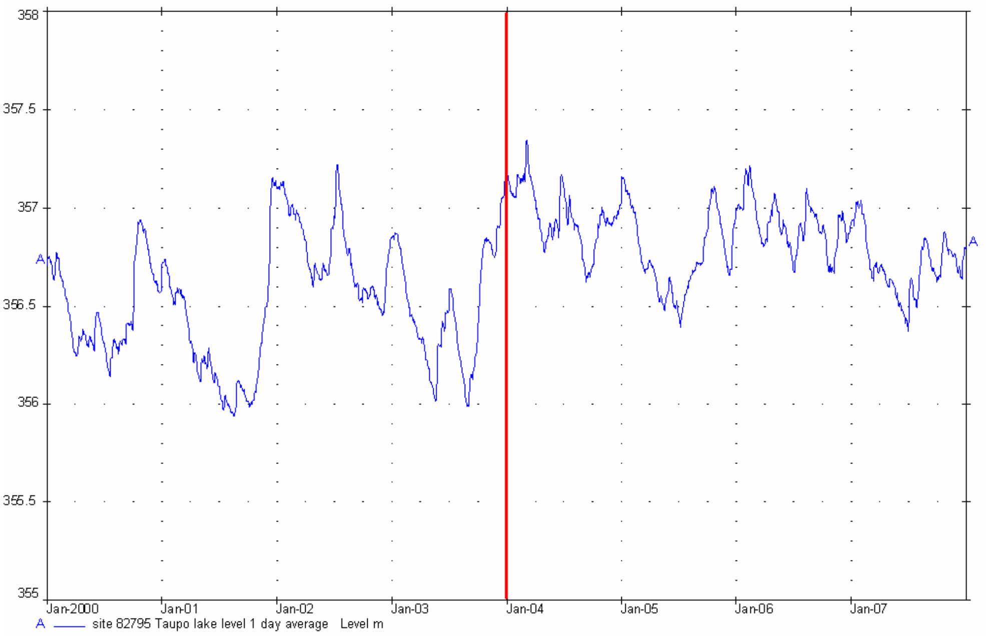


Figure 3.6 Daily average lake levels between 2000 and 2007. The move to new consents, including a single MCL, is indicated by the red line.

Since the end of 2003 the lake appears to have been held about 0.5 m higher and exhibits significantly less variation than in the previous four years (Figure 3.7). The maximum lake levels appear to have been largely unaffected.

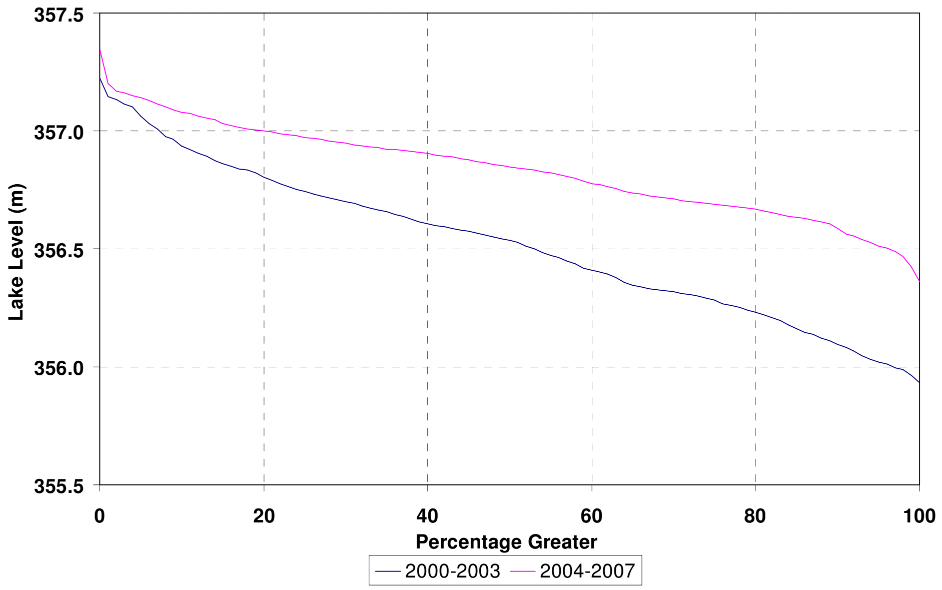


Figure 3.7 Distribution of lake levels from 2000-2003 and from 2004-2007. Lake levels since 2004 appear to be different to the earlier period.

A comparison of the inflow records for the 4-year periods (2000-2003 & 2004-2007) either side of the granting of the new consents shows no difference (Figure 3.8). It is therefore likely that this recent change in lake level variation is not the result of any general climatic influence. It is also unlikely that these changes are the result of the move to a single maximum lake level. In fact, the move to a single level, combined with exceedence limits, mean that Mighty River Power can now be more sophisticated in managing the risk of exceeding 357.25 than in the past. It is therefore likely that the short term change identified in Figure 3.6 is a function of: the short lengths of record used; improved reliability of predicting inflows (meaning the lake can be held higher without increasing the risk); changes within the national energy market; and an attempt to store water for winter to increase potential generating capacity during peak demand.

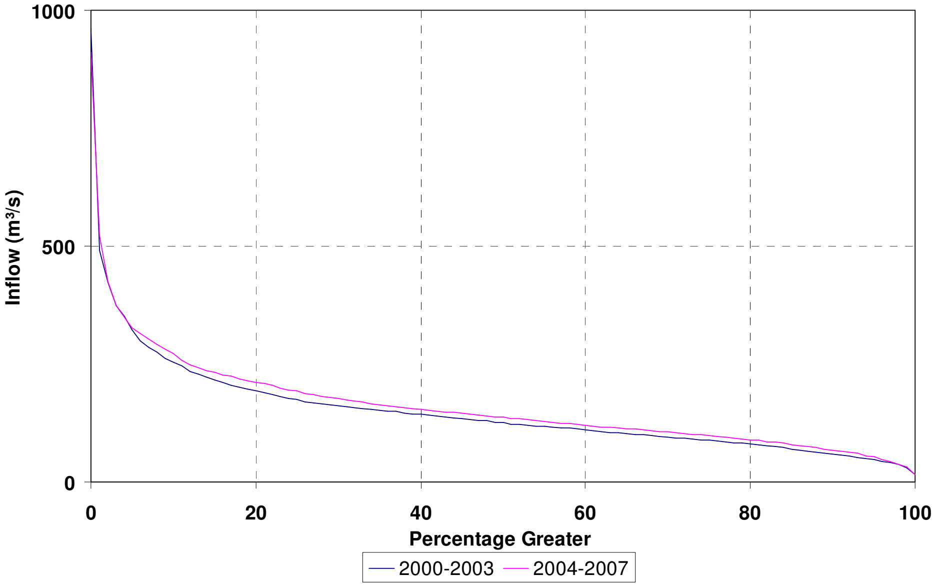


Figure 3.8 Distribution of lake inflows for two 4-year periods either side of the granting of the current consents.

3.4 Recommendation

Despite the fact that the lake level regime appears to have changed over the past 4 years, this is likely to be largely an artefact of the analysis of short term data records. The 1980-2007 record is still considered to be the most appropriate to use for the frequency analysis. In addition to the reasons stated above for using this record, the recent apparent change in lake level regime does not appear to have affected the distribution of high lake levels. That is, although there has been a short-term change in the overall distribution of lake levels, the high levels have remained relatively constant. It is these high levels (the annual maxima) that are used in the frequency analysis.

The current consents for operating the Taupo 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 1980-2007.

It is therefore recommended that the estimates for the lake level at various return periods shown in Figure 3.9 are the most appropriate with respect to the flood hazard.

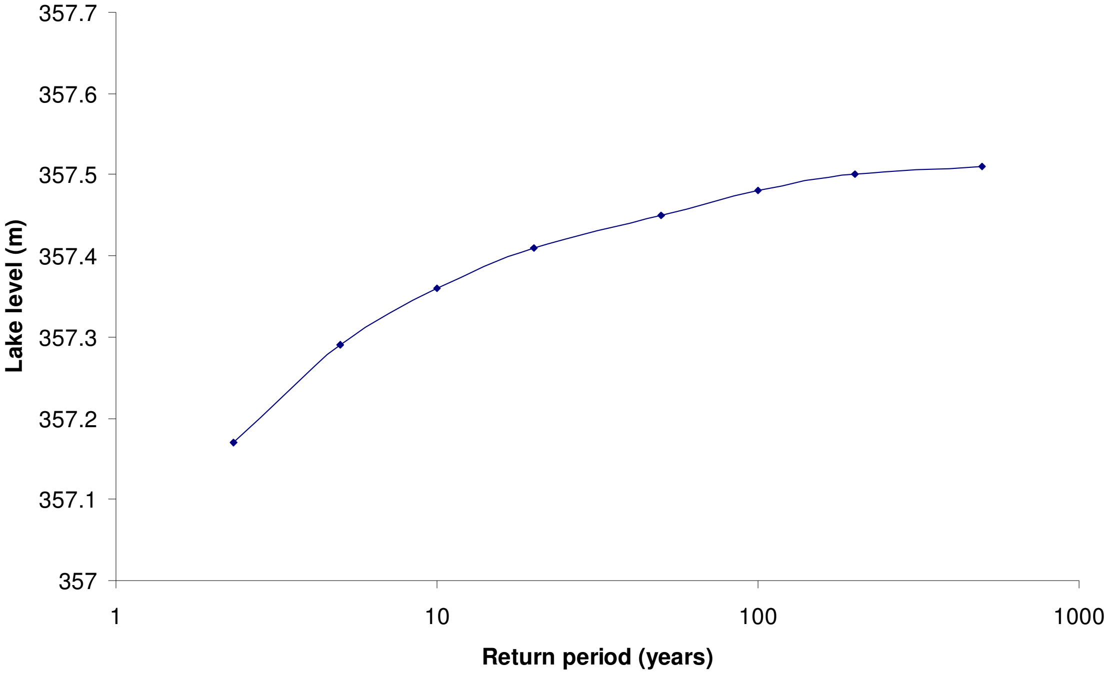


Figure 3.9 Estimates of lake levels at different return periods using 1980-2007 data and a PE3 distribution.

Surfaces of the estimated lake level for return periods of 2.33, 5, 10, 20, 50, 100, 200 and 500 years, based on the above assumptions, are contained in the data appendix.

In addition to the recommended flood levels in Table 3.5, and displayed in Figure 3.9, key levels (using the 1980-2007 actual lake record and a PE3 distribution) are:

- The maximum normal operating level of 357.25 m has a 4-year return period
- The Compensation Claims level of 357.387 m has an 15-year return period
- The maximum recorded level of 357.49 (1998) has a return period of 83 years

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

3.5 Summary

The use of the 1980-2007 actual lake level record is considered to be the most appropriate to use in this analysis. A PE3 distribution fits these data most closely. Based on these assumptions Lake Taupo could be expected to reach the levels listed in Table 3.6 for various return periods.

Table 3.6 Expected level of Lake Taupo for various return periods.

Return Period	Lake Level (m)
2.33	357.17
5	357.29
10	357.35
20	357.41
50	357.47
100	357.50
200	357.53
500	357.57

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, 2003).

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 changes in absolute temperature and rainfall in particular places.

The wide range of values in Table 4.1 shows the considerable uncertainty associated with the potential changes in temperature and rainfall even at the regional level. The impacts of future climate changes may, however, be even greater than these numbers suggest. This is because changes in average climate are projected to lead to greater variability and a higher frequency of extremes.

Table 4.1 Regional differences in global warming effects.

Region	Temperature	Precipitation
Northland, Auckland	+1.0 to +2.8	-10% to 0%
Western North Island from Waikato to Wellington	+0.8 to +2.7	0% to +20%
Eastern North Island from Bay of Plenty to Wairarapa	+0.9 to +2.7	-20% to 0%
Nelson, Marlborough, to coastal Canterbury and Otago	+0.8 to +2.5	-20% to +5%
West Coast and Canterbury foothills	+0.6 to +2.5	+5% to +25%
Southland and inland Otago	+0.6 to +2.2	0% to +30%

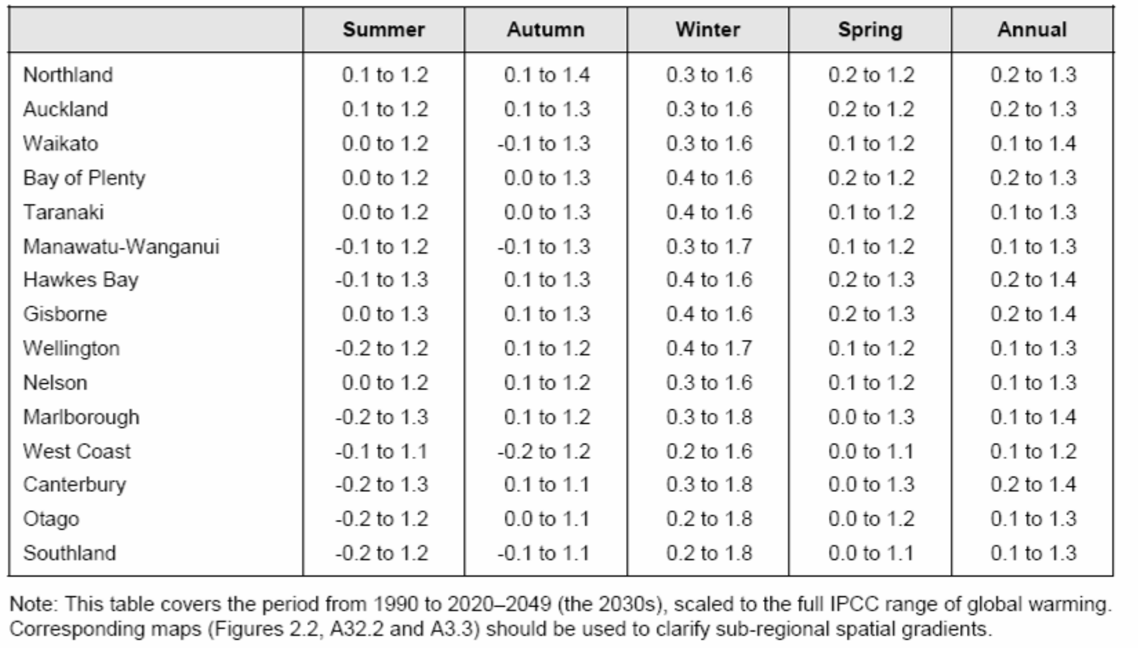
The Intergovernmental Panel on Climate Change (IPCC) recently concluded that more intense, and more frequent, precipitation events are likely over many areas. No detailed work on potential changes has been published yet for New Zealand. One recent study, however, led to a range of possible scenarios for the frequency and intensity of heavy rainfalls in Australia and New Zealand. This study concluded that the frequency of heavy precipitation events over the entire area could increase up to fourfold by 2070, although it was not ruled 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, 2004).

4.2 Climate projections for New Zealand

Climate projections for changes in temperature and rainfall from 1990 to 2035 (45 years change) and to 2085 (95 years change) have been prepared. These provide a range of possible values for each climate variable which reflect various greenhouse gas futures (represented by the 35 SRES scenarios) and the range of climate models. While the most likely value from the projection range is not indicated, the central values are perhaps more likely as they reflect the consensus between models rather than the extremes (Ministry for the Environment, 2004).

Temperature projections, corresponding to the full IPCC SRES range of scenarios, were prepared for 58 sites around New Zealand. Temperature changes for characteristic sites in each region are summarised in Table 4.2 (2030s) and Table 4.3 (2080s)

Table 4.2 **Projected changes in seasonal and annual mean temperature (°C) for each regional council area from 1990 to the 2030s.**

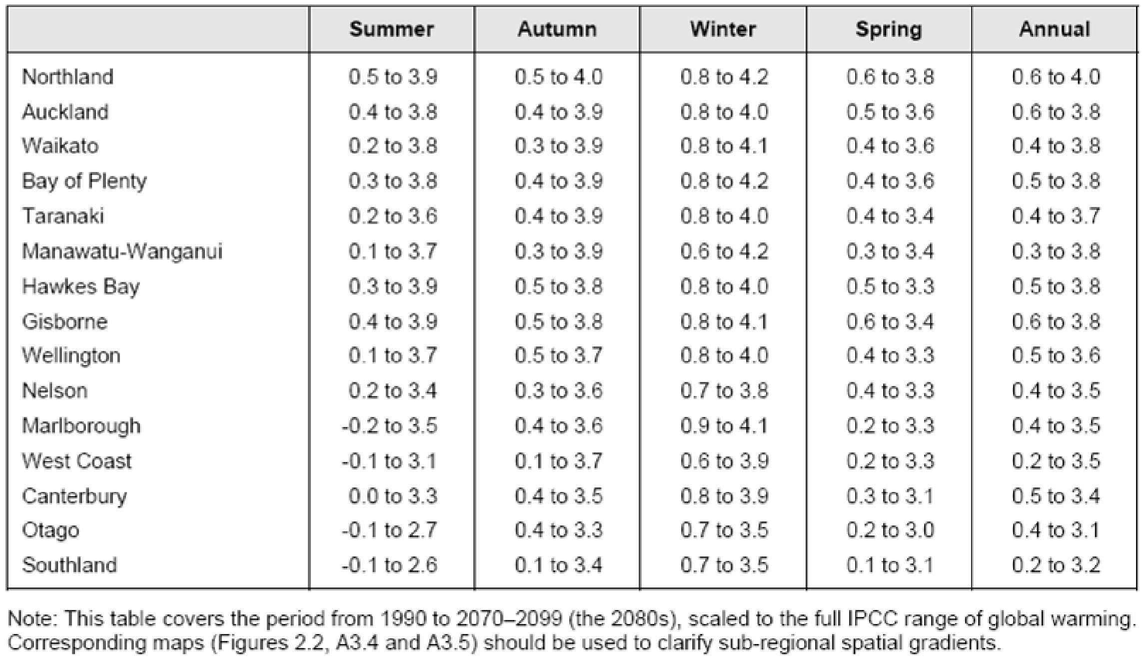


	Summer	Autumn	Winter	Spring	Annual
Northland	0.1 to 1.2	0.1 to 1.4	0.3 to 1.6	0.2 to 1.2	0.2 to 1.3
Auckland	0.1 to 1.2	0.1 to 1.3	0.3 to 1.6	0.2 to 1.2	0.2 to 1.3
Waikato	0.0 to 1.2	-0.1 to 1.3	0.3 to 1.6	0.1 to 1.2	0.1 to 1.4
Bay of Plenty	0.0 to 1.2	0.0 to 1.3	0.4 to 1.6	0.2 to 1.2	0.2 to 1.3
Taranaki	0.0 to 1.2	0.0 to 1.3	0.4 to 1.6	0.1 to 1.2	0.1 to 1.3
Manawatu-Wanganui	-0.1 to 1.2	-0.1 to 1.3	0.3 to 1.7	0.1 to 1.2	0.1 to 1.3
Hawkes Bay	-0.1 to 1.3	0.1 to 1.3	0.4 to 1.6	0.2 to 1.3	0.2 to 1.4
Gisborne	0.0 to 1.3	0.1 to 1.3	0.4 to 1.6	0.2 to 1.3	0.2 to 1.4
Wellington	-0.2 to 1.2	0.1 to 1.2	0.4 to 1.7	0.1 to 1.2	0.1 to 1.3
Nelson	0.0 to 1.2	0.1 to 1.2	0.3 to 1.6	0.1 to 1.2	0.1 to 1.3
Marlborough	-0.2 to 1.3	0.1 to 1.2	0.3 to 1.8	0.0 to 1.3	0.1 to 1.4
West Coast	-0.1 to 1.1	-0.2 to 1.2	0.2 to 1.6	0.0 to 1.1	0.1 to 1.2
Canterbury	-0.2 to 1.3	0.1 to 1.1	0.3 to 1.8	0.0 to 1.3	0.2 to 1.4
Otago	-0.2 to 1.2	0.0 to 1.1	0.2 to 1.8	0.0 to 1.2	0.1 to 1.3
Southland	-0.2 to 1.2	-0.1 to 1.1	0.2 to 1.8	0.0 to 1.1	0.1 to 1.3

Note: This table covers the period from 1990 to 2020–2049 (the 2030s), scaled to the full IPCC range of global warming. Corresponding maps (Figures 2.2, A32.2 and A3.3) should be used to clarify sub-regional spatial gradients.

Source *Ministry for the Environment and New Zealand Climate Change Office, 2004, Table 2.2.*

Table 4.3 **Projected changes in seasonal and annual mean temperature (°C) for each regional council area from 1990 to the 2080s.**



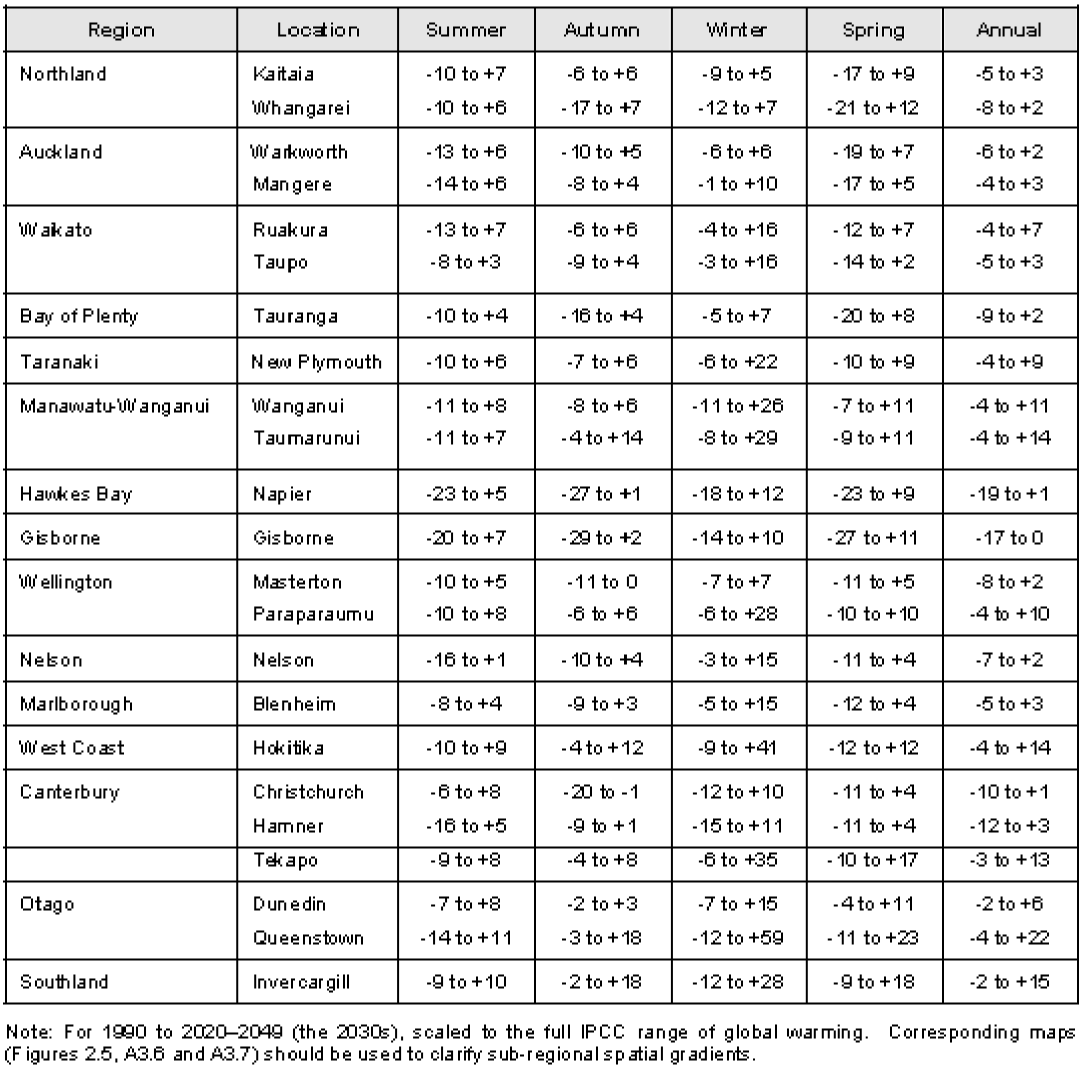
	Summer	Autumn	Winter	Spring	Annual
Northland	0.5 to 3.9	0.5 to 4.0	0.8 to 4.2	0.6 to 3.8	0.6 to 4.0
Auckland	0.4 to 3.8	0.4 to 3.9	0.8 to 4.0	0.5 to 3.6	0.6 to 3.8
Waikato	0.2 to 3.8	0.3 to 3.9	0.8 to 4.1	0.4 to 3.6	0.4 to 3.8
Bay of Plenty	0.3 to 3.8	0.4 to 3.9	0.8 to 4.2	0.4 to 3.6	0.5 to 3.8
Taranaki	0.2 to 3.6	0.4 to 3.9	0.8 to 4.0	0.4 to 3.4	0.4 to 3.7
Manawatu-Wanganui	0.1 to 3.7	0.3 to 3.9	0.6 to 4.2	0.3 to 3.4	0.3 to 3.8
Hawkes Bay	0.3 to 3.9	0.5 to 3.8	0.8 to 4.0	0.5 to 3.3	0.5 to 3.8
Gisborne	0.4 to 3.9	0.5 to 3.8	0.8 to 4.1	0.6 to 3.4	0.6 to 3.8
Wellington	0.1 to 3.7	0.5 to 3.7	0.8 to 4.0	0.4 to 3.3	0.5 to 3.6
Nelson	0.2 to 3.4	0.3 to 3.6	0.7 to 3.8	0.4 to 3.3	0.4 to 3.5
Marlborough	-0.2 to 3.5	0.4 to 3.6	0.9 to 4.1	0.2 to 3.3	0.4 to 3.5
West Coast	-0.1 to 3.1	0.1 to 3.7	0.6 to 3.9	0.2 to 3.3	0.2 to 3.5
Canterbury	0.0 to 3.3	0.4 to 3.5	0.8 to 3.9	0.3 to 3.1	0.5 to 3.4
Otago	-0.1 to 2.7	0.4 to 3.3	0.7 to 3.5	0.2 to 3.0	0.4 to 3.1
Southland	-0.1 to 2.6	0.1 to 3.4	0.7 to 3.5	0.1 to 3.1	0.2 to 3.2

Note: This table covers the period from 1990 to 2070–2099 (the 2080s), scaled to the full IPCC range of global warming. Corresponding maps (Figures 2.2, A3.4 and A3.5) should be used to clarify sub-regional spatial gradients.

Source *Ministry for the Environment and New Zealand Climate Change Office, 2004, Table 2.3.*

Rainfall projections were also prepared for 92 New Zealand sites. Large systematic variations exist in the projected rainfall within regions. Therefore, rainfall projections have been tabulated for specific places (Table 4.4).

Table 4.4 Projected percentage change in seasonal and annual precipitation for the 2030s for selected stations within each region.



Region	Location	Summer	Autumn	Winter	Spring	Annual
Northland	Kaitaia	-10 to +7	-6 to +6	-9 to +5	-17 to +9	-5 to +3
	Whangarei	-10 to +6	-17 to +7	-12 to +7	-21 to +12	-8 to +2
Auckland	Warkworth	-13 to +6	-10 to +5	-6 to +6	-19 to +7	-6 to +2
	Mangere	-14 to +6	-8 to +4	-1 to +10	-17 to +5	-4 to +3
Waikato	Ruakura	-13 to +7	-6 to +6	-4 to +16	-12 to +7	-4 to +7
	Taupo	-8 to +3	-9 to +4	-3 to +16	-14 to +2	-5 to +3
Bay of Plenty	Tauranga	-10 to +4	-16 to +4	-5 to +7	-20 to +8	-9 to +2
Taranaki	New Plymouth	-10 to +6	-7 to +6	-6 to +22	-10 to +9	-4 to +9
Manawatu-Wanganui	Wanganui	-11 to +8	-8 to +6	-11 to +26	-7 to +11	-4 to +11
	Taumarunui	-11 to +7	-4 to +14	-8 to +29	-9 to +11	-4 to +14
Hawkes Bay	Napier	-23 to +5	-27 to +1	-18 to +12	-23 to +9	-19 to +1
Gisborne	Gisborne	-20 to +7	-29 to +2	-14 to +10	-27 to +11	-17 to 0
Wellington	Masterton	-10 to +5	-11 to 0	-7 to +7	-11 to +5	-8 to +2
	Paraparaumu	-10 to +8	-6 to +6	-6 to +28	-10 to +10	-4 to +10
Nelson	Nelson	-16 to +1	-10 to +4	-3 to +15	-11 to +4	-7 to +2
Marlborough	Blenheim	-8 to +4	-9 to +3	-5 to +15	-12 to +4	-5 to +3
West Coast	Hokitika	-10 to +9	-4 to +12	-9 to +41	-12 to +12	-4 to +14
Canterbury	Christchurch	-6 to +8	-20 to -1	-12 to +10	-11 to +4	-10 to +1
	Hamner	-16 to +5	-9 to +1	-15 to +11	-11 to +4	-12 to +3
	Tekapo	-9 to +8	-4 to +8	-6 to +35	-10 to +17	-3 to +13
Otago	Dunedin	-7 to +8	-2 to +3	-7 to +15	-4 to +11	-2 to +6
	Queenstown	-14 to +11	-3 to +18	-12 to +59	-11 to +23	-4 to +22
Southland	Invercargill	-9 to +10	-2 to +18	-12 to +28	-9 to +18	-2 to +15

Note: For 1990 to 2020–2049 (the 2030s), scaled to the full IPCC range of global warming. Corresponding maps (Figures 2.5, A3.6 and A3.7) should be used to clarify sub-regional spatial gradients.

Source: Ministry for the Environment and New Zealand Climate Change Office, 2004, Table 2.4.

Since floods can occur at any time of the year the annual data provide a better indication of potential changes than the seasonal estimates. The lowest and highest projection patterns show a strong southwest to northeast gradient. Rainfall changes in the southwest of the country vary from no change (or a slight decrease) to a large increase in the annual mean. North-eastern areas vary from a large decrease to no change. There is a lot of variability between models, and for many locations even the sign of the rainfall change cannot be stated with any confidence.

Since a warmer atmosphere can hold more moisture (about 8% more for every 1℃ increase in temperature) the potential exists for heavier extreme rainfalls. The IPCC in its third assessment declared that more intense rainfall events are *"very likely over many areas"*. However, information available for deciding in which areas of New Zealand this might apply is limited.

The likely effects of increases of temperature and westerly wind speed on rain falling over New Zealands' mountains have also been modelled. It has been suggested that a 2°C change in temperature could lead to a 6-7% increase in both maximum, and catchment-averaged, rainfall. Similar increases were predicted for a 10% increase in wind speed. Increasing both wind speed and temperature together may lead to a 16% increase in rainfall (Ministry for the Environment, 2004).

4.3 The impact of climate change on Lake Taupo levels

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

- The fact that the level of the lake is controlled largely for hydropower purposes; and
- The Ministry for the Environment's climate change guidelines only estimate the amount of warming, and consequently the potential increase in rainfall. They do not predict changes in streamflow or lake levels (Ministry for the Environment, 2004). This is a significant gap in the 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 Taupo catchment; which should smooth any more subtle changes, and the buffering effect of the lake on inflows and outflows.

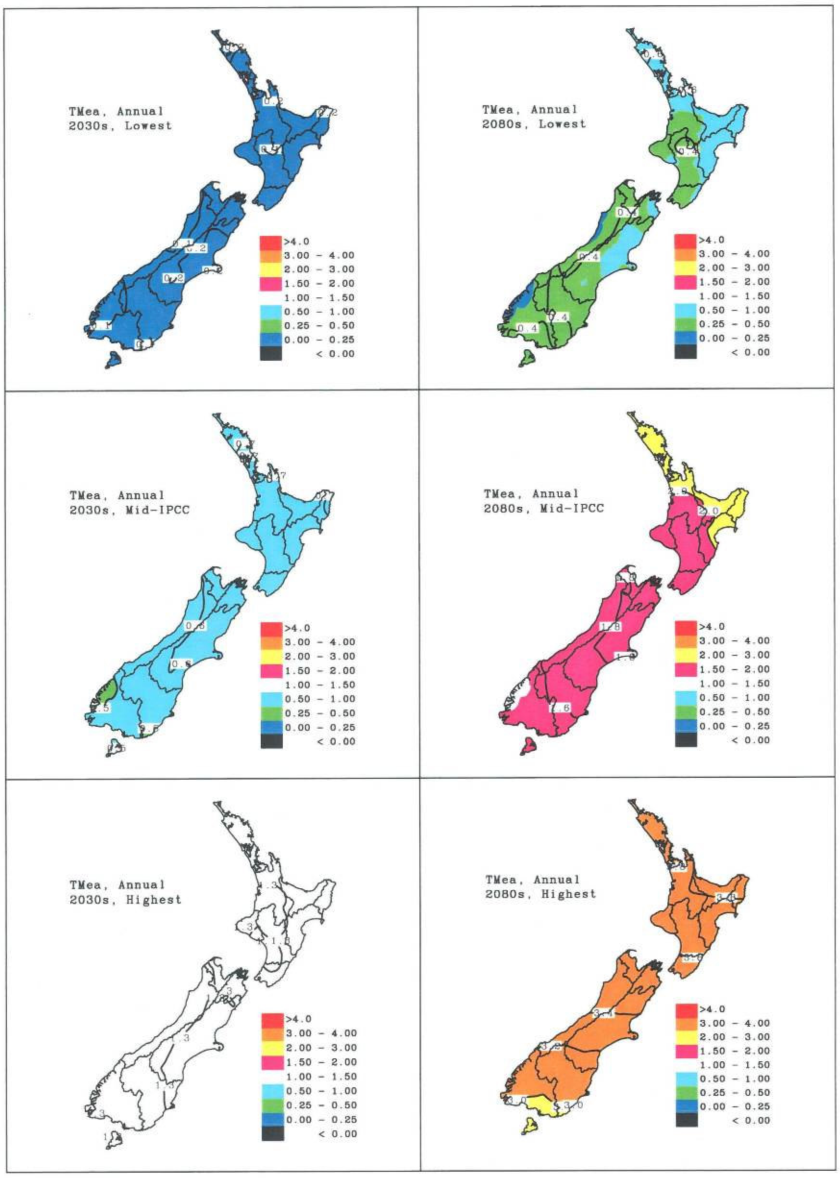
The operators of the Lake Taupo Gates are required to maintain the level between the operating minimum of 355.85 m and an operating maximum of 357.25 m. The maximum outflow of the Lake Taupo Gates and channel is approximately 310 m^3/s. Therefore, as long as inflows are less than this maximum outflow 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 greater than 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 (1980-2007) and projected climate change to the 2030s and the 2080s.

4.3.1 Methodology

A methodology has been developed for determining the projected increase in rainfall as a result of climate change in New Zealand (Ministry for the Environment, 2004). The projected increase in mean temperature by the 2030s and 2080s, based on 1990 levels, were presented in Tables 4.2 & 4.3. Projected changes to seasonal and annual precipitation by 2030 were in Table 4.4.

The mean annual temperature for the Lake Taupo catchment has been estimated to increase by between 0.1 and 1.3℃ by 2030s and 0.4 and 3.6℃ in 2080s (Figure 4.1).



Note: For 2020–2049 (2030s) and 2070–2099 (2080s), scaled to 'lowest', 'mid-IPCC' and 'highest' cases, as described in the text. Contours are every 0.1°C for 2030s and every 0.2°C for 2080s.

Figure 4.1 Projections for increases in temperature using three scenarios for 2030 and 2080 (Figure 2.2, Ministry for the Environment, 2004).

Data from Figure 4.1 is summarised in Table 4.5.

Table 4.5 Projected increases in mean annual temperature for the Lake Taupo catchment using three IPCC scenarios by the 2030s and 2080s.

Scenario	2030s (°C)	2080s(°C)
Lowest IPCC	0.1	0.4
Mid IPCC	0.6	1.8
Highest IPCC	1.3	3.6

The methodology recommends percentage adjustments per degree of warming that should be applied to the high intensity rainfall totals to account for the effect of global warming (Table 4.6). For example, a 48-hour duration 100 year return period rainfall will increase by 5.5 percent per degree of projected warming (highlighted in Table 4.6).

Table 4.6 Percentage increase in rainfall per degree of temperature for different rainfall durations.

	ARI (years)										
Duration	**2**	**5**	**10**	**20**	**30**	**50**	**60**	**70**	**80**	**90**	**100**
< 10 mins	8.0	8.0	8.0	8.0	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	8.0	8.0	8.0	8.0
20 mins	7.6	7.7	7.7	7.7	7.8	7.8	7.8	7.8	7.8	7.8	7.8
30 mins	7.4	7.5	7.6	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7
1 hr	7.1	7.2	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5
2 hr	6.7	7.0	7.1	7.2	7.3	7.3	7.3	7.3	7.4	7.4	7.4
3 hr	6.5	6.8	7.0	7.1	7.1	7.2	7.2	7.2	7.2	7.2	7.2
6 hr	6.3	6.6	6.8	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1
12 hr	5.8	6.2	6.5	6.6	6.7	6.8	6.8	6.8	6.9	6.9	6.9
24 hr	5.4	5.9	6.2	6.4	6.5	6.6	6.6	6.6	6.7	6.7	6.7
48 hr	4.6	4.9	5.1	5.2	5.3	5.4	5.4	5.4	5.4	5.5	**5.5**
72 hr	4.3	4.6	4.8	5.0	5.1	5.2	5.2	5.2	5.3	5.3	5.3

Source: Table 5.2, Ministry for the Environment, 2004.

Longer storm durations pose a greater flood risk to Lake Taupo because of the size of the catchment. Therefore, rainfall durations greater than 24-hours are those that are likely to have the greatest effect on flood levels. Since the percentage increase in rainfall decreases with increasing storm duration, and to take a conservative approach to flood risk, a storm duration of 48 hours was used in this analysis.

Assuming mean temperature increases of between 0.1°C and 1.3°C and 0.4°C and 3.6°C for the respective scenarios, the 100-year return period rainfall will increase by a maximum of approximately 7.2% for the 2030s and 19.8% for the 2080s (Table 4.7). This is based on the Highest IPCC scenario. The percentage increase will vary depending on the actual temperature increase, storm magnitude and storm duration.

Table 4.7 Estimated percentage increase in 48-hour rainfall totals for Lake Taupo as a result of global warming.

Return period	2030s			2080s		
	Lowest IPCC (0.1°)	Mid IPCC (0.6°)	Highest IPCC (1.3°)	Lowest IPCC (0.4°)	Mid IPCC (1.8°)	Highest IPCC (3.6°)
2.3	0.46	2.76	5.98	1.84	8.28	16.56
5	0.49	2.94	6.37	1.96	8.82	17.64
10	0.51	3.06	6.63	2.04	9.18	18.36
20	0.52	3.12	6.76	2.08	9.36	18.72
50	0.54	3.24	7.02	2.16	9.72	19.44
100	0.55	3.30	**7.15**	2.20	9.90	**19.80**

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

4.3.2 Relating increases in rainfall to runoff and lake levels

As mentioned, there is currently no 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 4.7 have been translated directly to percentage increases in flow.

4.4 Rises in lake level when inflows exceed maximum outflow

Daily average inflows between 1980 and 2007 were analysed to identify all occasions when inflows exceeded the maximum possible lake outflow (310 m^3/s). Theoretically, these are periods when lake levels would be expected to rise if there was no control of the Taupo Gates (Figure 4.2). 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.

During this period average daily inflows exceeded the maximum average daily capacity outflow on 307 occasions (Figure 4.3). While the majority of these synthesised flood events produce only minor increases in lake level, less than about 50mm, the July 1998 flood would have caused the lake to rise by approximately 375 mm. This assumes that the Taupo Gates were discharging at maximum capacity (310 m^3/s), and that no regulation or flood management actions were taken. If the Taupo Gates were shut, discharging a maximum of 30 m^3/s, the lake level would rise an additional 39 mm each day.

The longest consecutive period over which inflows exceeded the maximum outflow capacity was 9 days, during the 1998 flood. The maximum daily increase in lake level was 51mm (Figure 4.4).

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

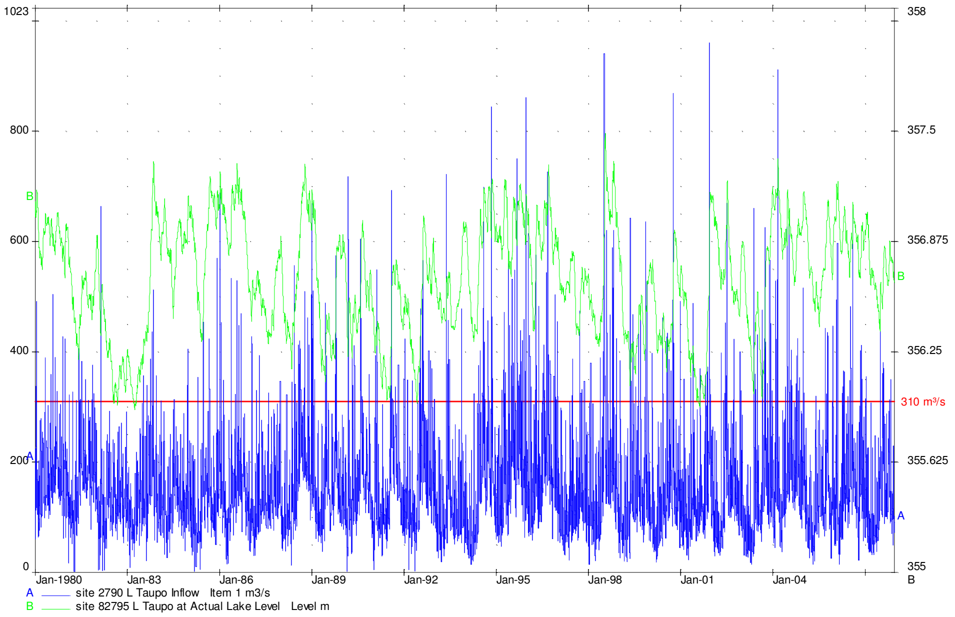


Figure 4.2 Periods when inflows exceed the maximum outflow capacity of the Taupo Gates and the resulting 'theoretical' change in lake level (1980-2007).

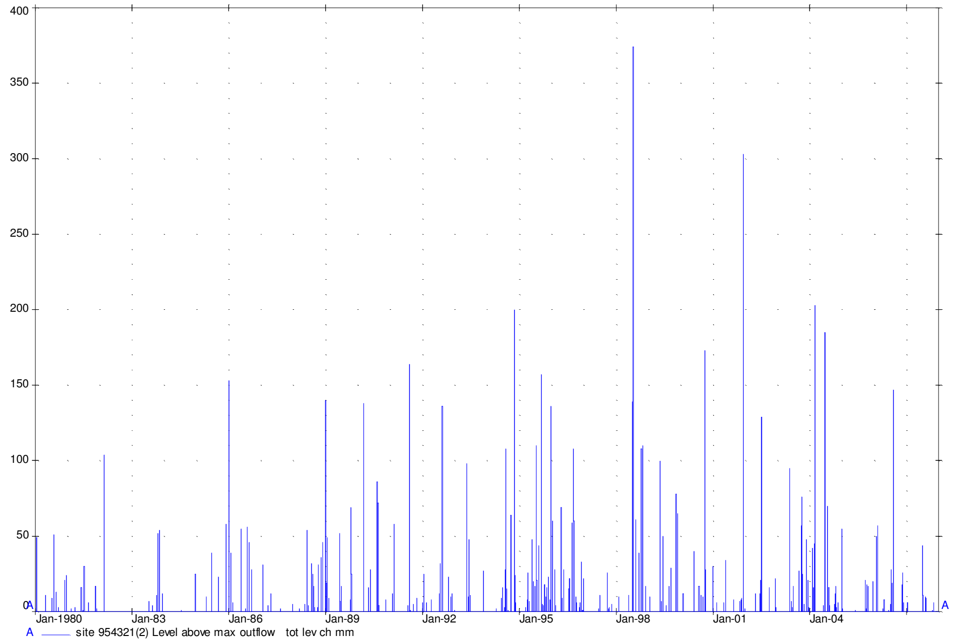


Figure 4.3 'Theoretical' increase in lake level for 'flood' events as a result of inflows exceeding the maximum outflow capacity of the Taupo Gates (1980-2007).

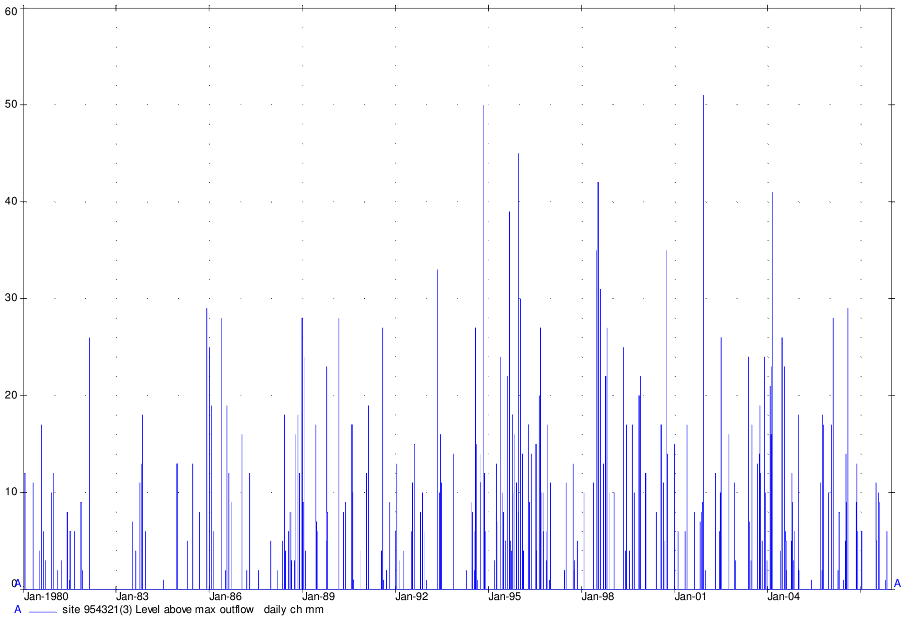


Figure 4.4 Daily increase in lake level for 'theoretical' flood events as a result of inflows exceeding the maximum outflow capacity of the Taupo Gates (1980-2007).

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 4.5, 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.

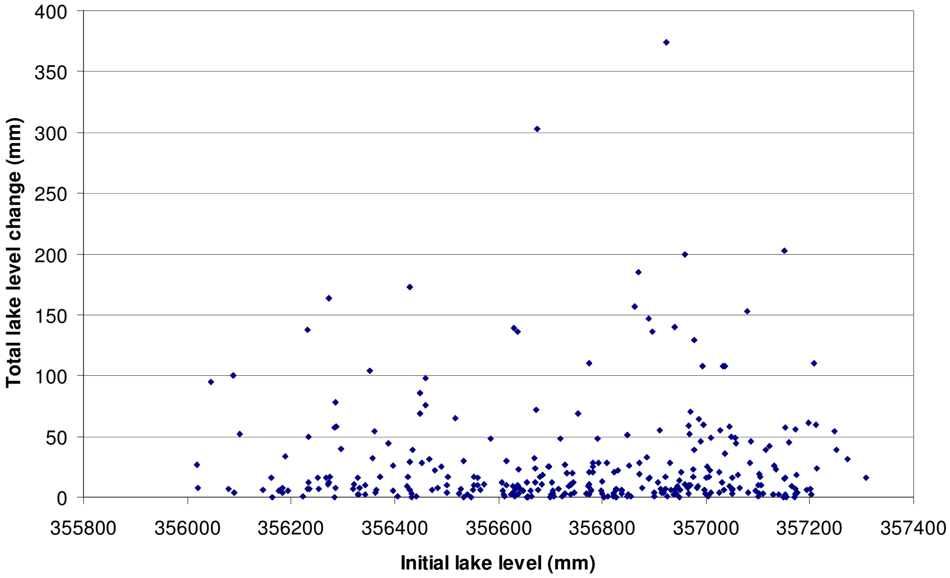


Figure 4.5 Total increase in lake level for specific inflow events is independent of the lake level at the onset of the event.

4.5 Global warming effects on inflows exceeding outflows

Assuming that the lake level inflow regime between 1980 and 2007 is typical of that into the future, the effects of global warming can be simulated by increasing all inflows by the percentage indicated earlier i.e., 7.2% for 2030 and 19.8% for 2080 for the high IPCC scenario. Having increased the inflows to reflect the effect of global warming the above analysis of lake levels caused by inflows exceeding 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 (Figures 4.6 & 4.7). The 2080 climate change scenario did result in two events when theoretical inflows would exceed outflows continuously for 13 days. However, each of these events would potentially cause a total increase in lake level of less than 300mm. In comparison, the climate change adjusted 1998 flood event would cause a lake level change of 525mm over 9 days. Again, this assumes that the Taupo Gates are fully open. If they were shut to restrict flow to 30 m^3/s then Lake Taupo would rise an additional 39 mm/day.

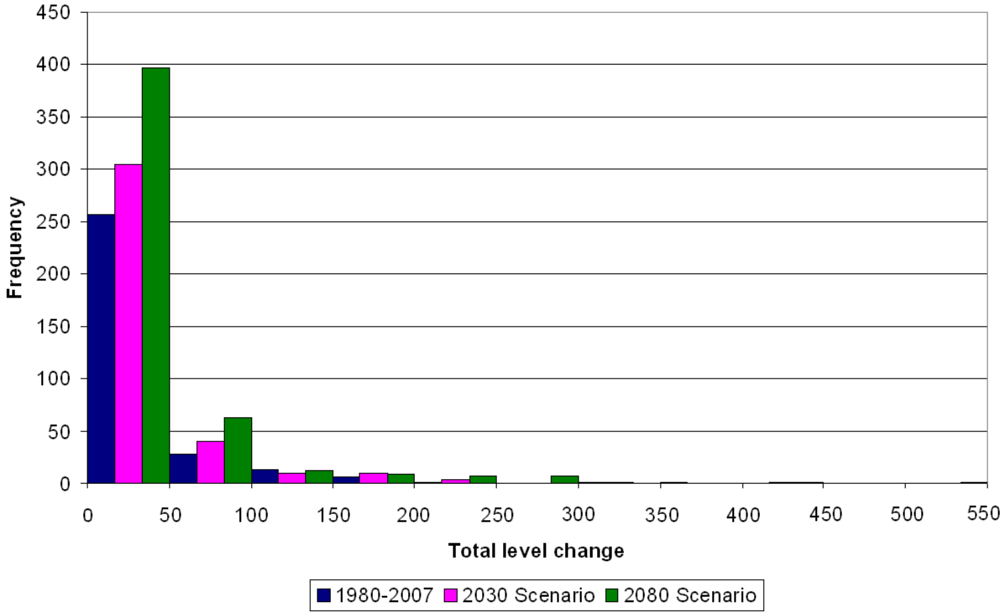


Figure 4.6 Frequency distribution of total change in lake level under three inflow regimes i.e., present, 2030s, and 2080s.

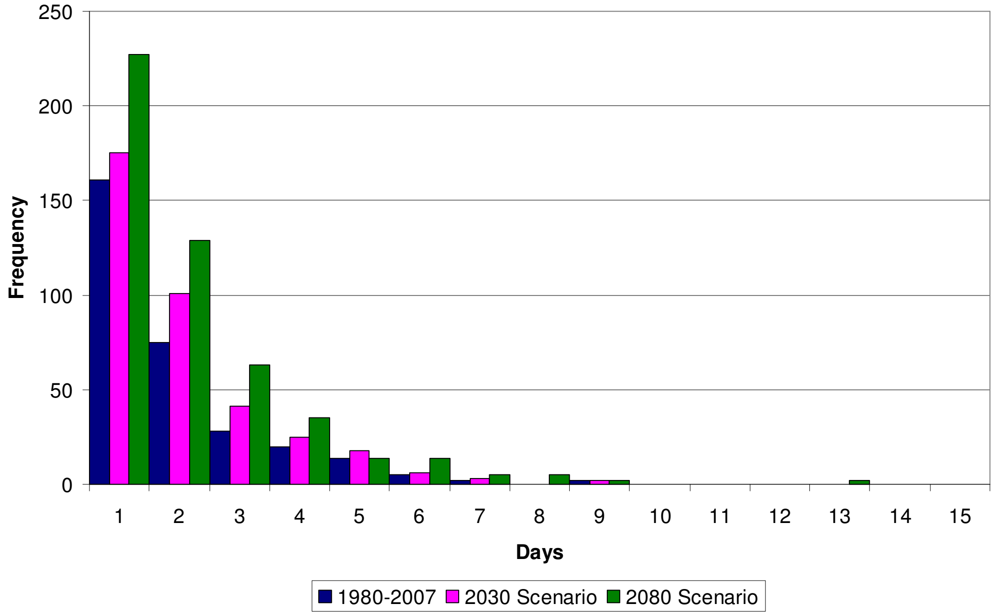


Figure 4.7 Frequency distribution of the duration of inflow events under three inflow regimes i.e., present, 2030s, and 2080s.

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., 1980-2007, 2030s, and 2080s). The results of these analyses are presented in Figure 4.8.

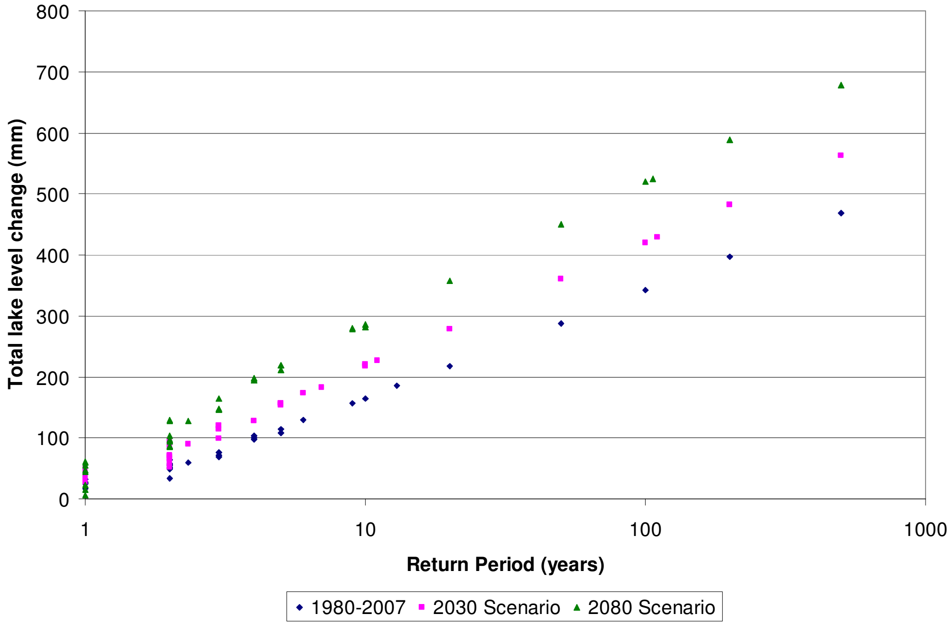


Figure 4.8 Magnitude of the increases in lake level caused by inflow events under three inflow regimes i.e., present, 2030s, and 2080s for different return periods.

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 4.8.

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

Return period	1980-2007 (mm)	2030s (mm)	2080s(mm)
2.33	60	89	127
5	114	157	212
10	165	218	286
20	217	279	357
50	288	360	450
100	342	420	520
200	397	482	588
500	469	563	679

Note: While these return periods extend out to 500 years the climate change effect on rainfall, on which they are based, is limited to 90 years.

4.6 Potential impact of global warming on lake levels during specific flood events

Two specific flood scenarios were used to evaluate the potential impact of climate change on the level of Lake Taupo. The 2030s and 2080s percentage increase in runoff (7.2% and 19.8% respectively) were applied to the 1998 and 2004 flood flows. Table 4.9 and 4.10 detail the recorded flood events, the climate change adjusted flows, and the rise in lake levels assuming that the maximum flow through the Taupo Gates is 310 m^3/s.

The actual lake level record shows that the 1998 flood resulted in the highest lake level since 1957. The lake rose from approximately 356.89 m to 357.49, an increase of 0.6 m. The 2004 flood recorded a maximum lake level of 357.35 m. This rose from approximately 357.131, an increase of 0.22 m.

Table 4.9 Impact of climate change on the 1998 flood.

1998 Flood	1998	Climate Change 2030s (7.2%)	Climate Change 2080s (19.8%)
Change in lake level (mm)	374	429	525
Average daily change in lake level (mm/day)	42	48	58
Days above maximum outflow (310 m^3/s)	9	9	9

Table 4.10 Impact of climate change on the 2004 flood.

2004 Flood	2004	Climate Change 2030s (7.2%)	Climate Change 2080s (19.8%)
Change in lake level (mm)	203	233	286
Average daily change in lake level (mm/day)	41	47	57
Days above maximum outflow (310 m^3/s)	5	5	5

For the modelled 1998 flood event the increases in inflow equate to an additional 55 mm and 151 mm rise in lake level for the 2030s and 2080s climate change scenarios, respectively. For the 2004 flood the increases equate to 6 mm and 16 mm. The duration of each event remains the same under both scenarios; 9 days for the 1998 event and 5 days for the 2004 event.

The assumption in the above analyses is that the Taupo Gates remained fully open during the each event. This did occur in 2004 and the actual rise in lake level was 217 mm (compared with 203 mm predicted above). During 1998, however, the Gates were shut on several occasions; either to store inflows, or under the provisions of the High Flow Management Plan and Flood Rules (Figure 4.9). The difference between having the Taupo Gates open or closed for the duration of the 1998 flood changes the potential rise in lake level from 374 mm to 728 mm (the actual rise recorded was 600 mm which is consistent).

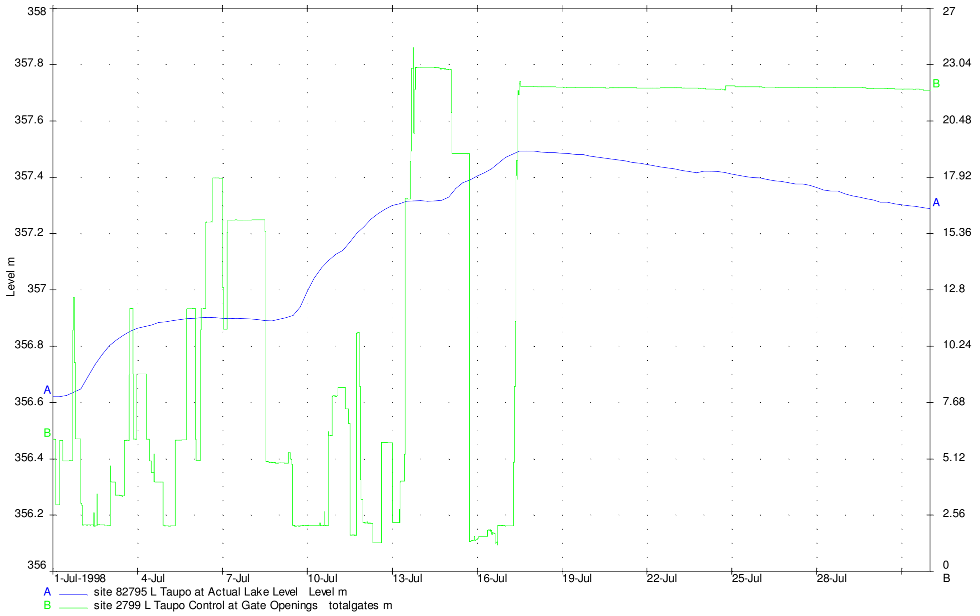


Figure 4.9 Lake Taupo levels and Gate operation during the 1998 flood event.

The position of the Taupo 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.

4.7 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 4.11, the projected increase in lake level caused by global warming on a 100-year event by the 2080s would be 178mm. The values in Table 4.11 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 4.11 Projected changes increases in total lake level as a result of global warming on inflows.

Return period	2030s (mm)	2080s(mm)
2.33	29	67
5	43	98
10	53	121
20	62	140
50	72	162
100	78	178
200	85	191
500	94	210

5 Tectonics

5.1 Introduction

The risk of flooding and inundation around Lake Taupo is not a simple function of the amount of water in the lake. This is because the Lake Taupo 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 5.1a&b). This relative movement of the land has the potential to have a significant effect on the flood risk and depth of inundation.

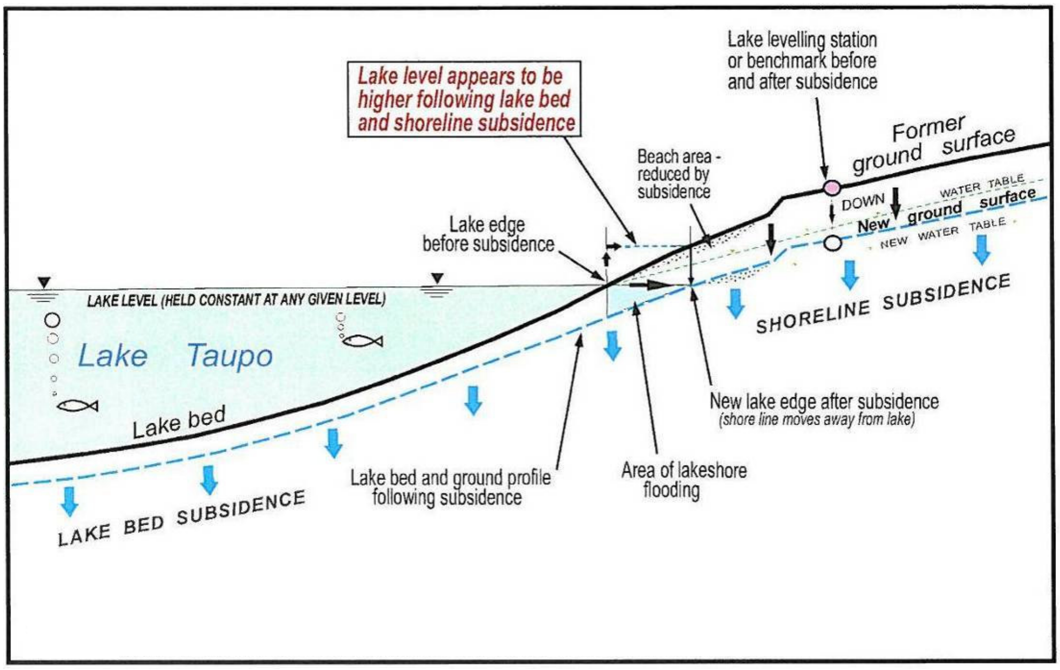


Figure 5.1a Effect of ground level subsidence on relative lake levels (Hancox, 2002).

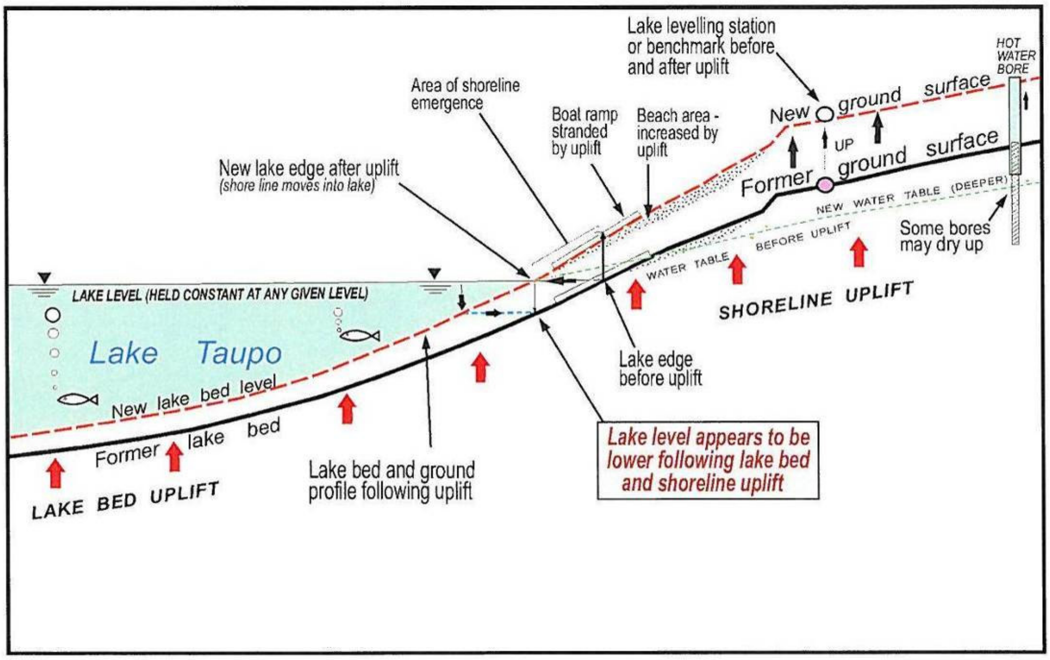


Figure 5.1b Effect of ground level uplift on relative lake levels (Hancox, 2002).

5.2 Tectonic situation

The triangle formed by Moturiki Island, Mt Ruapehu and White Island forms the Taupo 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 Taupo Volcanic Zone encompasses the three active volcanoes of Mts Ruapehu, Ngauruhoe and Tongariro, as well as Lake Taupo. The zone is approximately 50 km wide and 300 km long.

The combination of volcanism and faulting in the Taupo 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 Taupo Fault Belt (Figure 5.2)

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

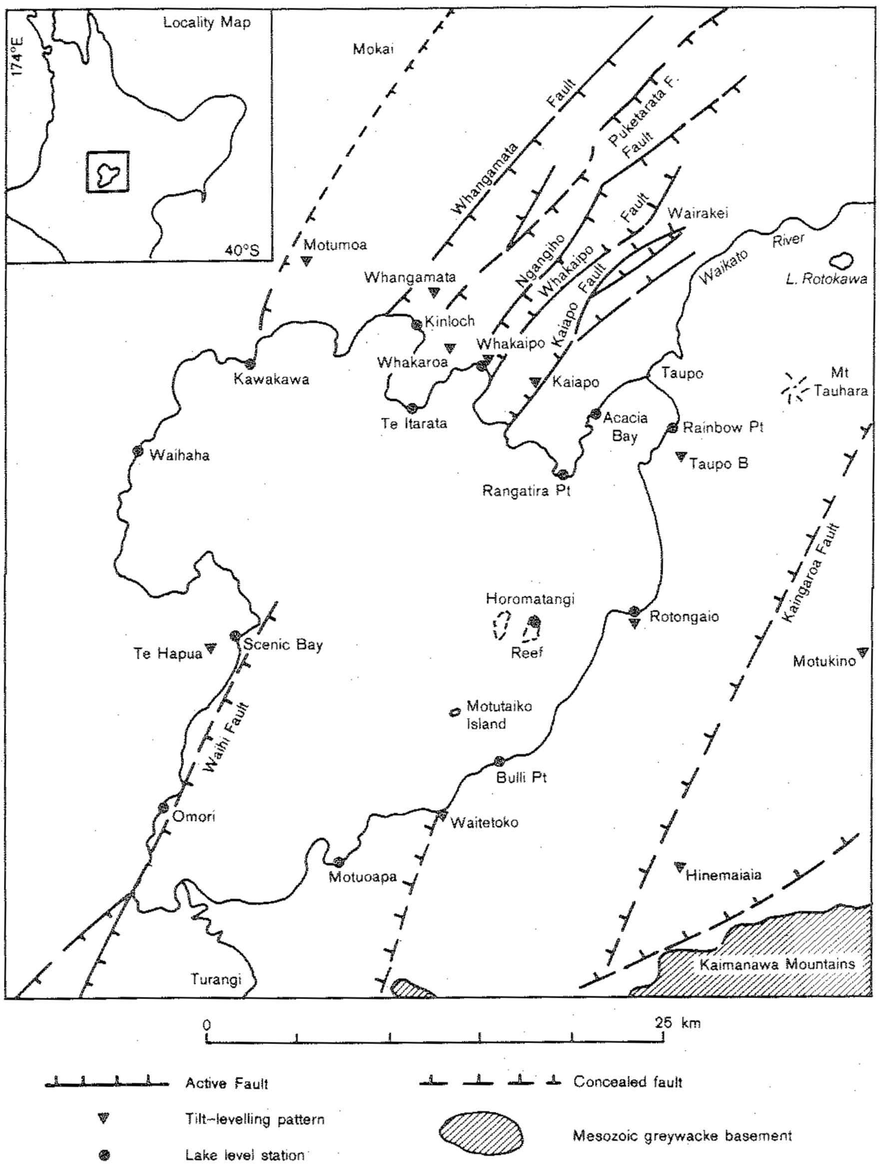


Figure 5.2 Tectonic setting, Lake Taupo (Otway, 1986).

5.3 Movement around Lake Taupo

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

5.3.1 Long term deformation

The Taupo eruption in 181 AD expelled ~35 km^3 of ash and pumiceous pyroclastic material, depositing the Taupo Pumice Ignimbrite over an area of about 20,000 km^2. After the eruption Lake Taupo refilled to ~34 m above its present level. Sediment erosion and deposition while the lake was at this level created a distinctive high alluvial terrace. This now forms a prominent geomorphic feature around the shoreline of Lake Taupo.

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 5.3). Terrace surveying indicates a long term differential deformation rate of 6-9 mm/yr. Maximum uplift of ~7-9 m (4-5 mm/yr) has occurred across the centre and northeastern end of Lake Taupo 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 1.8-3.6 m in the last 1800 years, with up to 2.3 mm/yr of subsidence near Turangi. A pattern of long term subsidence is also evident at the southern end of Western Bay (down 3.6 m in the last 1800 years) and at Kinloch (down 0.54 m in 1800 years (Otway *et al.*, 2002; Hancox, 2002).

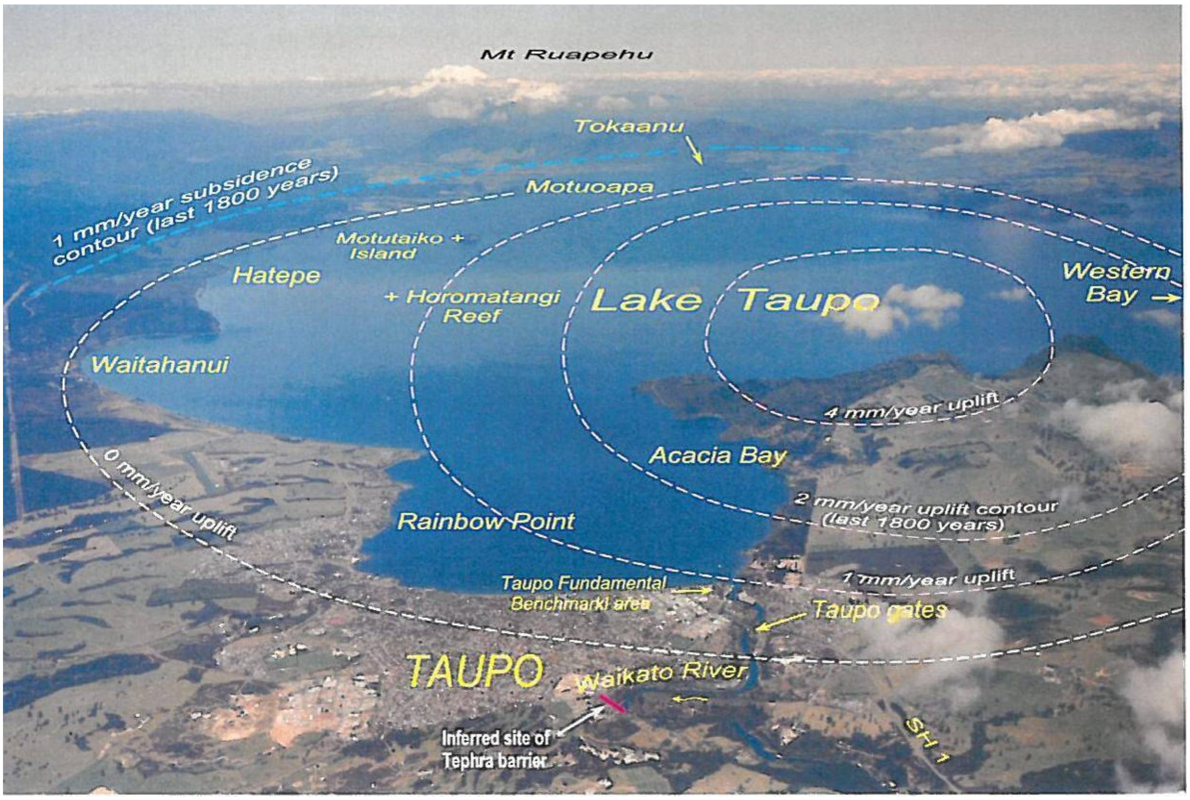


Figure 5.3 Long-term vertical ground deformation since 181 AD (Hancox, 2002).

5.3.2 Short term deformation

Recent studies have documented current movement patterns around the lake, with particular focus on the deformation that has occurred in 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 6-9 mm/yr (Figure 5.4). However, this is an average rate, and as might be expected, there are differences as to what areas went up and down, when, and by now much (Hancox, 2002).

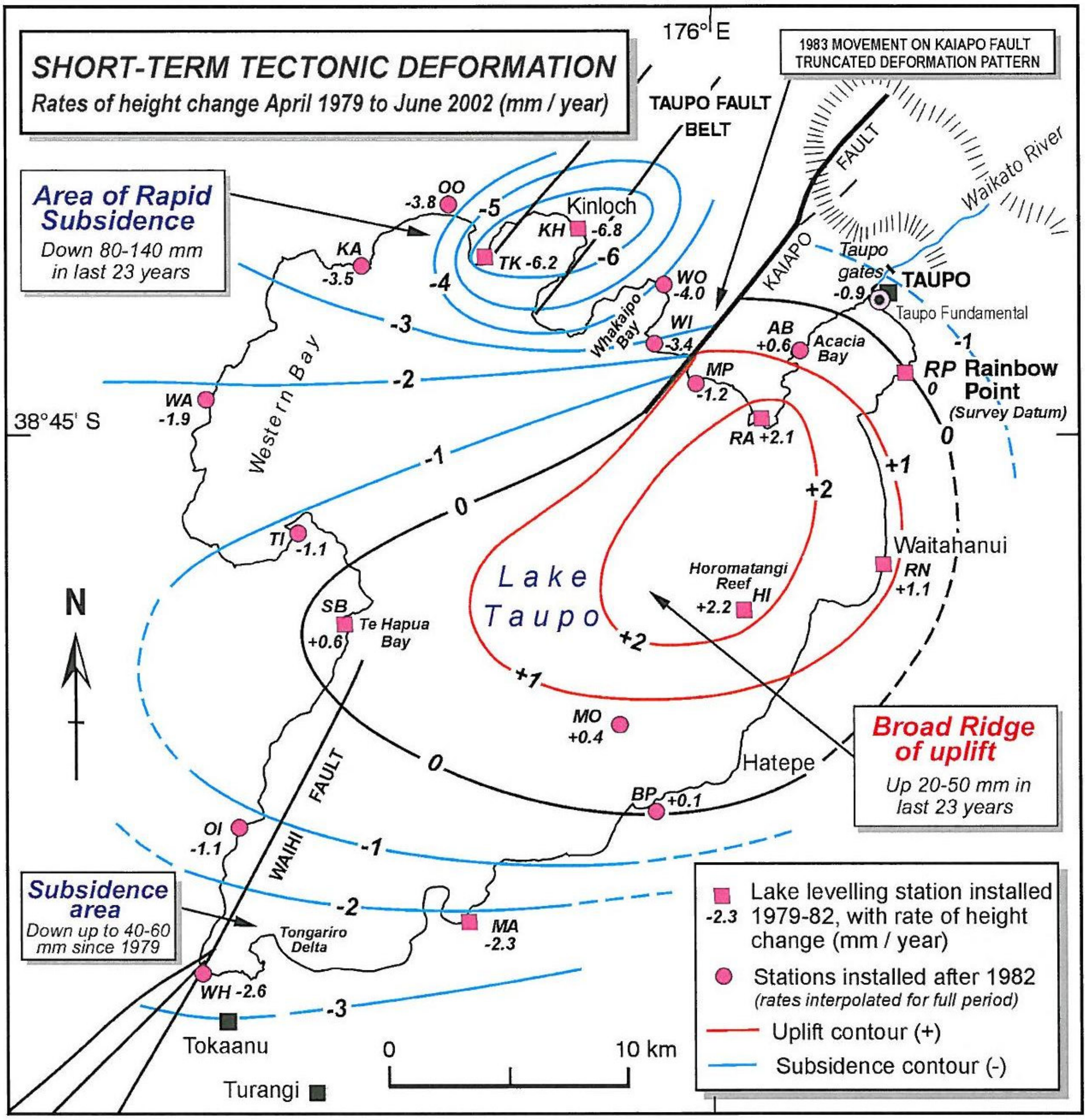


Figure 5.4 Tectonic deformation between 1979 and 2002 (Hancox, 2002).

Maximum uplift is occurring at the northeastern end of Lake Taupo, forming a broad ridge of uplift of up to ~ 1-2 mm/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 70 mm) while the Acacia Bay, Te Hapua Bay, and Waitahanui areas rose about half of this amount (Hancox, 2002).

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

Over the last ~80 years tectonic deformation at Lake Taupo 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 (occurring without obvious earthquake activity) (Hancox, 2002). This component of deformation is reasonably predictable.

5.3.3 Local subsidence and uplift

Localised uplift and subsidence has also been recorded around Lake Taupo, often in association with specific seismic events. For example, Whakaipo Bay subsided 3-4 m as a result of the 1922 earthquake swarm. Subsidence appears to have affected the entire headland between Whakaipo and Whangamata Bays. This subsidence does not show up in the surveys of the post-Taupo eruption lake terrace, however, 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 Taupo 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.

5.4 Overall pattern of deformation

The recent pattern of deformation, including both uplift and subsidence, for various places around Lake Taupo is summarised in Table 5.1. The short term deformation rate is similar to the long term rate, however, there are differences as to what areas went up and down, when, and by now much (Hancox, 2002). This variation in the rates of deformation is to be expected when comparing 'averages' taken over significantly different time periods, and when movement may be episodic.

Table 5.1 Average ground deformation rates (mm/yr) (Hancox, 2002).

Site	1979-2002
Kinloch	-6.8
Whakaipo	-4.0
Kaiapo	-1.2
Rangatira Point	+2.1
Acacia Bay	+0.6
Rainbow Point	0.0
Horomatangi Reef	+2.2
Rotongaio	+1.1
Bulli Point	+0.1
Motuoapa	-2.3
Waihi	-2.6
Scenic Bay	+0.6
Waihaha	-1.9
Kawakawa	-3.5

Note: Data have been adjusted to show movement relative to Rainbow Point.

5.5 Summary and recommendation

The above review shows near-continuous deformation around Lake Taupo. This 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 compaction 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.

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.

Table 5.2 lists the deformation rates for particular locations around Lake Taupo. The total amount of movement over particular time periods is also shown. For the purpose of establishing a flood level it is suggested that the 100-year values are most appropriate. These data were then used to create a deformation model of the Lake Taupo area (Figure 5.5). This model allows the effect of deformation on static water levels to be predicted for any position around the entire lake shore, and over any time period.

Table 5.2 Tectonic deformation (mm) over various time periods.

Time Period	Kinloch	Whakaipo	Kaiapo	Rangatira Point	Acacia Bay	Rainbow Point	Horomatangi Reef	Rotongaio	Bulli Point	Motuoapa	Waihi	Scenic Bay	Waihaha	Kawakawa
mm/yr	-6.8	-4.0	-1.2	2.1	0.6	0.0	2.2	1.1	0.1	-2.3	-2.6	0.6	-1.9	-3.5
2.33	-9	-9	-3	5	1	0	5	3	0	-5	-6	1	-4	-8
5	-34	-20	-6	11	3	0	11	6	1	-12	-13	3	-10	-18
10	-68	-40	-12	21	6	0	22	11	1	-23	-26	6	-19	-35
20	-136	-80	-24	42	12	0	44	22	2	-46	-52	12	-38	-70
50	-340	-200	-60	105	30	0	110	55	5	-115	-130	30	-95	-175
100	-680	-400	-120	210	60	0	220	110	10	-230	-260	60	-190	-350
200	-1360	-800	-240	420	120	0	440	220	20	-460	-520	120	-380	-700
500	-3400	-2000	-600	1050	300	0	1100	550	50	-1150	-1300	300	-950	-1750

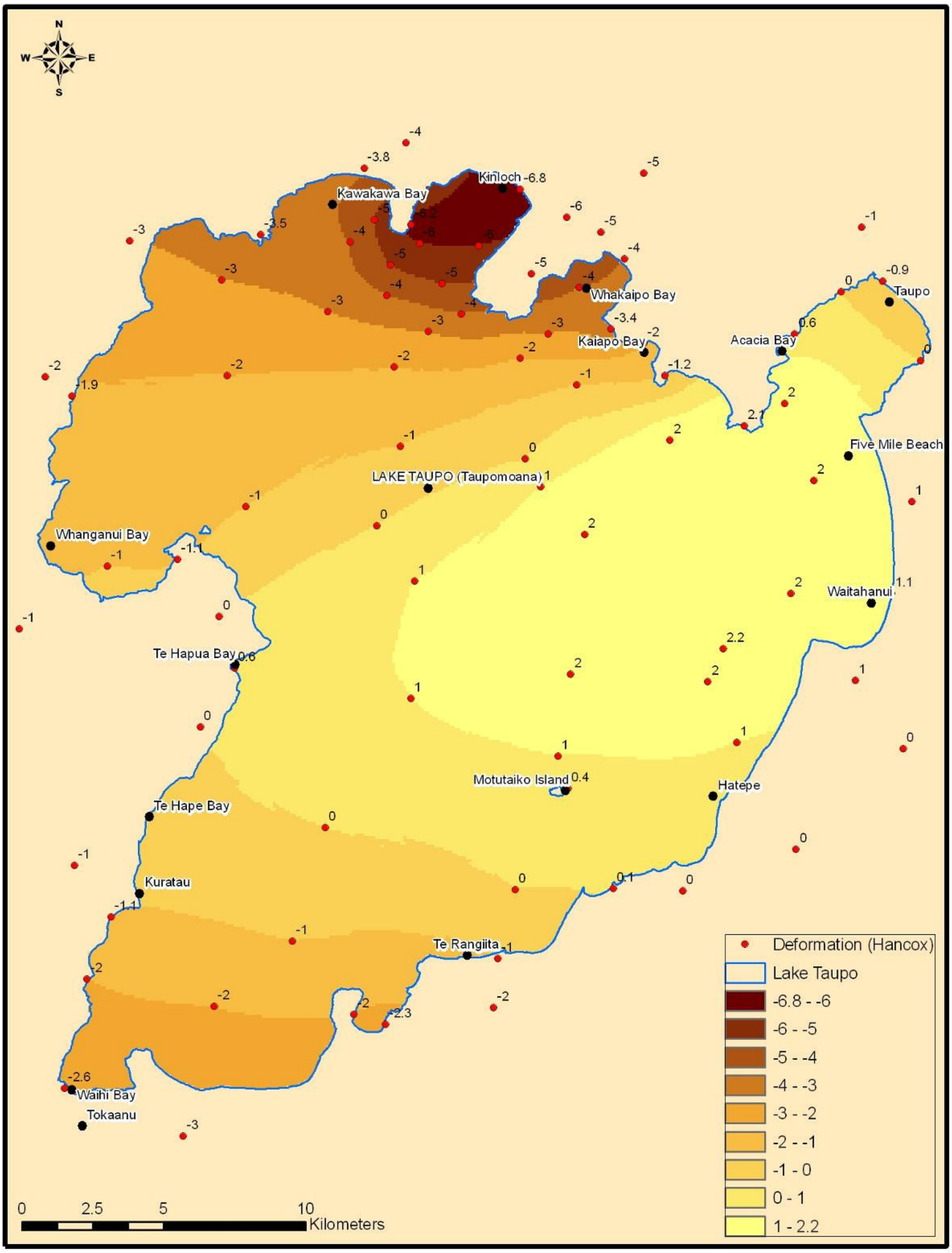


Figure 5.5 Average rates (mm/yr) of tectonic deformation between 1979 and 2002 (After Hancox, 2002).

6 Seiching

6.1 Background

Lakes such as Taupo 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 Taupo 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 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 Taupo. 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 100 m for Lake Taupo, the maximum expected wind setup caused by a 10 m/s wind along the long-axis of the lake would be approximately 4 mm and for a 21 m/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% exceedence run-up at Taupo foreshore for 10 and 20 m/s winds are 1.3 m and 2.7 m 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 of pressure difference causes an elevation difference of 10 mm. This is known as the inverted barometer effect. For data that are available, the maximum pressure difference across the lake is 6.7 hPa. This indicates a difference in levels of about 26 mm; equivalent to a 13 mm decrease at one end of the lake and a 13 mm increase at the other (Hicks *et al.,* 2000)

6.2 The measured seiche effect

Lake levels are measured at both Acacia Bay and Tokaanu; with the data being recorded every 5 minutes (Figures 6.1 & 6.2). Since the seiche period in Lake Taupo 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 trimmed from those data and they must be added back to determine the actual water level.

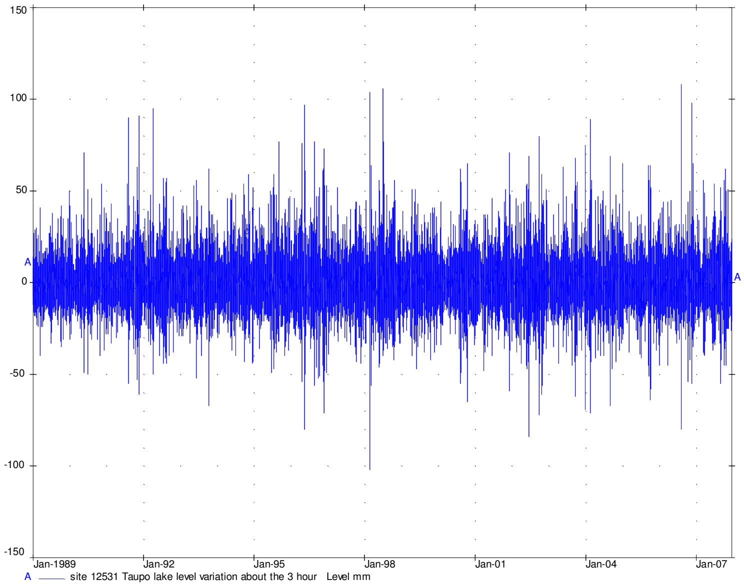


Figure 6.1 The seiche effect in the 5-minute lake level data at Acacia Bay.

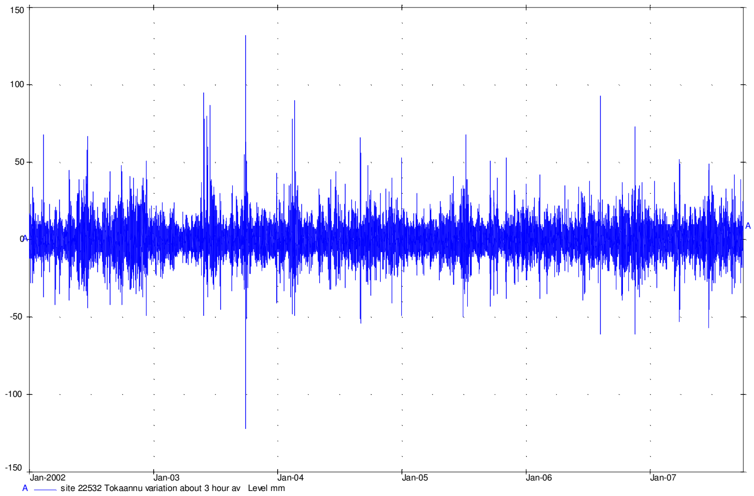


Figure 6.2 The seiche effect in the 5-minute lake level data at Tokaanu.

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 ±100 mm). 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 Taupo 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 6.3). A PE3 distribution fits the annual maximum seiche series best, although the seiche amplitude appears to become constant at 110 mm 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 Taupo.

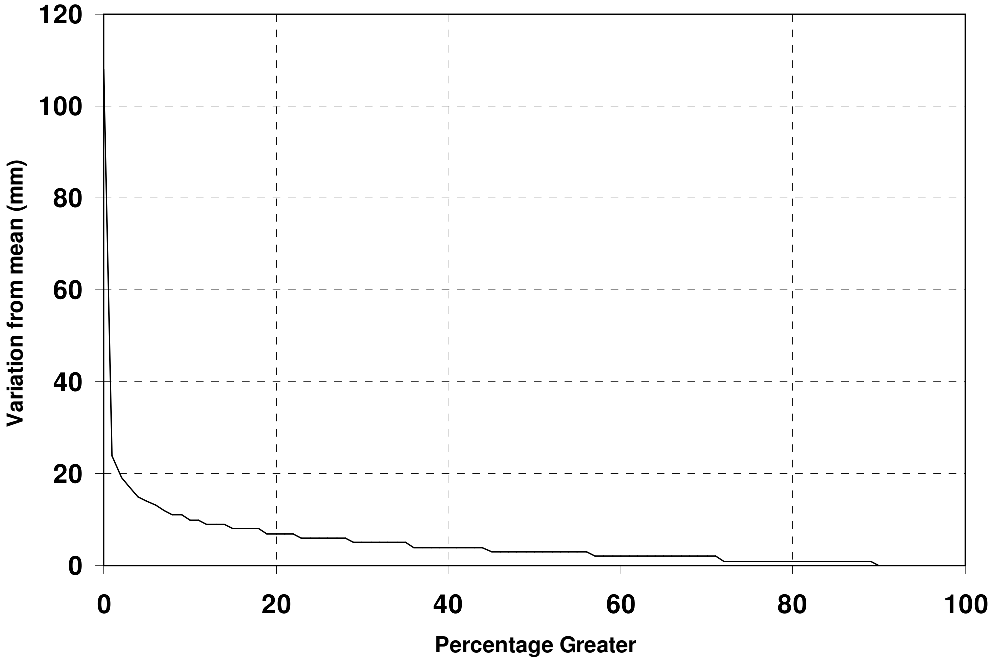


Figure 6.3 Distribution of the magnitude of the seiche effect above the 3-hourly static lake level at Acacia Bay (1989-2007).

6.3 Seismic-induced seiching

The location of Lake Taupo within the Taupo Volcanic Zone means that there is 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, they have 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.

6.4 Summary and recommendation

The seiche effect must be added to the 3-hourly static lake level data so as to more accurately reflect the elevation of the effective water surface. The magnitude of the seiche effect for different return periods (Table 6.1) must added to the lake level to indicate the potential static water level.

Table 6.1 Expected magnitude of the seiche effect.

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

7 Static Water Level

7.1 Summary

The general flood risk and depth of inundation for the land surrounding Lake Taupo are primarily controlled by the static water level in the lake. The static water level is a function of the 3-hourly lake level and the seiche; which must be added as it is removed when processing the 3-hourly lake level data. Over time it is likely that global warming and climate change will 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 Tables 3.6, 4.11, and 6.1 (Table 7.1). 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 Figure 5.5.

Table 7.1 Expected static water level for different return period events excluding deformation.

Return Period	Lake Level (m)	Climate Change 2080s (m)	Seiche Effect (m)	STATIC WATER LEVEL
2.33	357.17	0.07	0.08	357.32
5	357.29	0.10	0.09	357.48
10	357.35	0.12	0.10	357.57
20	357.41	0.14	0.11	357.66
50	357.47	0.16	0.11	357.74
100	357.50	0.18	0.11	357.79
200	357.53	0.19	0.11	357.83
500	357.57	0.21	0.11	357.89

8 Wind Waves

8.1 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. Airflows at Lake Taupo are topographically channelled so that waves are likely to be steeper near the two ends of the lake as a result of the longer fetch lengths.

As a wave breaks on 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 a porous media), vegetation, porosity (the percentage of the total volume of rock or soil that consists of open spaces), roughness, and wave reflection. Figure 8.1 highlights the difference between wave height and wave run-up.

8.2 Wind across Lake Taupo

The prevailing wind across Lake Taupo is 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 the fetch is the limiting factor in defining a wave, the areas most vulnerable to wave run-up are the northern and eastern shores (Figure 8.2). The southern end of the lake is generally sheltered from the dominant wind direction, as are enclosed areas such as Acacia Bay.

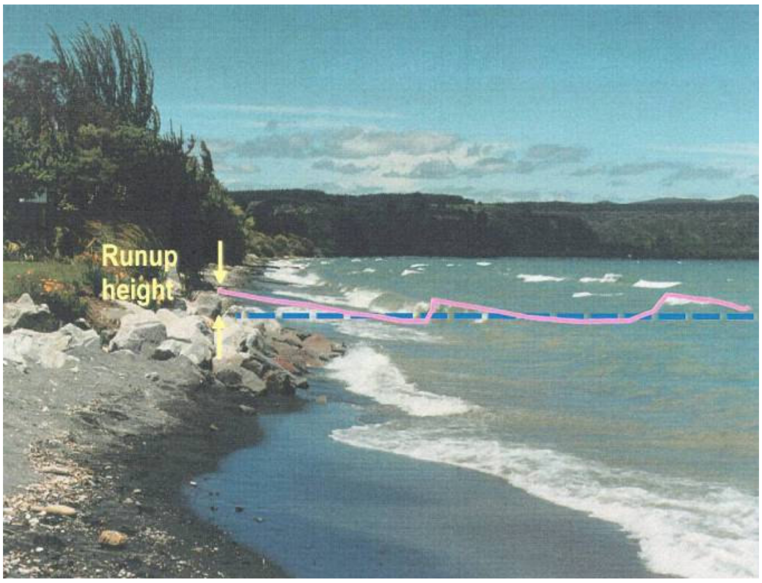


Figure 8.1 **Waves running up the beach at Waitahanui. Blue dashed line shows still lake level, pink line shows wave run-up caused by wind (Hicks *et al.,* 2002).**

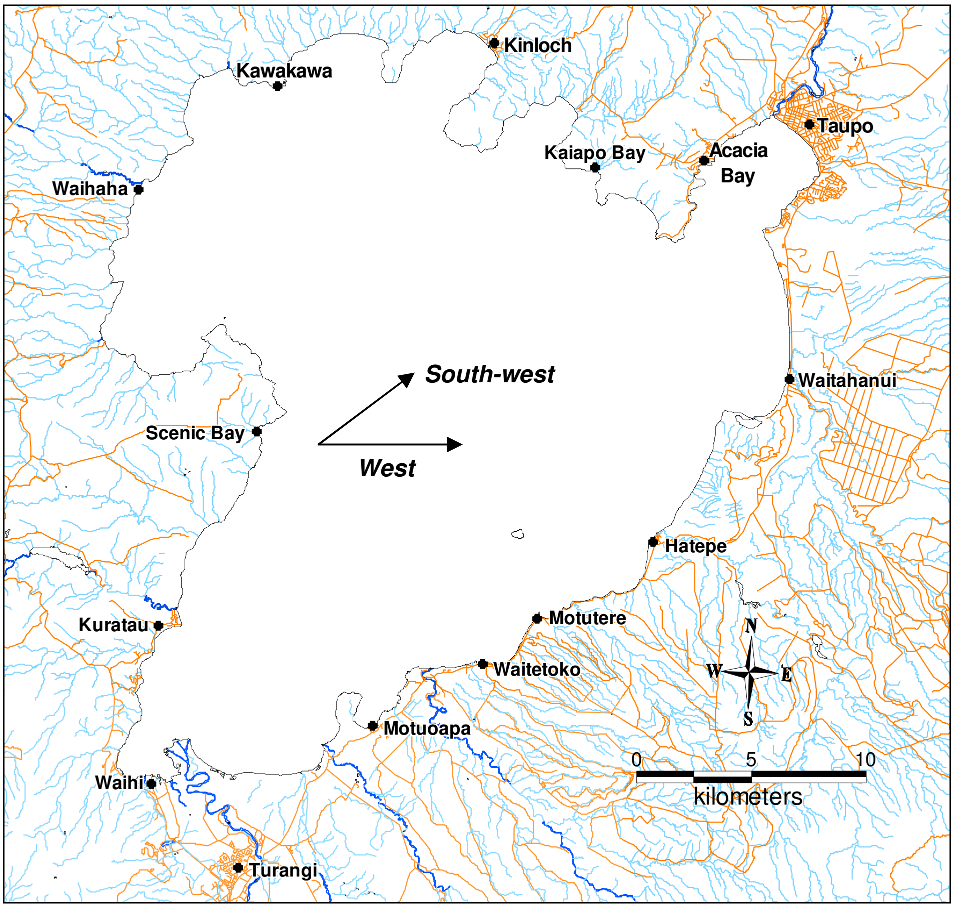
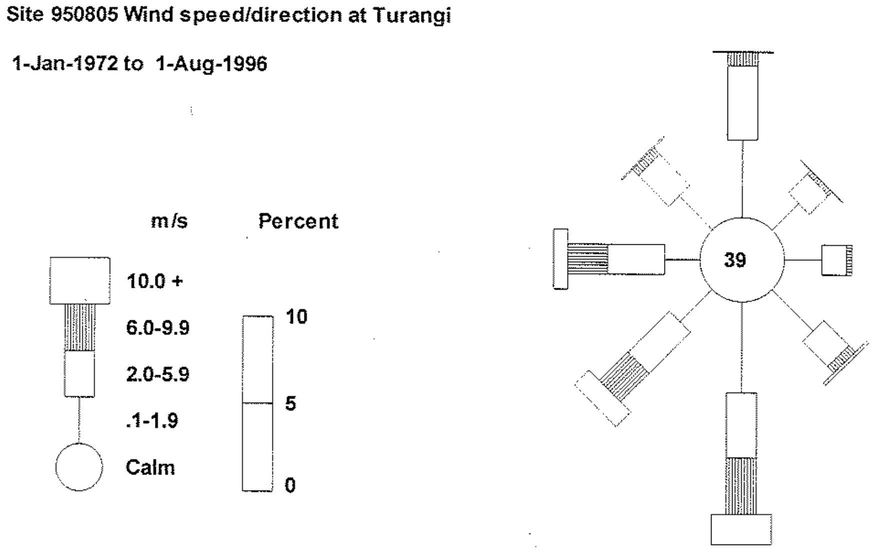


Figure 8.2 **Dominant wind direction across Lake Taupo is from the west and south-west.**

Wind data are recorded at two stations around Lake Taupo: the Taupo Airport, and the Turangi Meteorological Service Station. Results from these stations show the northern end of Lake Taupo is windier than the southern end. Turangi in the south also has a greater number of calm days (39) compared to Taupo (26) (Figure 8.3) (Macky and Bowler, 1998).



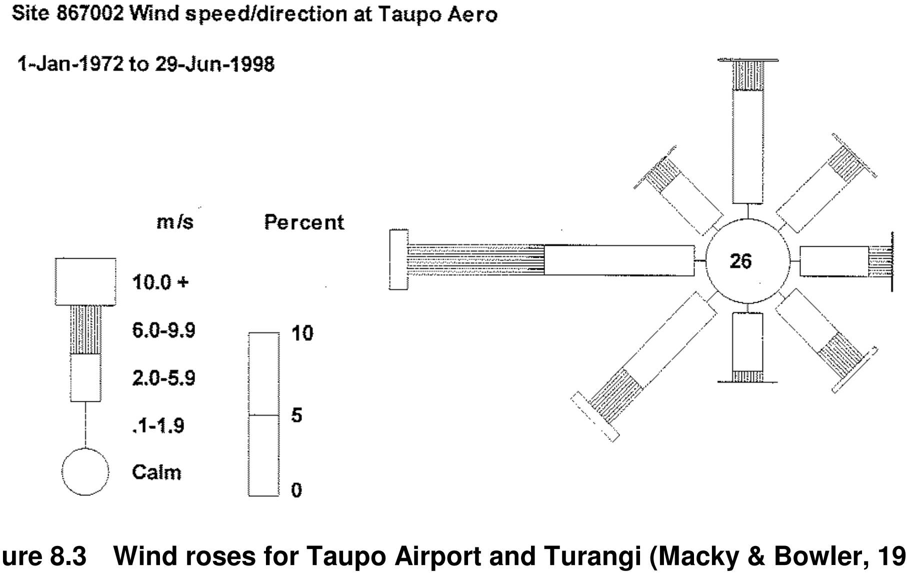


Figure 8.3 Wind roses for Taupo Airport and Turangi (Macky & Bowler, 1998).

Wind direction and strength vary with the season and long-term trends. Figure 8.4 shows seasonal wind roses based on data from the Taupo Airport. The westerly wind dominates in all seasons, yet is stronger and more frequent during spring.

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

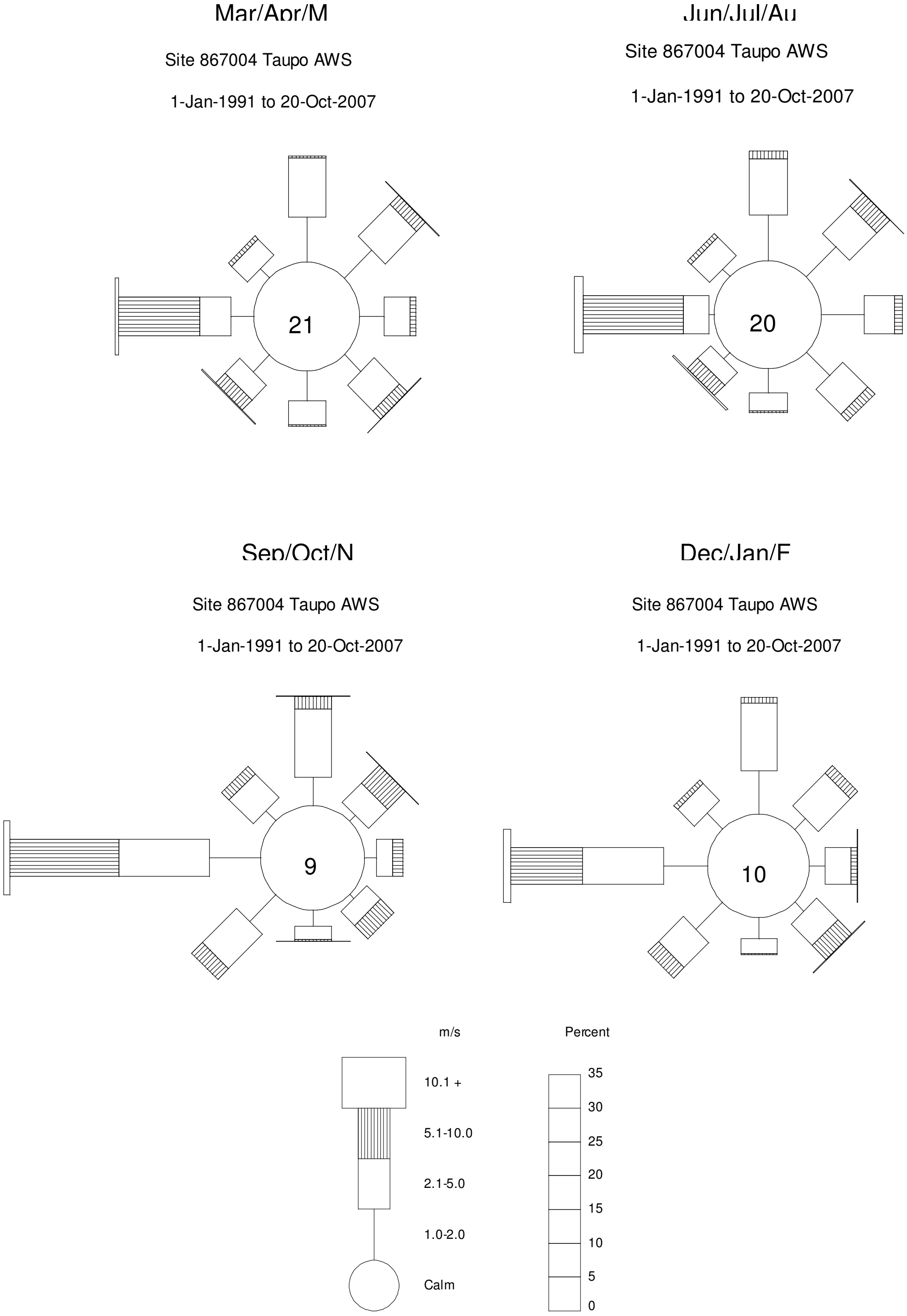


Figure 8.4 Seasonal wind roses, Lake Taupo Airport 1991-2007.

8.3 Wave run-up modelling

The most detailed and extensive coverage of wave information for Lake Taupo is contained in Hicks *et al*. (2000). The model uses 27 years of 3-hourly wind speed and direction data from Taupo Airport. This dataset provides an unbroken record long enough to characterise the wind-wave climate, to identify inter-annual variability, and to search for any correlation between the wind-wave record, lake level, and the Southern Oscillation Index. A 3-hour time interval was chosen because this is the approximate time required to generate a 'fully-arisen-sea' state over the broader fetches of Lake Taupo under strong wind conditions.

Some previous work relating to waves on Lake Taupo 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) data for the current study. This is because Hicks *et al.* (2002) data: were calculated for the entire lake shore; include wave run-up rather than just wave height; has become the 'standard' for wave data relating to Lake Taupo.

The Taupo 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 a Taupo Airport (Macky & Bowler, 1998). Given this, the wind-wave modelling results presented in the following sections will over-predict the wave energy around the southern shore, although the recurrence intervals are probably still reasonable (Hicks *et al.,* 2006).

8.3.1 Lakewave model

Wave run-up around Lake Taupo was estimated by Hicks *et al.* (2000) using the hindcast model *"Lakewave".* The model used the daily 3-hour maximum recorded wind at the Taupo 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 Lake Taupo shores. 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
- 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).

8.3.2 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 (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% exceedence run-up height. This is the wave run-up height that is exceeded 2% of the time under the prevailing wind conditions.

8.3.3 Model accuracy

A qualitative assessment of the accuracy of the model was undertaken as part of Hicks' *et al.* (2000) study using oblique photographs. Under brisk south-westerly conditions the average wind recorded at Taupo airport was 6.8 m/s from 250 degrees. *Lakewave* predicted 3.9 s deep-water waves (wavelength equal to 23.7 m) at Wharewaka Point. In comparison, the deep-water wavelength scaled off the photographs of Wharewaka Point at the time was 20 m. 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).

8.3.4 Model calibration

The *Lakewave* model for Lake Taupo and its output have not been calibrated. Given the importance of the wave climate, to both erosion studies and wave run-up levels, it would be valuable to collect an accurate record of the distribution of actual wave heights under various conditions. Such a wave record, measured at a short time interval, and from at least two locations with distinctly different wave environments, would allow *Lakewave* to be accurately calibrated. This would improve the confidence that can be placed in current estimates of wave height and run-up.

8.3.5 Model output analysis

Lakewave and the available wind data were used to produce estimates of the 2% exceedence run-up at 937 locations around Lake Taupo (Figure 8.5). 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 Taupo. Greatest wave run-up is apparent around the NE shore of the lake, particularly along Taupo 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, meant that individual site analysis was impractical. Therefore, the wave run-up data presented in Figure 8.5 were used to divide the shoreline of Lake Taupo into 10 wave run-up environments, within which similar wave run-up behaviour is expected. These 10 distinct environments are shown in Figure 8.6. The wave environment of the Taupo 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 8.7. 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% exceedence wave run-up was only 0.56 m. Taupo Foreshore on the other hand is exposed to stronger winds and has the longest fetch. Consequently it has a maximum wave run-up of 1.63 m.

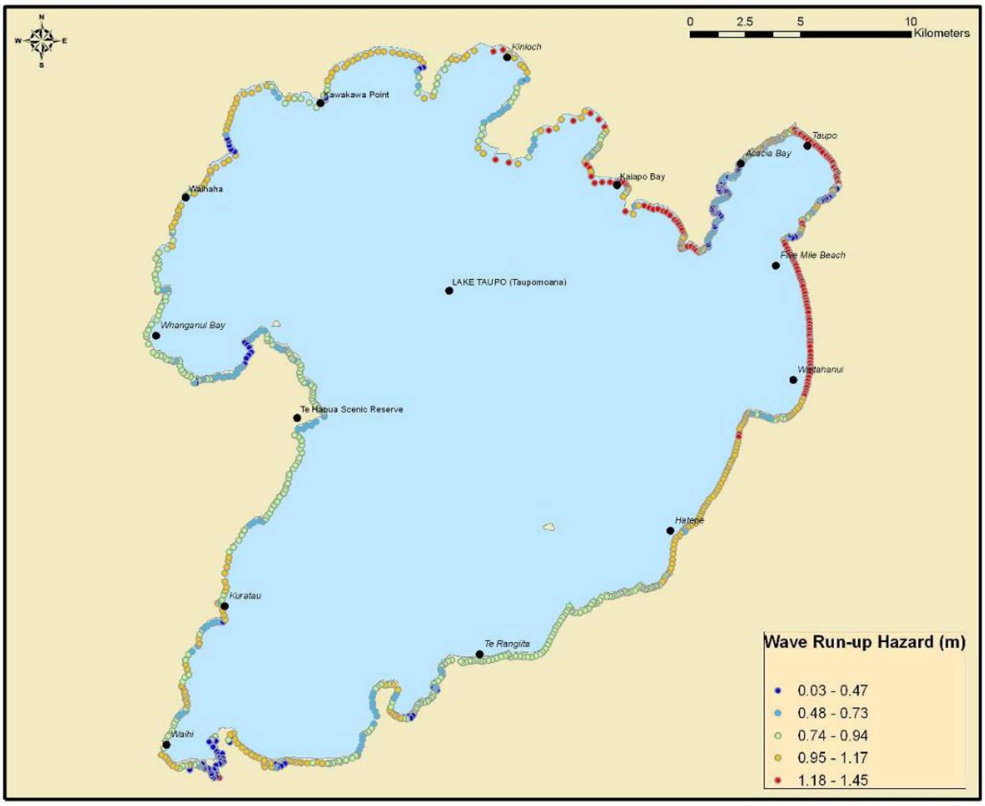


Figure 8.5 Wave run-up (2% exceedence) around the shore of Lake Taupo.

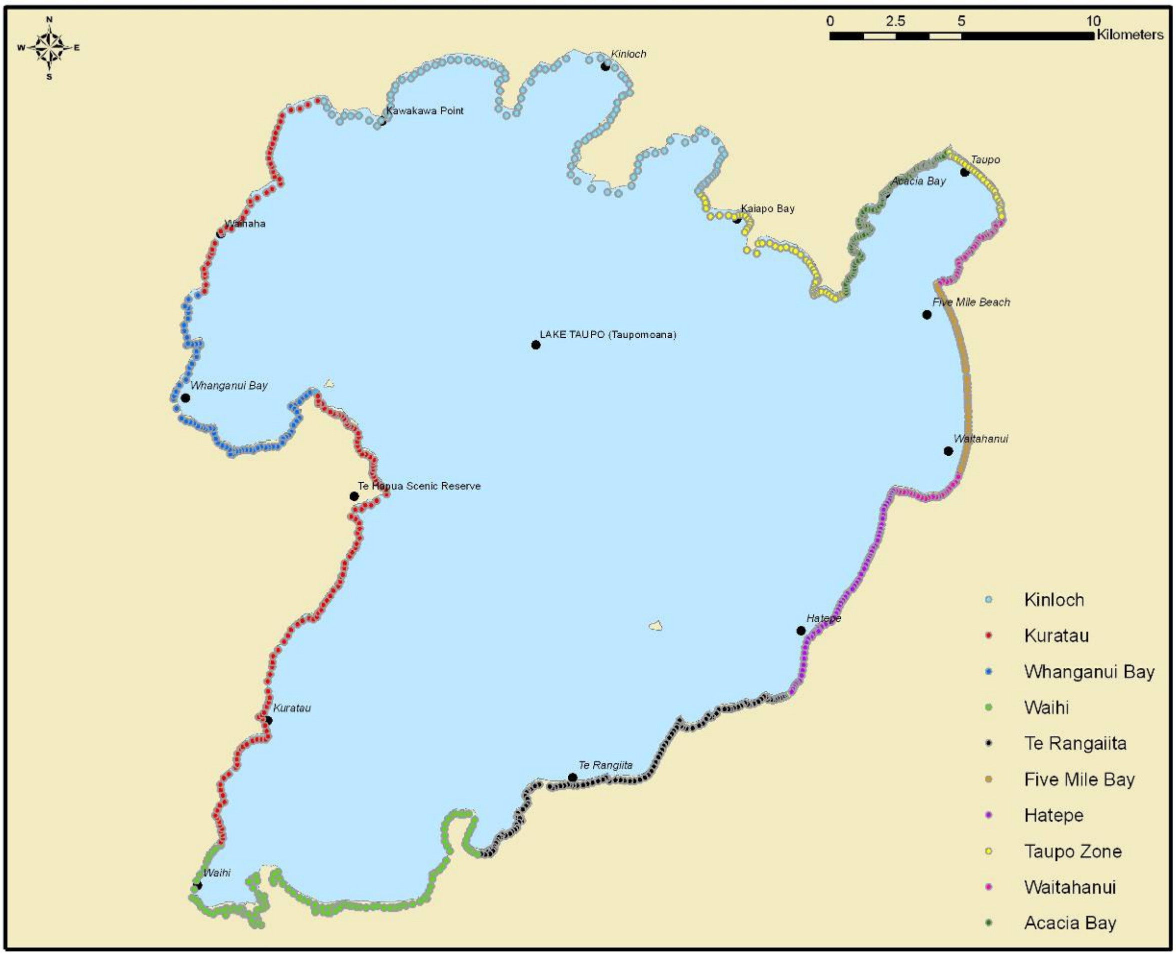


Figure 8.6 Wave run-up environments around the shore of Lake Taupo.

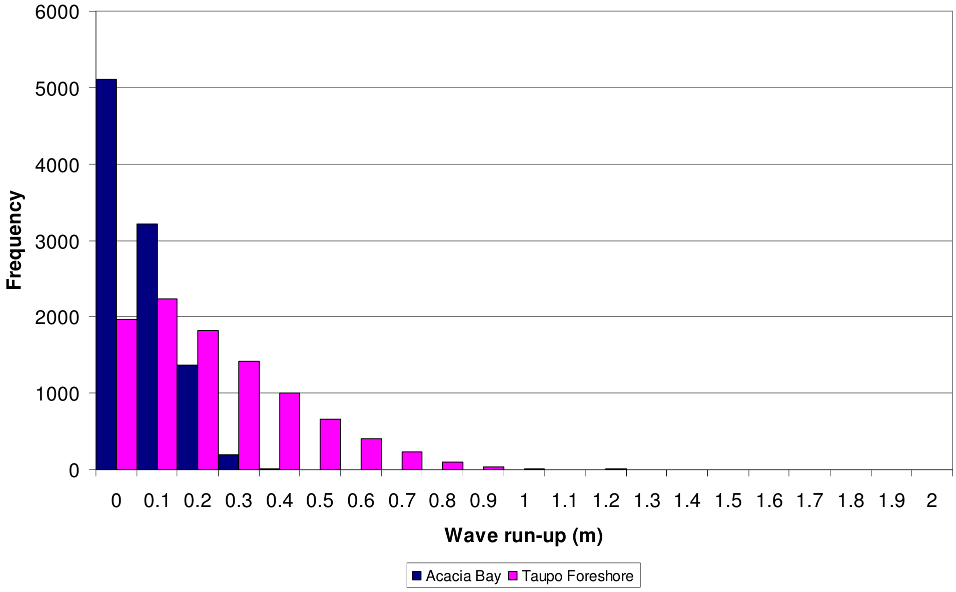


Figure 8.7 Wave run-up environments at Acacia Bay and on Taupo foreshore.

Frequency distributions for the 2% exceedence 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 8.8).

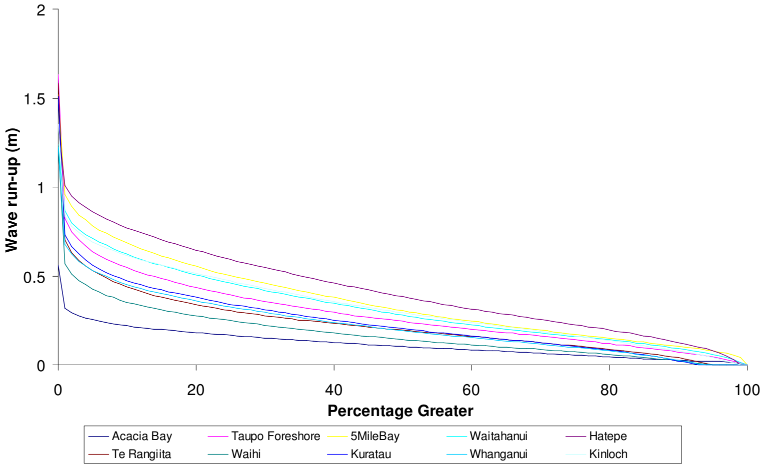


Figure 8.8 Different wave run-up environments around the Lake Taupo foreshore.

Since the wave run-up results are dependent on the wind regime any variability in the wind regime must be identified and its impact quantified. Therefore wind roses were prepared for four sets of data: the entire length of record (Figure 8.9A); the wind record prior to Hicks *et al.,* (2000) (Figure 8.9B); the wind record after Hicks *et al.,* (2000) (Figure 8.9C); and the wind record for 1998 (Figure 8.9D). These wind roses indicate that the wind record shows very little variation from 1990 until 2007. Although 1998 contained a significant flood and erosion event the wind data for that year was typical of the rest of the record.

A statistical analysis of the 2% exceedence wave run-up for each of the 10 wave environments shows no significant differences over each of the various time periods (Table 8.1). The only difference is that the highest wave run-up occurred during the early part of the record (up until 1999) and therefore the maximum for the shorter, later periods is less. The rest of the statistical descriptors are almost identical. It would therefore appear that the wave run-up data are consistent for the entire length of record.

A frequency analysis was undertaken of the wave run-up data for each of the 10 distinct wave environments. While a Gumbel distribution was most appropriate for five of the sites, a PE3 distribution was used for three sites and a GEV distribution for the last two. In general, the appropriate distributions fit the data well providing good estimates of the magnitude of wave run-up events for particular return periods (Table 8.2). Table 8.3 presents a statistical summary of the variability in wave run-up across the 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.

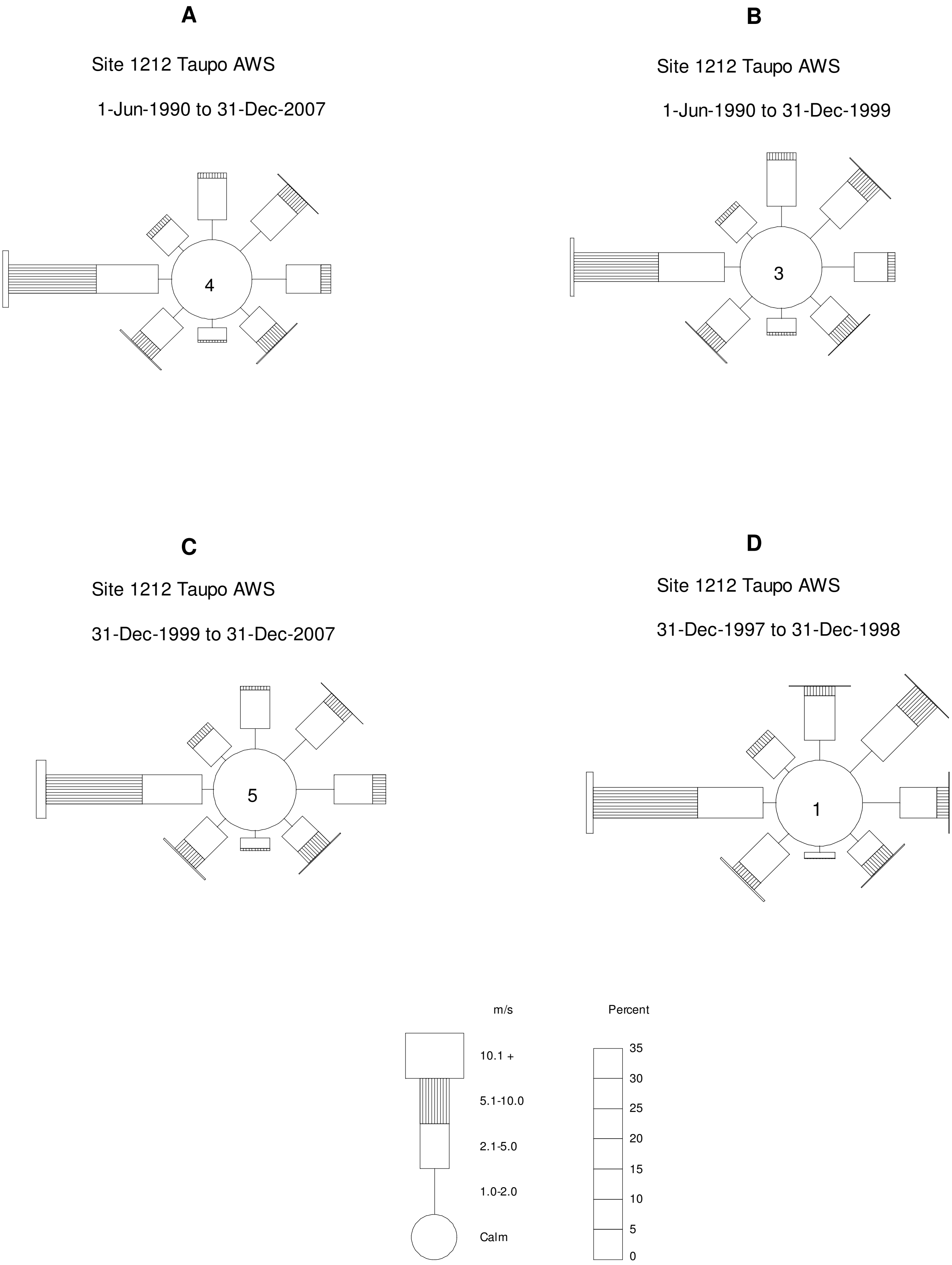


Figure 8.9 Wind roses for different time intervals.

Table 8.1 Analysis of the effect of wind record on 2% exceedence wave run-up.

Whole record (1-01-79~24-01-06)	Recorded LL	Acacia Bay	Taupo Foreshore	5 Mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
Minimum	355.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	356.68	0.12	0.28	0.36	0.32	0.42	0.22	0.17	0.24	0.22	0.33
Maximum	357.49	0.56	1.63	1.52	1.23	1.35	1.58	1.24	1.51	1.22	1.35
Lower quartile	356.43	0.05	0.13	0.16	0.15	0.21	0.10	0.06	0.09	0.09	0.15
Median	356.68	0.10	0.24	0.29	0.27	0.38	0.19	0.14	0.20	0.19	0.29
Upper quartile	356.94	0.17	0.40	0.51	0.47	0.61	0.31	0.26	0.36	0.34	0.49
98th percentile	357.22	0.31	0.78	0.92	0.83	0.98	0.68	0.53	0.71	0.65	0.81
Record (1-01-79~31-12-99)											
Minimum	355.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	356.69	0.11	0.29	0.36	0.33	0.43	0.22	0.17	0.24	0.22	0.33
Maximum	357.49	0.56	1.63	1.52	1.23	1.35	1.58	1.24	1.51	1.22	1.35
Lower quartile	356.44	0.04	0.14	0.17	0.16	0.22	0.08	0.06	0.08	0.08	0.16
Median	356.68	0.10	0.25	0.30	0.28	0.39	0.19	0.13	0.20	0.18	0.30
Upper quartile	356.95	0.17	0.41	0.51	0.47	0.61	0.32	0.26	0.36	0.34	0.49
98th percentile	357.23	0.31	0.79	0.92	0.82	0.98	0.70	0.55	0.72	0.66	0.81
Record (1-01-00~24-01-06)											
Minimum	355.94	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	356.64	0.12	0.26	0.34	0.31	0.40	0.22	0.17	0.23	0.22	0.30
Maximum	357.35	0.40	1.25	1.28	1.14	1.27	0.85	0.83	1.01	0.90	1.11
Lower quartile	356.39	0.07	0.10	0.13	0.13	0.19	0.12	0.08	0.11	0.11	0.12
Median	356.67	0.11	0.20	0.24	0.23	0.33	0.20	0.14	0.20	0.19	0.24
Upper quartile	356.90	0.17	0.38	0.51	0.47	0.60	0.29	0.25	0.33	0.32	0.47
98th percentile	357.16	0.28	0.75	0.93	0.83	0.98	0.56	0.47	0.63	0.59	0.80
Record (1-01-98~31-12-98)											
Minimum	356.29	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	356.78	0.12	0.27	0.35	0.32	0.42	0.22	0.17	0.23	0.22	0.31
Maximum	357.49	0.39	0.91	1.10	1.02	1.14	0.82	0.76	0.99	0.81	0.91
Lower Quartile	356.45	0.06	0.13	0.15	0.15	0.21	0.10	0.07	0.10	0.10	0.15
Median	356.75	0.10	0.22	0.30	0.27	0.38	0.19	0.13	0.17	0.16	0.27
Upper Quartile	357.09	0.17	0.38	0.53	0.49	0.62	0.29	0.25	0.33	0.33	0.48
98th percentile	357.42	0.31	0.73	0.90	0.82	0.97	0.66	0.54	0.73	0.65	0.78

Table 8.2 Estimated 2% exceedence wave run-up for 10 environments at different return periods.

	Acacia Bay	Taupo Foreshore	5 Mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
Best-fit Distribution	*Gumbel*	*GEV*	*Gumbel*	*PE3*	*GEV*	*PE3*	*PE3*	*Gumbel*	*Gumbel*	*Gumbel*
Return Period										
2.33	0.39	0.99	1.13	1.03	1.18	0.85	0.74	0.96	0.84	0.96
5	0.42	1.14	1.25	1.11	1.25	0.98	0.85	1.08	0.91	1.06
10	0.45	1.26	1.34	1.16	1.30	1.09	0.94	1.17	0.98	1.15
20	0.47	1.38	1.43	1.20	1.33	1.19	1.03	1.26	1.04	1.23
50	0.51	1.54	1.55	1.24	1.36	1.32	1.14	1.38	1.11	1.34
100	0.53	1.67	1.64	1.26	1.37	1.42	1.22	1.47	1.17	1.42
200	0.56	1.79	1.72	1.29	1.38	1.52	1.30	1.50	1.23	1.50
500	0.59	1.96	1.85	1.31	1.40	1.65	1.41	1.67	1.31	1.60

Table 8.3 Estimated average 2% exceedence wave run-up for Lake Taupo across the 10 different wave run-up environments.

Return Period	Minimum	Mean	Maximum	Range	Lower quartile	Median	Upper quartile
2.33	0.39	0.91	1.18	0.80	0.84	0.96	1.02
5	0.42	1.00	1.25	0.83	0.93	1.07	1.13
10	0.45	1.08	1.34	0.89	1.00	1.15	1.24
20	0.47	1.16	1.43	0.96	1.07	1.21	1.31
50	0.51	1.25	1.55	1.04	1.16	1.33	1.37
100	0.53	1.32	1.67	1.14	1.23	1.40	1.46
200	0.56	1.38	1.79	1.23	1.29	1.44	1.50
500	0.59	1.48	1.96	1.37	1.33	1.51	1.67

Figure 8.10 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 20 years. After this the increase is significantly more gradual.

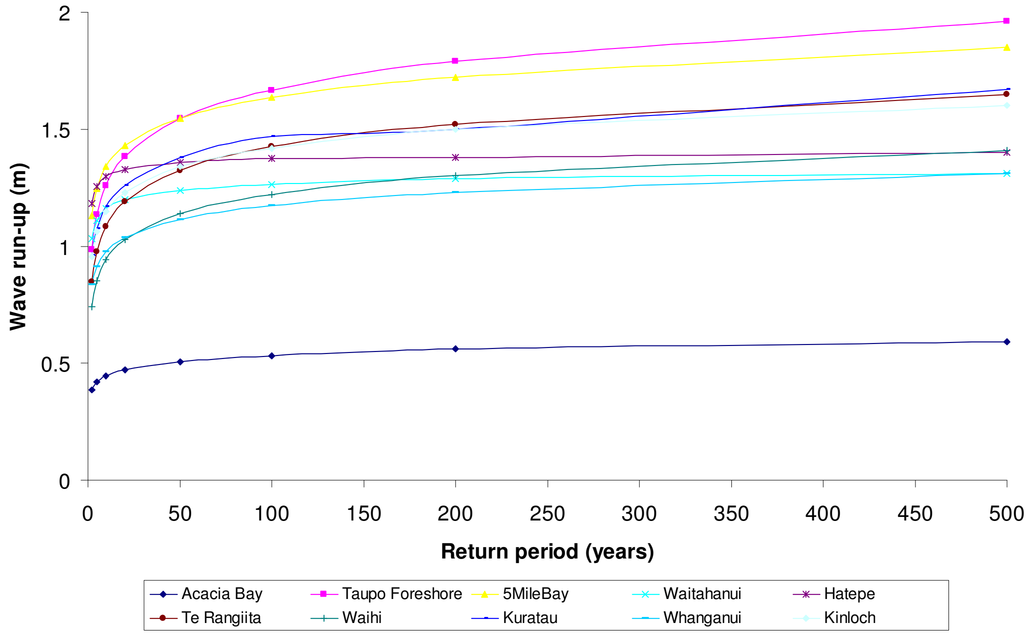


Figure 8.10 Wave run-up for the different environments at different return periods.

Figures 8.11 & 8.12 show how the rate of change in wave run-up and lake level varies with increasing return period. At sites subject to strong winds the wave regime has a greater potential effect on water levels than the lake level. It can also be seen that as the return period of a particular event increases, out past 20 years, the significance of changes in the lake level component of water level tends to decrease in importance.

8.4 Coincidence of high lake levels and strong wind events

8.4.1 Background

Of particular concern with regard to the extent and level of flooding around Lake Taupo 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).

As discussed above, the wind climate at Taupo 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 Taupo Airport (Hicks *et al.,* 2000).

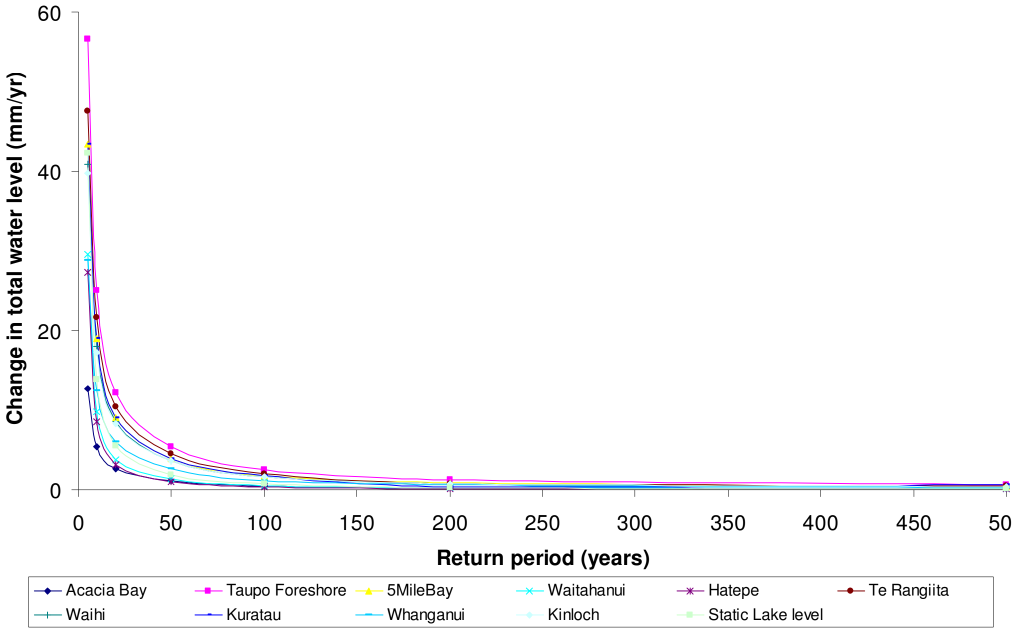


Figure 8.11 **Change in water level as a result of wave run-up for the different environments at different return periods.**

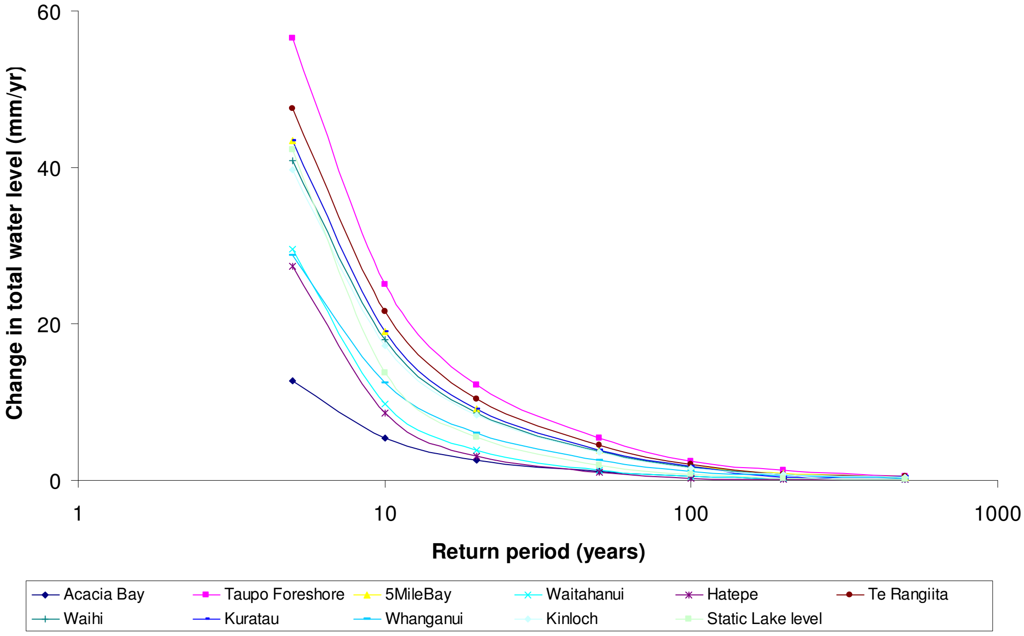


Figure 8.12 **Change in water level as a result of wave run-up for the different environments at different return periods (log return period).**

Following the installation of the Taupo 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 (Hicks *et al.,* 2000).

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).

8.4.2 Analysis

A plot of the daily maximum lake level against daily 2% exceedence run-up on the Taupo Foreshore (Figure 8.13) suggests that the two variables are unrelated. Maximum lake levels are associated with low wave run-ups, while the maximum run-ups are all associated with 'average' lake levels.

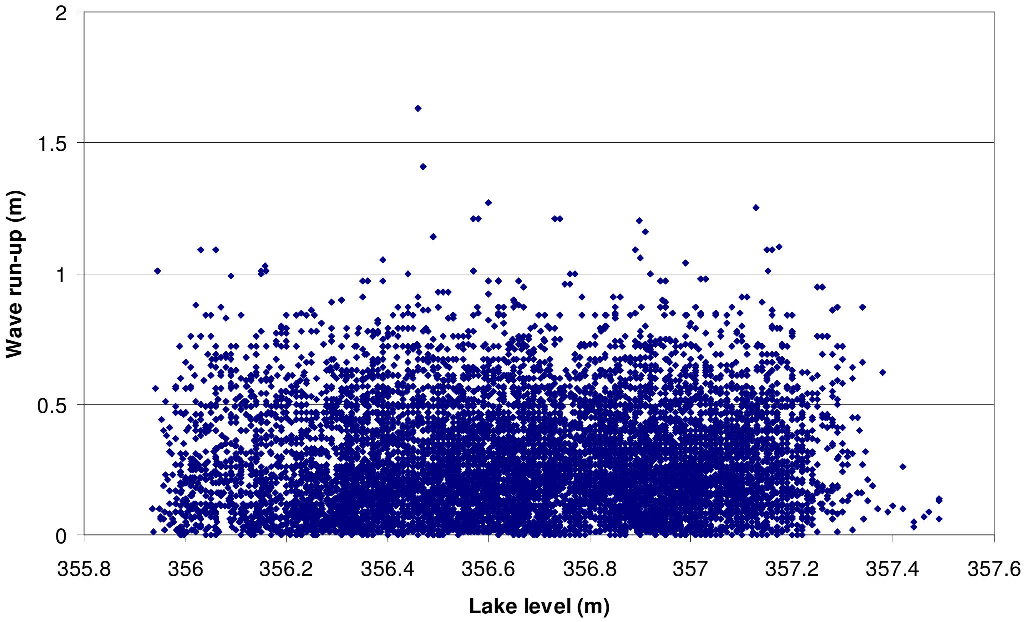


Figure 8.13 Variation in daily wave run-up on Taupo foreshore and lake level (1979-2006).

To see whether any pattern exists within the scatter a separate plot of the annual maxima was produced (Figure 8.14). Again, there is considerable scatter but no trend of greater run-ups at higher lake levels.

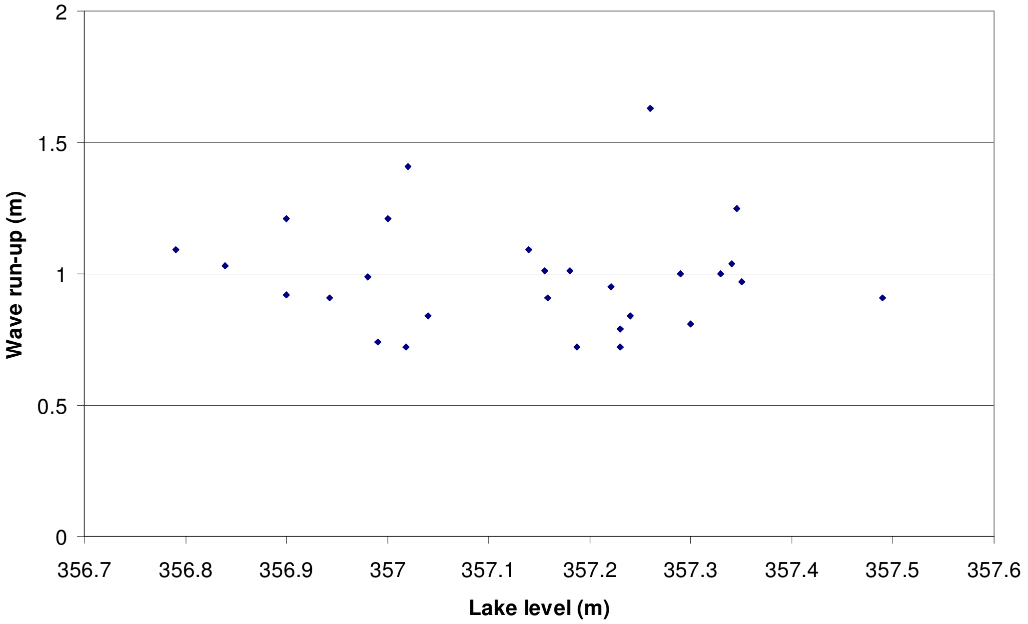


Figure 8.14 Variation in annual maxima of daily wave run-up on Taupo foreshore and lake level.

Beca (2006) showed that at some sites there has been an increased incidence of strong wind events during periods of 'higher than natural' lake level. Their analysis of the highest wind events on record showed that these events tend to occur during summer. Over recent years the lake level during summer has been held higher than it would have been under the natural regime. This increases the potential for strong winds to occur during periods of 'higher than natural' lake levels. However, just because these events occurred at levels that were 'higher than natural' does not imply that the lake level was indeed high e.g., a lake level of 357.1 is higher than 357.0 but both levels reflect only 'average' conditions. An attempt was therefore made to analyse the relationship between the actual lake level and strong wind events.

Figure 8.15 shows the lake level during the 10 strongest wind events at both Kuratau and Waitahanui. No clear pattern exists between lake level and wind strength. In fact, the strongest wind events at both locations occurred during relatively low lake levels. It would appear that the two variables are therefore largely independent. Large wave run-up events do occur during high lake levels, but they also occur during low and moderate lake levels.

Following the 1998 flood event considerable concern was expressed regarding the coincidence of the high lake level and large waves. Analysis of this event shows that while the high lake level was a rare event (RP of 83 years using a PE3 distribution and the 1980-2007 record) the wave run-up on Taupo foreshore had a return period of only 2 years.

This lack of a clear pattern between the lake level and wave run-up data is not surprising. Although there is likely to be a weak relationship between wind and rainfall events, even this is 'distorted' by the fact that lake levels are controlled. Thus, any physical relationship between the variables is masked by the lake level control for electricity generation. As a result, wave run-up and lake level can be treated as two independent variables.

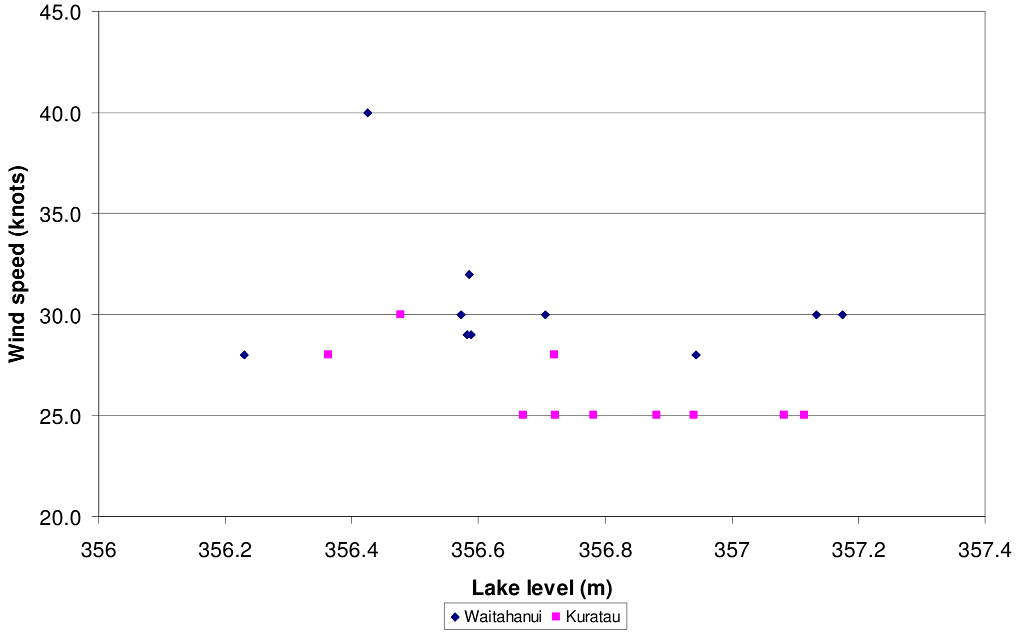


Figure 8.15 The ten largest wind speed events and corresponding lake levels, Waitahanui and Kuratau, 1972-2006.

8.5 Storm surge and landslides

Storm surges and landslides can both cause wave run-up around the shores of Lake Taupo. 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 already 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.

8.6 Summary and recommendation

Wave run-up acts on top of the static water level and can therefore increase the extent of flooding and depth of inundation. To incorporate the effect of wave run-up into the flood hazard of Lake Taupo it must be added to the appropriate static water level. Although wave run-up increases the effective water level around the lake its effects can be managed by different strategies to those needed to manage increases in the static water level of the lake.

To take account of the effect, and variation, in wave run-up at different places around Lake Taupo the data in Table 8.5 must be added to the static lake level for a specified return period and the amount of tectonic deformation over this time period.

Table 8.5 Wave run-up for various locations at different return periods (m).

Return Period	Acacia Bay	Taupo foreshore	5-mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
2.33	0.39	0.99	1.13	1.03	1.18	0.85	0.74	0.96	0.84	0.96
5	0.42	1.14	1.25	1.11	1.25	0.98	0.85	1.08	0.91	1.06
10	0.45	1.26	1.34	1.16	1.30	1.09	0.94	1.17	0.98	1.15
20	0.47	1.38	1.43	1.20	1.33	1.19	1.03	1.26	1.04	1.23
50	0.51	1.54	1.55	1.24	1.36	1.32	1.14	1.38	1.11	1.34
100	0.53	1.67	1.64	1.26	1.37	1.42	1.22	1.47	1.17	1.42
200	0.56	1.79	1.72	1.29	1.38	1.52	1.30	1.50	1.23	1.50
500	0.59	1.96	1.85	1.31	1.40	1.65	1.41	1.67	1.31	1.60

9 Land Use

9.1 Background

Recent work has investigated the link between land use and runoff in pumice catchments (Environment Waikato, 2006). Previous work (Hamilton, 2001) indicated that:

- Changing land use from forested 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.
- 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.

Not withstanding 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 9.1.

Table 9.1 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

9.2 Introduction

There has been a significant change in the land cover of the Lake Taupo 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 9.1). Much of this change has occurred since the flow record of Lake Taupo has been recorded (i.e., 1906) and therefore the effect of this 'past' change has been included in the previous analysis of lake levels.

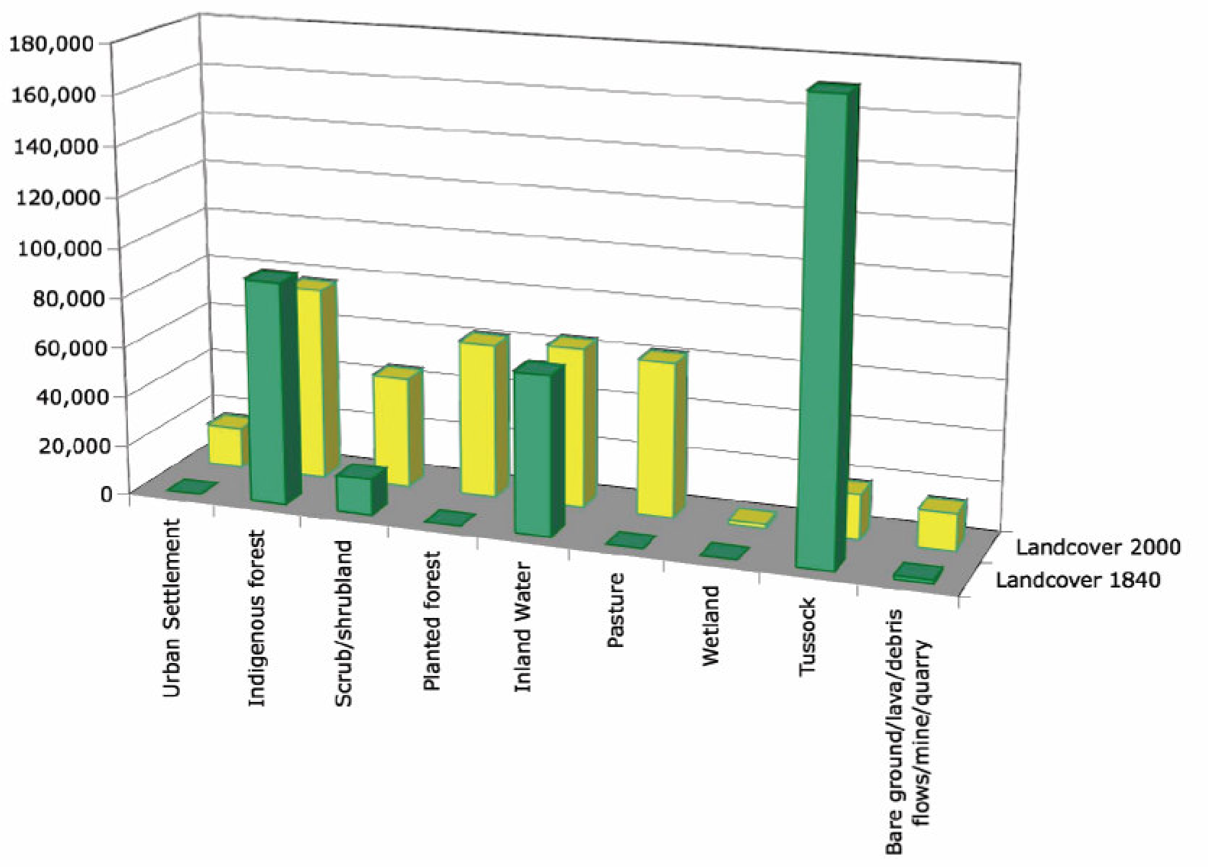


Figure 9.1 Land use changes between 1840 and 2000, Lake Taupo catchment (Hamilton, 2005).

Figure 9.2 shows the land cover surrounding Lake Taupo 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 9.3)

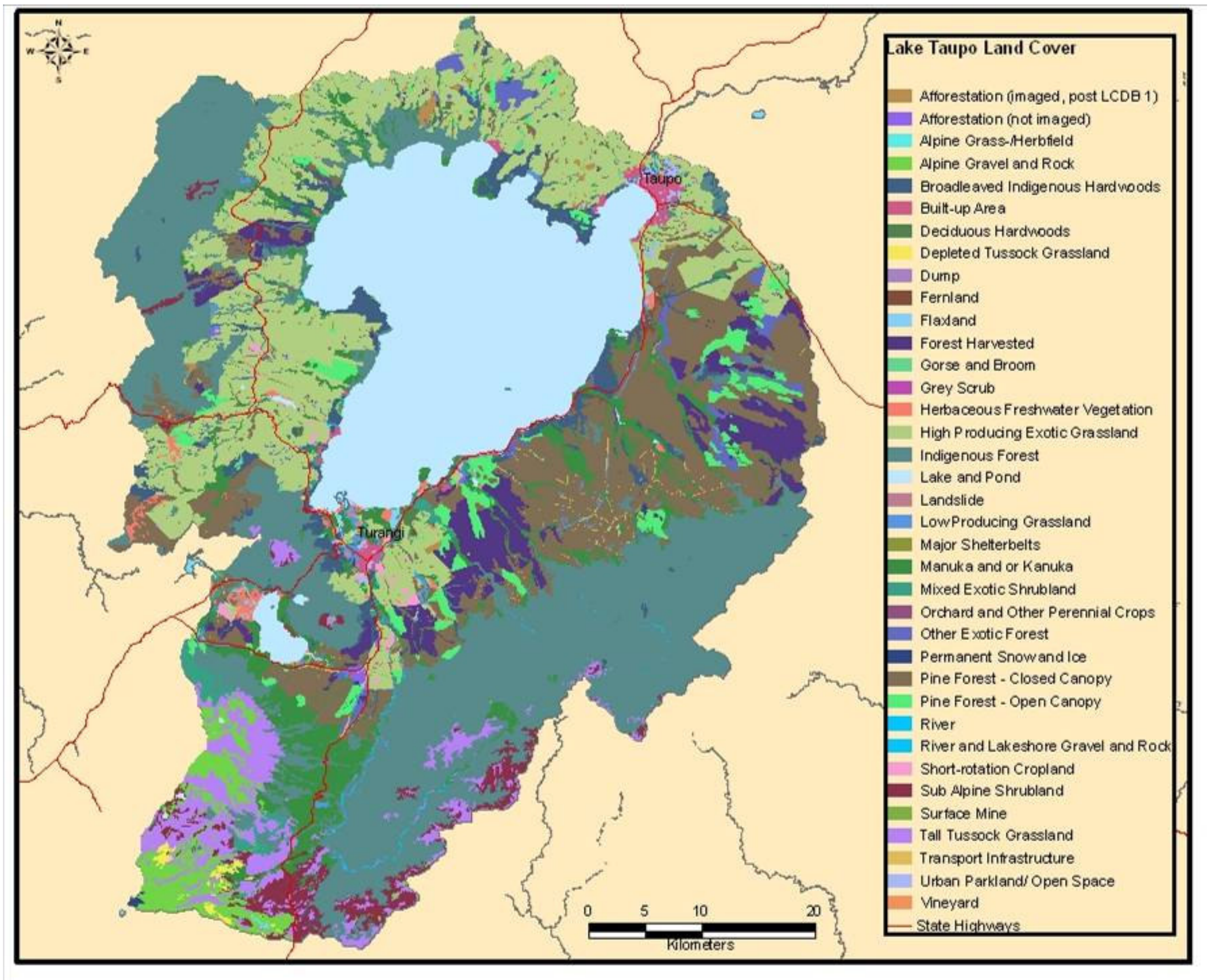


Figure 9.2 Land Cover in the Taupo catchment (Source: LCDB2-2004).

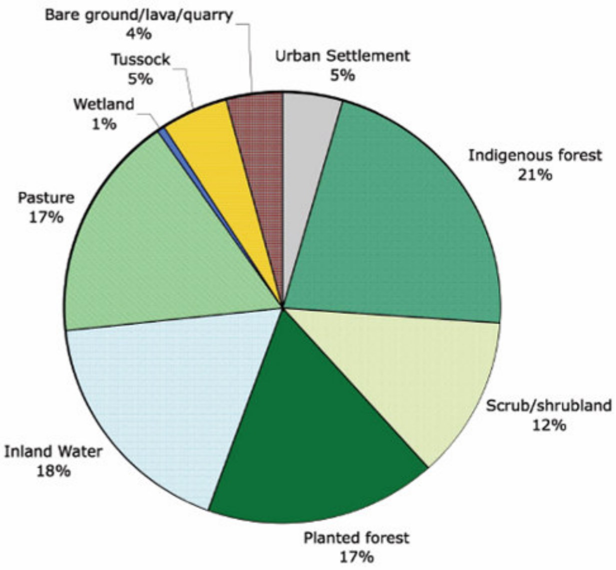


Figure 9.3 Land use Taupo catchment, in 2000 (Hamilton, 2005).

9.3 Potential effect of converting all forestry to pasture

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

At present there are approximately 493 km^2 under either open or closed forestry within the catchment. Another 135 km^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 628 km^2 converted to pasture. Using the information presented in Table 9.1, this would have the potential effects summarised in Table 9.2.

Table 9.2 Potential effect on the hydrologic regime if all 628 km^2 of forest lands within the Lake Taupo 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 peak discharge 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
200	*1.45*	*911*	*0.091*	*57*	*91*
500	*2.18*	*1369*	*0.125*	*79*	*126*

Note: The estimates for 200 and 500-year RP events were not provided in the original report (Environment Waikato, 2006) and so have been estimated through curve fitting.

9.4 Potential effect of land use change on lake levels

Some change to the rainfall – runoff relationship might be expected within the catchment as a result of a change in landuse. 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 Taupo catchment rather than vegetation type (Fahey and Rowe, 1992).
- 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. These effects will be smoothed further down the catchment. Since the levels in Lake Taupo reflect the net effect of all changes and processes occurring in all sub-catchments any change will not be discernable in lake levels.
- The majority of inflow to Lake Taupo 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 Taupo these are likely to be managed and compensated for in the manner in which the Taupo Gates are operated.
- The effect of land use change on the hydrologic regime of Lake Taupo since 1906 are already included in the flow and level records used in all the above analyses. 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.
- Even if all the area currently under forestry was converted to pasture, an extremely unlikely scenario, this would increase the lake level during the 100-year event by only 72 mm.

9.5 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.

10 Conclusion

10.1 Introduction

The risk of flooding, and the potential extent and depth of inundation around Lake Taupo 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; wind generated waves; seiching; climate and land use change, and tectonic deformation of the lake bed and shore.

These factors combine to form 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, beach profile and material, and 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 will 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.

10.2 100-year static water level

As discussed, 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 further. 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 10.1). Tectonic deformation, however, varies significantly around the lake (Figure 10.1). Where an area is subsiding, the reduction in the ground level must be added to the other factors to produce a site-specific static water level.

Table 10.1 Expected static water level for different return period events.

Return Period	Lake Level (m)	Climate Change 2080s (m)	Seiche Effect (m)	TOTAL STATIC WATER LEVEL
2.33	357.17	0.07	0.08	357.32
5	357.29	0.10	0.09	357.48
10	357.35	0.12	0.10	357.57
20	357.41	0.14	0.11	357.66
50	357.47	0.16	0.11	357.74
100	357.50	0.18	0.11	357.79
200	357.53	0.19	0.11	357.83
500	357.57	0.21	0.11	357.89

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 level.

Therefore, the static water level used for defining the flood level should include: the 100-year lake level (357.50 m); the climate change effect on the 100-year event (0.18 m); the 100-year seiche (0.11 m); and a 100 years of accumulated tectonic deformation. This static water level therefore delineates areas where inundation to some degree is inevitable with a 100-

year return period, or with a likelihood of 1% each year. The possibility of inundation will increase over time as accumulated tectonic subsidence becomes more significant.

A map of the static water level defined in the above manner (357.79 m + deformation) is included in the data appendix to this report.

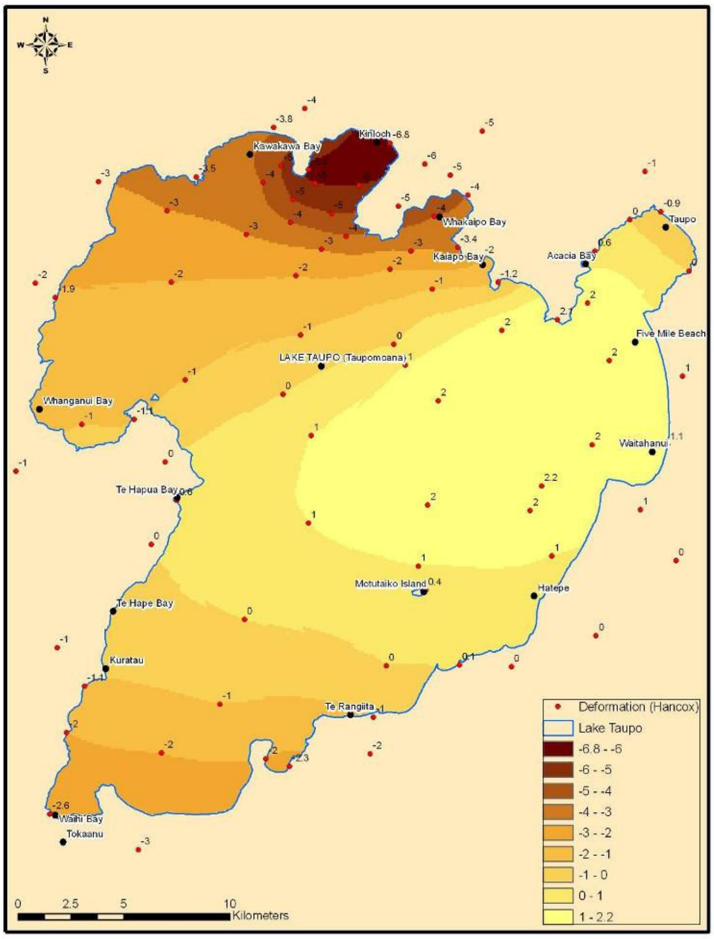


Figure 10.1 Average rates (mm/yr) of tectonic deformation (After Hancox, 2002).

10.3 Wave run-up effect

The static water level provides the 'surface' upon which waves will form. The size of these waves, as discussed previously, 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 model.

It can be seen from Table 10.2, and as was discussed previously, the effect of wave run-up is greatest over the relatively low return periods. 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.

A map of the wave run-up defined in the above manner is included in the data appendix to this report.

Table 10.2 Wave run-up for various locations at different return periods (m).

Return Period	Acacia Bay	Taupo foreshore	5-mile Bay	Waitahanui	Hatepe	Te Rangiita	Waihi	Kuratau	Whanganui	Kinloch
2.33	0.39	0.99	1.13	1.03	1.18	0.85	0.74	0.96	0.84	0.96
5	0.42	1.14	1.25	1.11	1.25	0.98	0.85	1.08	0.91	1.06
10	0.45	1.26	1.34	1.16	1.30	1.09	0.94	1.17	0.98	1.15
20	0.47	1.38	1.43	1.20	1.33	1.19	1.03	1.26	1.04	1.23
50	0.51	1.54	1.55	1.24	1.36	1.32	1.14	1.38	1.11	1.34
100	0.53	1.67	1.64	1.26	1.37	1.42	1.22	1.47	1.17	1.42
200	0.56	1.79	1.72	1.29	1.38	1.52	1.30	1.50	1.23	1.50
500	0.59	1.96	1.85	1.31	1.40	1.65	1.41	1.67	1.31	1.60

10.4 Combined flood hazard level

The flood hazard level is the combined effect of the static water level and the wave run-up. But, as mentioned, 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% level, or 1 in 100-year combined return period event is often used in hazard planning. However, a 1% 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 combination of events that produces the greatest elevation will therefore give the most conservative assessment of flood risk.

For Lake Taupo, the 10-year static water level (including 100 years of climate change and deformation as discussed) combined with the 10-year wave run-up would have the greatest combined effect of all the various 1 in 100-year combined return period events. This combination of events therefore provides a buffer above the 100-year static water level to accommodate the potential effects of wave run-up. This line therefore delineates the area, above the 100-year static water level, where there is a risk that waves of varying depths will run over the land with a probability of 1 in100-years or 1%. This buffer area can be shown on the digital terrain model based on topography. However, simply mapping the buffer area based on elevation fails to take into account site-specific features that may impact on the effects of wave action. This need for site-specific assessment should be reflected in any policy or planning provisions.

10.5 Areas affected by each condition

The static water level and combined flood hazard water level vary around the lake and their position depends on the topography of the land. The levels were therefore overlaid on the LiDAR-derived terrain model to determine their position around the entire lake shore. Maps of the static water level, and combined flood hazard water level defined in the above manner are included in the data appendix to this report. These maps are intended to form the basis for developing sound, long term hazard management policies.

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12 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.