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Tsunamis, seismic seiches, and undetermined wave events on New Zealand lakes, 1846–2022: a review

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Cover: Hooker Lake, 13 October 2021. Shot from time-lapse imagery, showing an avalanche in the Hayter Stream catchment (centre) entering Hooker Lake and the subsequent tsunami distributing debris across the lake. *Photo: Aubrey Miller (Mountain Research Centre, University of Otago, Dunedin)*. Used with permission.

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CONTENTS

Appendix 1

Tsunamis, seismic seiches, and undetermined wave events on New Zealand lakes, 1846–2022: a review

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Abstract

Baseline information is presented for 74 tsunamis, seismic seiches, and undetermined wave events (collectively termed lake waves), that occurred on 38 New Zealand lakes over 176 years, between 1846 and 2022. Wind generated waves and seiches were not included. The present review involved a literature search to collate existing information and help identify historic locations, generating mechanisms, wave height, frequency, and effects of lake waves.
The review increases the knowledge of a natural hazard that has been scarcely researched and is poorly understood. Findings show that, apart from meteorite impact, lake waves have been generated by all known mechanisms, ranging from local to global scale. Most ($n = 48$; 65%) have been associated with seismic shaking, either directly, or with co-seismic processes.
Lake waves have been recorded in natural, modified, and artificial lakes, ranging in size from the country's largest (Lake Taupō / Taupōmoana) to some of the smallest (artificial ponds); some of the deepest (e.g., Lake Te Anau / Te Ana-au) to shallowest, and from the highest-altitude lake (Crater Lake, Mount Ruapehu) to lakes near sea-level. The greatest wave height was calculated at c.10 m (Maud Lake tsunami, May 1992), based on valley dimensions and wave run-up damage occurring c.20 m above the lake surface. Lake wave occurrence was found to be far more frequent than previously documented. To date, lake waves have caused minimal property damage or personal injury. The risk they present is predicted to increase in the future in association with intensifying lakeside development and, possibly, with climate-change increasing the frequency of mass-movement, avalanche, and ice-calving/collapse events around the country's alpine lakes.

Key words: lakes, lake waves, New Zealand, seismic seiche, tsunami, undetermined waves.

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1. Introduction

New Zealand's location across the active Australian–Pacific tectonic plate boundary, combined with its maritime location in the South Pacific Ocean (Figure 1), makes the country prone to all known geologic and climatic hazards (e.g., Spenden & Crozier 1984; Owens 2001; Downes et al. 2017). Yet, on a national scale, no research has been undertaken examining the historical occurrence of tsunamis, seismic seiches, or other undetermined waves (collectively termed lake waves) on the country's lakes, despite New Zealand having at least 3,820 lakes greater than one hectare in area, with the eight largest each being greater than 100 km^2 (Schallenberg et al. 2013). Most lake-wave research has been recent, site-specific, and has focused on event prediction, based on return-periods of seismic ground-shaking intensities, lakebed faulting, and various forms of mass-movement (e.g., Clark et al. 2011, 2015; Mackey 2015; Fraser & McMorran 2016; Mountjoy et al. 2019; Wang et al. 2020), or the analysis of palaeo-volcanic events (e.g., de Lange et al. 2002; de Lange & Moon 2016). Allen et al. (2009) modelled glacial hazards in the Aoraki / Mount Cook region and focused on potential glacial-flood (displacement) waves caused by mass-movements of debris, rock, and ice: Brambus (2017) undertook a similar investigation over a wider region of the Southern Alps / Kā Tiritiri o te Moana.

Besides McSaveney (1992a, b, 1993, 2002) and Dykes et al. (2017) who, respectively, provided details on two historic tsunamis on an unnamed proglacial lake at Maud Glacier (hereafter called Maud Lake[1]), and two on Tasman Lake, most information for lake waves in New Zealand is found in contemporary newspaper reports. In a few instances, passing reference has been given to historic lake waves in scientific and technical literature, as the focus of such publications has been on the initial generating mechanisms like earthquake shaking (e.g., Hogben 1890; Downes 1995, 2006) or landslides (e.g., Hawley 1984; Hancox et al. 2004), rather than the subsequent lake waves produced. This contrasts with oceanic tsunamis, for which research is extensive and several national databases have been compiled (Laing 1954; de Lange & Healy 1986; Fraser 1998; Goff 2008; Goff et al. 2009; Downes et al. 2017; GNS[2] 2021a). A considerable volume of research has also been undertaken for wind-generated waves and seiches on New Zealand's lakes (e.g., Bottomley 1954; Ridgway 1974; Gilmour 1991, Carter & Lane 1996; Schallenberg et al. 1999), so these waves are not considered here in any further detail.

Having established a research gap, an extensive literature search was undertaken to establish baseline information, identifying historic locations, generating mechanisms, wave height, and frequency of lake waves in New Zealand, and damage these events have caused to life and property. This research complements natural hazard research and risk analyses currently being undertaken in New Zealand by government departments and agencies, local councils, and private companies, as many of the country's lake margins become increasingly developed for urban subdivisions, hydroelectricity production, agriculture, community water supplies, recreation, and tourism ventures. Locations of reported lake waves are shown in Figure 1, with evidential details for each listed chronologically in Appendix 1.

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[1] As called by Warren and Kirkbride (1998).

[2] GNS = Institute of Geological and Nuclear Sciences (New Zealand). Database is described in Downes et al. (2017).

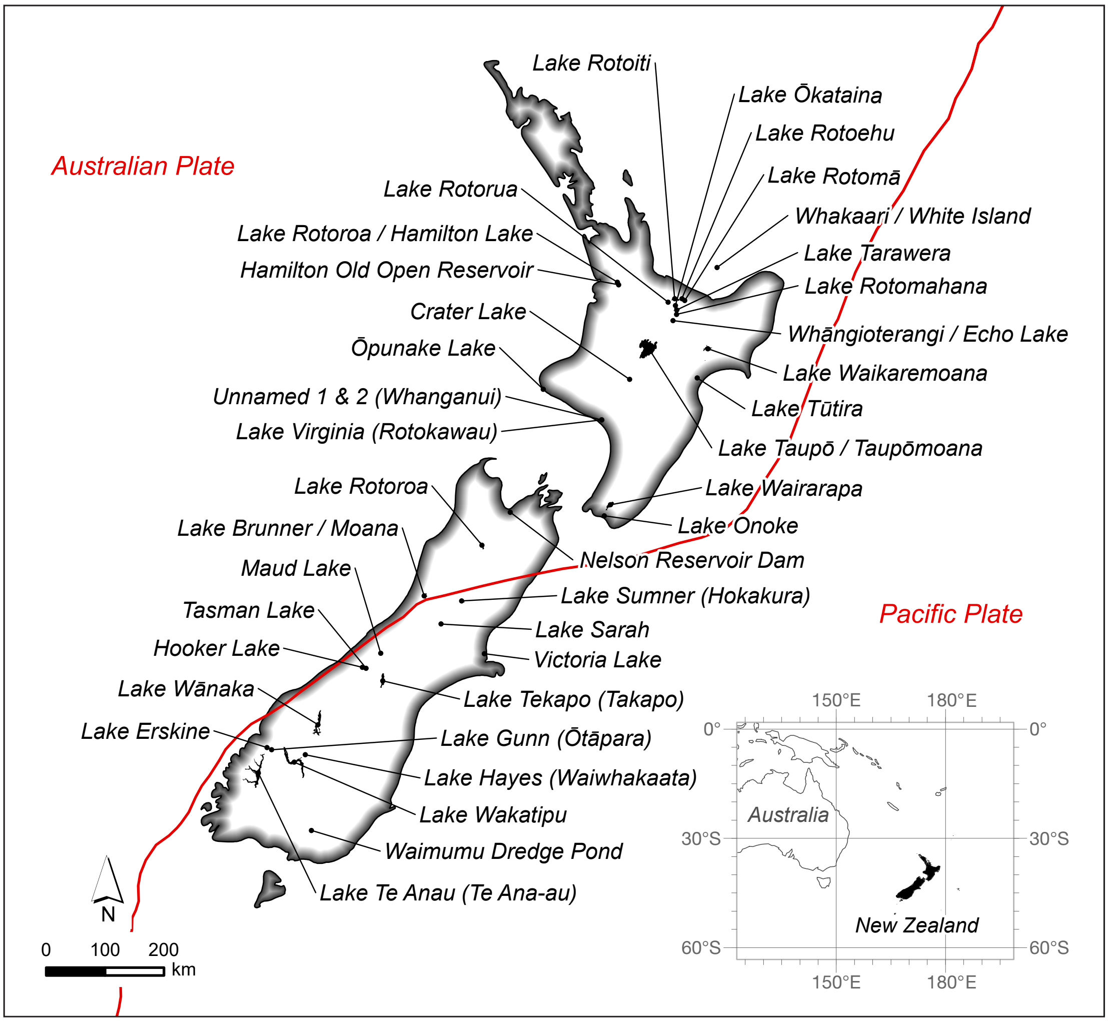

Figure 1. Location of New Zealand lakes from where lake waves have been reported. Red line is the Australian / Pacific tectonic plate boundary.

2. Methods

2.1 Information sources

The information in this report was derived from:

1. The *Papers Past* website (accessed 2020–2022). All New Zealand's newspapers have been scanned by the National Library of New Zealand, from each paper's first publication date up until at least 1920 and some to the 1970s. The scanning process is ongoing, and the website is regularly updated. This site provided most information, especially for the period 1846–1930s.
2. Major New Zealand and international earth-science journals (focusing on earthquakes, landslides, tsunamis and seiches), and especially published papers containing lists of tsunamis or earthquake events, such as Eiby (1968), de Lange and Healy (1986), Downes (1995), Downes and Grapes (1999), and Downes and Dowrick (2014). The events listed in these papers contained some detail on lake waves and provided a starting point for further information searches.
3. New Zealand Crown Research Institute website databases such as the *New Zealand Tsunami Database* [NZTD] (Downes et al. 2017; GNS 2021a) and the *Historic Weather Event Catalogue* (NIWA[3] 2021).
4. GNS landslide and earthquake reports for specific events.
5. Readily available reports on natural hazards (council reports, consultant reports etc.).
6. Postgraduate research theses.
7. General internet searches and miscellaneous general history books/reports.
8. Personal communication with other earth-science researchers who provided evidence (video, photographic, and eye-witness accounts) of lake wave occurrence.
9. Lake types identified in Table 1 are based on Lowe and Green (1987).

Words and phrases (and derivatives or combinations of them) such as agitated, disturbance, earthquake, earthquake-wave, landslide (slip/slump/fall), lake (water[s], surface), oscillation, pulsation, ripple, seiche, surge, tidal-wave, tsunami, and whirlpool, and specific-locality names of known, or potential lake-wave events were searched. As contemporary newspaper articles were often the only accounts, especially for older events, extracts from these have been quoted verbatim in Appendix 1, so as not to distort their originality. Therefore, original units of measurement (imperial or metric), earthquake magnitudes (M_W, $\hat{M}_W$, M_L, M_S, etc.), earthquake intensities (MM, R-F), and spelling (especially of Māori words) have been maintained. Also, as many lakes and places in New Zealand have multiple names (English, common Māori, traditional Māori), place names used are official names from Toitū Te Whenua Land Information New Zealand (2022), except for those in direct quotes.

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[3] NIWA = National Institute of Water and Atmospheric Research (New Zealand).

2.2 Definitions

Tsunami: Long-period waves generated by water displacement through processes such as mass movement (rock, debris, ice, snow) into or beneath a lake, fault displacement or tilting of the lakebed/basin, volcanic/geothermal activity, sedimentary gas expulsion, atmospheric coupling (i.e., volcanic-meteorological events), and meteorite impact. Most lake tsunamis are locally generated from sources within or immediately adjacent to the lake, apart from those caused by meteorite impact and atmospheric coupling. Downes et al. (2017) identified 15 tsunami-generating mechanisms in the NZTD, although ice-calving/collapse was not included. For this paper, all waves caused by material falling into a lake and displacing water are called tsunamis, regardless of the scale or volume of the material deposited (e.g., mass movement, small rockfalls etc.). Clark et al. (2015) separated 'splash waves' from tsunamis for events such as small rockfalls into lakes, but until further research is undertaken, this is not possible for most of the events identified in Appendix 1 so they have been grouped together in this review.

Seismic seiche: Based on Kvale (1955) and McGarr (2020), these are oscillating standing waves, set up in closed water bodies such as lakes, caused by the passage of seismic waves from an earthquake. They can be generated by local or distant (transglobal) earthquakes. Such waves can continue long after the initial release of earthquake energy. In this review, these waves are distinct from tsunamis as they are independent of the water displacement generating mechanisms listed above (and wind-forcing).

Undetermined wave: Unusual waves or oscillations (excluding wind-generated waves), but no distinct generating mechanisms were identified, preventing their determination as either tsunamis or seismic seiches.

Wave height: The vertical height of a wave, from its crest to trough.

Wave run-up elevation: The maximum vertical elevation above the lake surface, to which a lake wave reaches on the lake shore or adjacent land.

Subaerial landslide: A mass movement of earth that originated above the lake surface and collapsed into the lake. For this review, all mass movements such as landslides, slumps, and rockfalls are included.

Subaqueous slide: Mass-movement that originated below the lake surface (e.g., delta collapse, debris flows and slides).

Definitions for various earthquake magnitude and intensity notation are provided in Downes and Dowrick (2014). In cases when a generating mechanism produced a series of waves on unconnected lakes (e.g., 1931 Napier earthquake) the lake waves are listed as separate (multiple) events in Appendix 1. Conversely, in events such as the May 1992 Mount Fletcher rock avalanche / Maud Glacier[4] ice collapse, which produced a single wave that travelled across multiple, connected lakes, the lake wave was listed as a single event.

2.3 Validity

For oceanic tsunamis, previous researchers have used a combination of numeric and descriptive methods to rank the validity of tsunami occurrence, ranging from the most detailed and valid, to the vaguest and least reliable reports (e.g., Cox & Morgan 1977; de Lange & Healy 1986; Downes et al. 2017). Based on available evidence for individual events and the validity classes of Downes et al. (2017), the validity of lake-wave occurrences listed in Appendix 1 have been defined (in descending order) as Definite, Probable, and Possible.

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[4] The Mount Fletcher rock avalanche also caused a smaller ice collapse on the Grey Glacier, which also fell into Maud Lake. For convenience in the text, both ice collapses are collectively referred to as the Maud Glacier ice collapse. See McSaveney (1992a, b, 1993, 2002) for details.

3. Results

Seventy-four lake-wave events have been recorded on 38 lakes throughout New Zealand (Figure 1); results are summarised in Tables 1–4, below. Lakes in Table 1 are listed from north to south.

Table 1. Lakes affected and number of lake waves recorded in New Zealand. (NI) = North Island, (SI) = South Island.

LAKE	LAKE TYPE	TOTAL NUMBER OF WAVES	WAVE TYPE AND NUMBER		
			TSUNAMI	SEISMIC SEICHE	UNDETERMINED
Whakaari / White Island (NI)	Volcanic	1	1		-
Rotoroa / Hamilton (NI)	Peat	2	-	2	-
Hamilton old open reservoir (NI)	Artificial	1	-	1	-
Rotoehu (NI)	Volcanic	1	1	-	-
Rotoiti (NI)	Volcanic	3	1	2	-
Rotomā (NI)	Volcanic	1	-	1	-
Rotorua (NI)	Volcanic	1	-	1	-
Ōkataina	Volcanic	2		2	
Tarawera (NI)	Volcanic	3	1	-	2
Rotomahana (NI)	Volcanic	3	2	1	-
Whāngioterangi / Echo (NI)	Volcanic	1	1	-	-
Taupō / Taupōmoana (NI)	Volcanic	13	7	4	2
Waikaremoana (NI)	Landslide	1	-	1	-
Tūtira (NI)	Landslide	1	1	-	-
Crater Lake (NI)	Volcanic	6	6	-	-
Ōpunake Lake (NI)	Artificial	1	1	-	-
Virginia (Rotokawau) (NI)	Dune	1	-	1	-
Unnamed (1) Whanganui (NI)	Dune	1	-	1	-
Unnamed (2) Whanganui (NI)	Dune	1	-	1	-
Wairarapa & Onoke (NI)	Riverine & Bar	2	2	-	-
Nelson reservoir dam (SI)	Artificial	1	-	1	-
Rotoroa (SI)	Glacial	3	1	-	2
Brunner / Moana (SI)	Glacial	1	1	-	-
Sumner (Hokakura) (SI)	Glacial	1	1	-	-
Victoria (SI)	Artificial	1	-	1	-
Sarah (SI)	Glacial	1	1	-	-
Maud & Tekapo (Takapo) (SI)	Pro-glacial & Glacial	2	2	-	-
Hooker	Pro-glacial	2	2	-	-
Tasman (SI)	Glacial	4	4	-	-
Wānaka (SI)	Glacial	2	1	1	-
Wakatipu (SI)	Glacial	4	1	3	-
Erskine	Glacial	1	1	-	-
Gunn (Ōtapāra)	Glacial	1	1	-	-
Hayes (Waiwhakaata) (SI)	Glacial	1	-	-	1
Te Anau (Te Ana-au) (SI)	Glacial	2	1	-	1
Waimumu dredge pond (SI)	Artificial	1	-	1	-
Totals		**74** (100%)	**41** (55%)	**25** (34%)	**8** (11%)

Table 2. North Island, South Island, and New Zealand sub-totals, from Table 1.

LOCATION	WAVE TYPE AND NUMBER			
	TSUNAMI	SEISMIC SEICHE	UNDETERMINED	TOTAL
North Island	24	18	4	46 (62%)
South Island	17	7	4	28 (38%)
New Zealand total	**41 (55%)**	**25 (34%)**	**8 (11%)**	**74 (100%)**

Table 3. Lake-wave association with generating mechanisms. At least eight more mass-movement cases are probable (see Discussion and Appendix 1). Note that sum of waves, and (%), are greater than 74 and 100%, respectively, as many lake waves were counted more than once, reflecting their association with multiple generating mechanisms.

LAKE-WAVE GENERATING MECHANISM	NUMBER (%) OF LAKE WAVES ASSOCIATED WITH GENERATING MECHANISMS
Seismic shaking	48 (65%)
Mass-movement of land (subaerial/subaqueous slides)	18 (24%)
Volcanic/geothermal activity	14 (19%)
Ice-calving/collapse	10 (14%)
Gas-expulsion	6 (8%)
Undetermined	6 (8%)
Rainfall	3 (4%)
Avalanche (snow, ice)	3 (4%)
Liquefaction	2 (3%)
Faulting/tilting (lakebed/margins)	1 (1%)
Atmospheric coupling	1 (1%)

Table 4. Validity of lake-wave occurrence.

VALIDITY	NUMBER OF LAKE WAVES
Definite	48
Probable	16
Possible	10

4. Discussion

4.1 Historic record and validity

It is acknowledged that the list of historic events presented in Appendix 1 is incomplete for the following reasons. Many of New Zealand's lakes, particularly the South Island's glacial lakes, are remote from populated areas and hence numerous lake-wave events may not have been witnessed nor recorded. Globally, other researchers such as Kvale (1955), Roberts et al. (2013) and Clark et al. (2015) have noted similar correlations between population density and the number of historic records for such events. Similarly, many potential wave-generating mechanisms like earthquakes and landslides, have occurred at night, and again, eyewitness accounts may have been missed.

Comparatively little information was found for the period between the mid-1930s and early 2000s. This generally correlates to the availability of digitised newspapers. Many of the newspapers on the *'Papers Past'* website have only been scanned up the 1920–30s so far, and modern digital-format, web-based newspapers only go back approximately 10–15 years. Physically searching newspapers from this digital-gap period was outside the project's scope, although more recent references indicate that few events would have been missed from this gap. Likewise, more events may have been identified by searching data for lake and reservoir levels held by electricity-generation companies, irrigation companies, and local councils, but this was also out-of-scope. That said, real-time lake-level data for most of New Zealand's lakes are non-existent, further increasing the possibility of lake-wave events being undetected. Research into lake waves in New Zealand is a recent phenomenon and has focused on modelling future events rather than documenting historical occurrence, and thus, historical information is limited. Finally, some records may have been missed in the literature search.

Owing to potential inaccuracies of old newspaper reports (Munro & Fowler 2014), some of which were identified in this research, it is also accepted that some historical accounts relying solely on old newspapers may not be as accurate as others based on several independent sources of information. Therefore, in some cases, details reported in Tables 1–4 and Appendix 1 may change as more information is found and further analysis is undertaken. Nonetheless, in similar investigations for historic oceanic tsunamis, Cox and Morgan (1977), de Lange and Healy (1986), Fraser (1998), and Downes et al. (2017), noted the value and importance of newspapers as an information source, which holds true for this review. Despite the limitations of the information found, the events listed in Appendix 1 provide a baseline for further research and the following initial observations can be made.

4.2 Distribution

Lake waves have been recorded in 38 lakes (natural, modified, and artificial) throughout the country, from Whakaari / White Island's crater lake in the north to the Waimumu dredge pond in the south (Figure 1; Table 1). No lake wave records were found for the far north of the country (Auckland or Northland regions), despite both regions having numerous natural lakes and artificial reservoirs. The lack of records from Northland maybe attributed to either an absence of events, or observation bias (sparsely populated), whilst the most likely explanation for Auckland is an actual absence of lake wave occurrence: Auckland is the most densely populated region in the country, making the probability of lake wave observation high, if any had occurred.

Forty-six lake waves (62%) have been recorded in 21 North Island lakes, and 28 lake waves (38%) in 17 South Island lakes. That the North Island has recorded nearly two-thirds of the total number lake waves, compared to just over a third for the South Island, is considered as much a function of observation bias as it is of environmental factors. This is because, historically, many North Island lake-margins have had higher population densities than those of the South Island. For example, Lake Taupō / Taupōmoana has the highest recorded incidences of lake waves (n = 13) for an individual lake and has historically had some of the most populated lake margins in the country[5]. This concurs with Roberts et al. (2013, p.134) who noted that the documentation of lake tsunamis in British Columbia (Canada) and Washington State (USA), was *"… biased to areas of population and the recent historic period"*.

Lake waves have occurred on lakes ranging in size from Lake Taupō / Taupōmoana, New Zealand's largest lake (616 km^2; Livingston et al. 1986b), to some of the smallest, such as Victoria Lake in Christchurch (< 2.0 ha), and in some of the country's deepest lakes, like Lake Te Anau (Te Ana-au, 417 m deep), to some of the shallowest, with several being ≤ 2.0 m deep (e.g., Irwin 1975; Livingston et al. 1986a, b). Lake waves have also occurred in the country's highest lake, Crater Lake (Mount Ruapehu) at c. 2,734 m above sea level (e.g., Allen 1907; *Evening Post* 23 March 1945, p. 6.) and in some of its lowest, such as Lake Wairarapa at ≤ 1.0 m above mean sea level (Livingston et al. 1986b).

4.3 Generating mechanisms

Lake waves in New Zealand have been generated by all known mechanisms, apart from meteorite impact. These include seismic shaking, co-seismic and non-seismic mass-movement of rock, debris, ice, snow, and liquefaction, into, or beneath lake waters; volcanic/geothermal activity (eruptions in lakes, lava bombs falling into lakes), sedimentary gas-expulsion, atmospheric coupling, fault-rupture or tilting of lakebeds (or immediate lake vicinities), and other, undetermined means. Most lake waves (n = 48; 65%) have been associated with earthquakes, either as a direct consequence of seismic shaking or from secondary, co-seismic effects (e.g., mass-movement, lake-bed faulting, etc.). Given New Zealand's high seismicity levels, owing to its position across an active tectonic plate boundary, this perhaps, is not unexpected. In cases where calculated earthquake magnitudes are known, M_L 5.3 was the lowest magnitude found to be associated with lake-wave generation (1956 and 2022 Taupō / Taupōmoana tsunami events), although based on some of the descriptive accounts in Appendix 1, it is probable that earthquakes of < M_L 5.3 have generated lake waves. The historic record also shows that large-magnitude geological events (earthquakes and volcanic eruptions) can generate more lake waves over a wider area, than climatic events (rainfall-induced landslides, ice calving, avalanches), which tend to produce an individual lake wave at a specific site (Figure 2). Although 18 (24%) of lake waves have been attributed to some form of subaerial or subaqueous mass-movement, it is most likely that at least eight (11%) more lake waves have been associated with this. In these events[6], landslides were recorded in the immediate vicinity of various lakes, but no reports were found of subaerial or subaqueous mass movement directly affecting the lakes.

In the North Island, lake waves have been generated by all mechanisms identified, although those associated with ice-calving/collapse have been restricted to Crater Lake on Mount Ruapehu; the only North Island lake with a permanent icefield adjacent to it. In the South Island, lake waves have been generated by all mechanisms, barring volcanic/geothermal activity (which is confined to the North Island), and atmospheric coupling,

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[5] Rapid population growth and development is occurring around many of New Zealand's lake margins, for example, around some of the large, South Island glacial lakes, such as lakes Brunner / Moana, Tekapo (Takapo), Ōhau, Hāwea, Wānaka, Wakatipu.

[6] Event dates, and lakes, where mass movement was most likely associated with lake-wave occurrence, but no direct evidence has yet been found of landslides into, or beneath the lakes: 24 June 1869 (Hayes); 26 January 1903 (Te Anau [Te Ana-au]); 17 June 1929 (Rotoroa [South Island] and Brunner / Moana); 15 July 1935 (Taupō / Taupōmoana); 24 June 1942 (Wairarapa); 8 May 1943 (Wānaka); 14 January 1953 (Rotoiti, North Island).

although the latter remains a possibility. In many events, multiple, simultaneous trigger-mechanisms were involved (Table 3; Appendix 1). Further research on the lake waves identified in this paper could add to, or align the generating mechanisms more directly, to those categories identified in the established NZTD, thus producing more consistency between the datasets.

Lake waves in New Zealand have been generated by local, national, and remote, global-scale mechanisms. As examples, the May 1992 tsunami affecting Maud Lake and Lake Tekapo (Takapo), was generated by a very localised event – the Mount Fletcher rock avalanche / Maud Glacier ice-collapse (e.g., McSaveney 2002). On a national scale, Grapes (2000), noted that the 1855 Wairarapa earthquake caused seismic seiching in lakes and rivers from Lake Rotoiti in the North Island to near Christchurch in the South Island; an approximate range of 920 km. At a global scale, the 1883 Krakatoa eruption (Indonesia) caused a volcano-meteorological tsunami on Lake Taupō / Taupōmoana (*The Thames Star* 15 September 1883, p. 2; de Lange & Healy 1986; Lowe & de Lange 2000), some 7,900 km from the source. Similarly, the February 1938 Banda Sea earthquake in Indonesia (Okal & Reymond 2003) was the apparent source for the seismic seiche reported on Virginia Lake (Rotokawau) (e.g., *Evening Post* 5 February 1938, p. 10; Appendix 1). Besides these two global-scale examples, all other reported lake waves (97%) were generated by mechanisms originating within New Zealand.

4.4 Wave height and wave run-up elevation

Reported maximum wave heights for lake tsunamis have been higher than for seismic seiches. The highest lake wave to have been instrumentally recorded, was the c. 3.1 m high tsunami on Tasman Lake, in the February 2011, Haupapa / Tasman Glacier ice-calving event (Dykes 2013; Dykes et al. 2017). However, based on environmental damage and valley dimensions, calculations, and estimates for the tsunami height during the May 1992, Maud Lake event (Appendix 1), ranged from c. 10 m (McSaveney 2002; calculated) to ≥ 20 m (Dore 1992; estimated). A tsunami height of c. 10 m is most credible and comparable to some of the largest oceanic tsunamis recorded around the New Zealand coast (e.g., de Lange & Healy 1986; Fraser 1998; GNS 2021a; NIWA 2021). If Dore's (1992) wave height estimate of ≥ 20 m is correct, then this would be the highest tsunami (oceanic, lake, or river) recorded during historic times in New Zealand, exceeding the supposed 15 m high landslide-generated tsunami in the Waikari River, during the 1931 Napier earthquake (Tait 1977, Donaldson 2016, Donaldson et al. 2019). However, based on Tait's (1977) recollections, it is not clear from Donaldson (2016) or Donaldson et al. (2019), whether the 15 m refers specifically to the wave height, or the wave run-up elevation above the river level[7]. Likewise, McSaveney (2002, p. 61) casts doubt on an c. 20 m wave height for the May 1992 Maud Lake event; although McSaveney reported icebergs being stranded 20 m above the lake, near Godley Hut, he stated: *"The witnesses' descriptions of where icebergs were deposited include runup of water as well as iceberg momentum and there is uncertainty as to whether "20 m above the lake" refers to a height of 20 m or that ice was stranded 20 m from the lake on the steep shores"*. Nevertheless, a tsunami run-up height of 20 m above the lake surface is comparable with modelling results by Clark et al. (2015) and Fraser and McMorran (2016), who calculated that tsunami run-up heights of up to 25 m could occur at lakes Tekapo (Takapo), Pukaki, and Ōhau through large landslides entering these lakes. Detailed surveying undertaken by GNS after the November 2022 Taupō / Taupōmoana tsunami, showed maximum wave run-up elevation was approximately one metre above the usual high-water mark, and the maximum run-up limit extended about 40 metres inland from the high-water mark (Geonet 2022c; Appendix 1).

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[7] 15 m high is most likely the wave run-up elevation above the river, based reported inundation depths on the on highest river terrace surface, (*Poverty Bay Herald* 13 February 1931, p. 2; Tait 1977; Mackanzie 2007; Orr 2007; Donaldson 2016, p. 7).

Donaldson (2016) and Donaldson et al. (2019) stated the 1931 Waikari River tsunami was the largest tsunami of any type recorded in New Zealand during historic times. However, this tsunami's effects were very localised, being confined to a small area of meandering river terraces, in a narrow, steep-sided valley. In contrast, the Maud Lake tsunami travelled 45 km from its source in Maud Lake, then down the Godley River valley into Lake Tekapo (Takapo), raising the 87 km^2 lake by c. 90–98 mm (Dore 1992; McSaveney 1993, 2002; Appendix 1). On that basis, this event could qualify as the largest terrestrial-based tsunami in historical times, even if the wave height was less than the 1931 Waikari River event.

Reported wave heights for seismic seiches and undermined waves (mostly based on visual observations), have ranged from c. 12 mm to 4.5 m. (e.g., *Christchurch Star* 17 June 1929a, b; *Poverty Bay Herald* 4 February 1931). The upper limit is comparable to modelling results by Wang et. al. (2020) who showed that seismic seiche wave heights in the southern arm of Lake Tekapo during a Mw 8.2 Alpine Fault earthquake could reach c. 4.0 m. Where estimates for seismic seiche and undetermined wave heights are given in Appendix 1, most are < 2.0 m.

4.5 Duration

Reported durations for lake-wave oscillations have ranged from a few minutes to approximately one month. The longest period of observed seismic seiching was on Lake Rotorua, where Pond and Smith (1886) reported continuous lake oscillations for just over a month, following the 10 June 1886, Mount Tarawera volcanic eruption and associated earthquake swarm. Oscillations caused by undetermined means (possibly through mass-movement) occurred continuously for a week on Lake Taupō / Taupōmoana in February 1933 (e.g., *Auckland Star* 21 February 1933; *Nelson Evening Mail*, 23 February 1933). In contrast, the longest recorded tsunami durations have been shorter. For example, McSaveney (2002) noted a rapid rise in Lake Tekapo's (Takapo) level from the arrival of Maud Lake tsunami flood-wave, 5.6 hours after the wave's generation, which then declined exponentially over several days. Likewise, almost immediately after the February 2011 Haupapa / Tasman Glacier ice-calving event, Dykes et al. (2017) reported a large, rapid rise in the level of Tasman Lake, which then returned to a lower level around four days after the event (and preceding rainfall input). In Appendix 1, where durations of lake waves are given, most range from a few minutes to a few hours. Examples include at: Lake Sarah (December 1881), Lake Taupō / Taupōmoana (July 1935, November 2022), Virginia Lake (Rotokawau) (February 1938), Crater Lake (March 1945), Lake Rotoiti (North Island), Lake Rotomā and Lake Ōkataina (all January 1953).

4.6 Frequency

Previous authors have stated, or implied, that lake waves in New Zealand are rare, low-frequency events. As examples, Clark et al. (2015, p. 9) stated: *"There have been relatively few reported occurrences of tsunami and seiche waves on lakes in New Zealand, but this is probably due to a short written history (since ~ AD 1840), rather than a real absence of record"*. When discussing large-scale rock avalanches in the Southern Alps/Kā Tiritiri o te Moana, Hawley (1984, p. 123) commented that: *"A remote, but real possibility exists that one of these may fall into a lake (natural or "Hydro") and create waves of damaging proportions"*. Painter (2004, p. 11) reported on risks relating to water and mass-movement in New Zealand, and when referring to oceanic tsunamis wrote: *"Not so often noted is the risk of such a surface wave caused by a landslide entering an inland water body such as a lake or large reservoir"*. Recent research on potential lake waves in New Zealand, based on their association with return-periods of seismic ground-shaking intensities and/or landslides, also infer a low frequency of occurrence (e.g., Clark et al. 2011; Ward et al. 2015). Mackey (2015, p. 65) declared: *"Lake tsunamis are rare and unpredictable",* and when assessing tsunami hazards at Lake Tekapo (Takapo), Mountjoy et al. (2019) noted that on a global scale, the risk from landslide-generated tsunamis in lakes remains unquantified. For large-scale, ice-calving events at the Haupapa / Tasman Glacier (New Zealand's largest glacier) and Tasman Lake, Dykes et al. (2017; p. 342), concluded that they: *"… are a rarity"*, and when assessing flood hazards in the Taupō District, Ward et al. (2015, p. 101) excluded wave run-up caused by landslides into lakes: *"… since such events have been extremely rare (and random)"*.

This review challenges those notions. Although detailed statistical analysis has not been undertaken (as large gaps in the current record first need to be filled), 74 lake waves over a 176-year period shows that lake wave occurrence in New Zealand has been far more frequent than previously documented. For example, the NZTD lists over 800 oceanic tsunamis (of all magnitudes) for a comparable period, but it lists only six lake tsunamis. Figure 2 shows the basic frequency distribution of lake wave occurrence. The large gap in the record, corresponding to the availability of digitised newspapers (1930s–early 2000s) can be clearly seen, as can years with spikes in the frequency (three or more lake waves), where large-magnitude geological events generated multiple waves.

The frequency of lake waves, especially in the South Island's glacial lakes, could increase in the future with predicted climate change affecting the frequency of landslide, avalanche, and ice-calving events in the Southern Alps / Kā Tiritiri o te Moana. As examples, Warren and Kirkbride (1998) examined ice-contact lakes in the Southern Alps / Kā Tiritiri o te Moana, noting that climate change had altered glacier behaviour, which in turn, initiated ice-calving

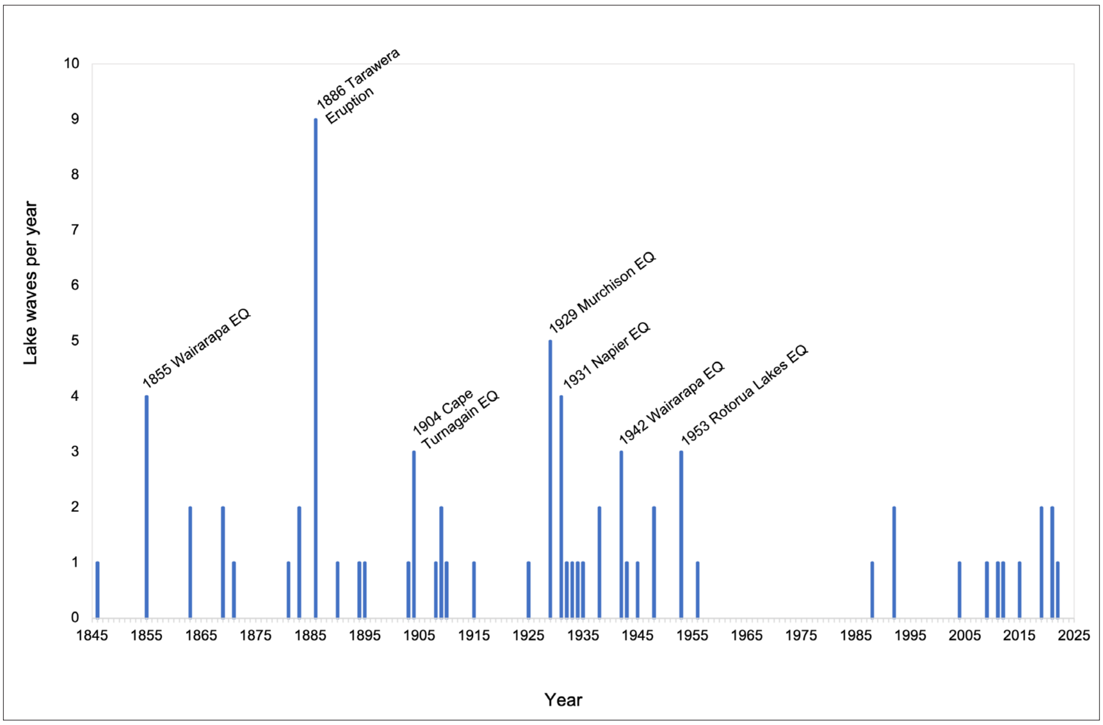

Figure 2. Lake-wave occurrence, 1846–2022. EQ = Earthquake. In years with three or more lake waves recorded, the wave generating mechanisms have been dominated by the named, large-magnitude geological events (rather than climatic events), which produced waves on multiple lakes. As shown, the 1886 Mount Tarawera eruption is the dominant lake wave generating event, although this could be misleading, as the 1855 Wairarapa Earthquake most likely generated many more lake waves than the four recorded (see Grapes 2000; Appendix 1). Gaps in the record, especially from the 1930s to early/mid 2000s, correlate with an absence of digitised newspapers – the basis of this review – and prior to the early 1900s, many newspapers were not published daily so events may not have been reported. Prior to the early/mid 1900s, much of New Zealand was very sparsely populated, making the probability of lake wave observation highly unlikely. The recent cluster of events between 2009–2022 reflects increasing observation, monitoring, and reporting, from several of the South Island's remote glacial and pro-glacial lakes, and Lake Taupō / Taupōmoana.

events. McSaveney (2002, p. 68) reported on rockfalls and rock avalanches in the Southern Alps / Kā Tiritiri o te Moana, stating that climatic warming and glacier-thinning (over centuries) have unloaded the toes of some exceptionally steep slopes, which is likely to have increased the frequency of catastrophic rock collapses (albeit, a small increase), and that: *"Glacier recession, however has increased the number of lakes in the Southern Alps, and heightened the risk of down-stream flooding"*. However, Allen et al. (2011, p. 33) examined possible climate change impacts on rock avalanches and other landslides in the Southern Alps/Kā Tiritiri o te Moana and concluded that it was not yet possible to distinguish the influence of atmospheric warming from the *"… simultaneous effects of weather, erosion, seismicity, and uplift along an active plate margin"*. Determining lake wave frequency for an individual lake would require detailed multi-variate analyses of all potential generating mechanisms at the specific site, as lake-wave generation is often dependent on the occurrence of multiple, and simultaneous, mechanisms.

4.7 Personal injury and near-misses

Only one case of personal injury caused by lake waves has been reported. In the 1904 Lake Rotomahana seismic seiche event (Cape Turnagain earthquake), a tour-boat guide badly injured his hand as he tried to hold a boat against the jetty whilst the lake was seiching (*Poverty Bay Herald* 17 August 1904a; Downes 2006). There have been several 'near-misses' when people have been physically swept away or knocked over by lake waves or have been in small boats on lakes when the waves struck. Examples include an unnamed lake at Whanganui (January 1855), Lake Wakatipu (April 1871), Lake Tarawera (June 1886), Waimumu dredge pond (March 1909), Lake Taupō / Taupōmoana (March 1910; March 1956), Lake Brunner / Moana (June 1929), Lake Waikaremoana (February 1931), Lake Wairarapa (June 1942), Whāngioterangi / Echo Lake (May 1948), Lake Te Anau (Te Ana-au, June 1948), and Tasman Lake (February 2011) (see Appendix 1).

4.8 Property/structural damage

To date, lake waves have caused little damage to private property or public infrastructure, primarily because most of the major historical events have occurred in sparsely populated and low-developed lake locations (at the time of occurrence). The most significant structural damage recorded, occurred near the outlet of Lake Rotoroa (South Island) during the June 1929 Murchison earthquake tsunami, where the Te Kauparenui / Gowan River bridge and the lake's jetty were destroyed and the Lake Rotoroa Hotel was severely damaged (e.g., *Nelson Evening Mail* 19 June 1929a). Lesser damage has included the washing-out of small sections of the four-wheel-drive access road to Godley Hut during the May 1992 Maud Lake tsunami (McSaveney 2002), and on several occasions small watercraft have been washed away from boatsheds, jetties, and moorings, as at Lake Tarawera (June 1886), Lake Taupō / Taupōmoana (March 1910, November 2022), Lake Brunner / Moana (June 1929), Lake Sumner (Hokakura) (March 1929), Lake Waikaremoana (February 1931), and Lake Te Anau (Te Ana-au, July 1988) (see Appendix 1).

4.9 Environmental damage

The most significant environmental damage caused by a lake wave was around the margins of Maud Lake and in the Godley River valley during the Maud Lake tsunami of May 1992. Dore (1992) and McSaveney (1992a, b; 1993, 2002) described large masses of rock, ice, and vegetation debris being deposited up to 20 m above the lake level around the lake margins, and widespread, severe scouring of vegetation and sediment from the Godley riverbed for many kilometres downstream of the lake. The November 2022, Lake Taupo / Taupōmoana tsunami caused shoreline erosion (undercutting) at several localities around the lakeshore, and deposited silt, pumice, and driftwood, up to 40 m inland from the from the lake's normal high-water level, at the time of occurrence (Geonet 2022c; Appendix 1).

5. Conclusion

This review provides the most comprehensive information on historic New Zealand lake waves to date and establishes a baseline for further research. The major findings are that lake waves have occurred on all types of lakes, the length and breadth of the country and, apart from meteorite impact, they have been generated by all known mechanisms, ranging from local to global scale. Ultimately, most lake waves have been generated by, or associated with, seismic shaking. Lake-wave heights have ranged from a few millimetres (barely detectable) to c. 10 m (catastrophic), with tsunamis having the greatest height. It was also found that lake waves have occurred at a much higher frequency across New Zealand than previously considered, which could have implications for future lakeside planning and developments. Historically, lake waves have caused minimal damage, although the hazard and risk they pose are expected to increase in the future as the frequency of lake waves potentially increases with climate change, and as many of the country's lake margins become increasingly developed. More historic research (and modelling of potential events) is needed to better understand the hazard and risk that lake waves pose in New Zealand.

5.1 Further research

Further research and modelling of potential generating mechanisms, wave height and travel paths, would: 1) expand on the historic information presented and refine the detail therein, especially in relation to wave-type and validity; 2) help improve understanding the lake-wave hazard, in terms of locations, generation processes and potential flow-paths, and 3) help identify the physical, social, and economic costs that the lake-wave hazard poses in New Zealand. The most obvious starting point for such information would be searches of newspapers from the 1930s to the early 2000s (i.e., those not yet scanned into the 'Papers Past' website, or produced in modern, digital format). Additionally, data on lake and reservoir levels held by various organisations could be correlated to the dates of known earthquake or landslide events to determine if lake waves occurred on these dates, as they may not have been reported in newspapers or elsewhere. Likewise, universities and other research organisations are establishing time-lapse video recorders around several of the South Island's glacial lakes, primarily for avalanche and mass-movement research but analysis of such footage may identify more lake waves of various types, as in the September and October 2021 Hooker Lake tsunamis. Information from these sources would help improve the overall understanding of a little-known and poorly understood natural hazard in New Zealand.

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Appendix 1. Tsunamis, seismic seiches, and ‘undetermined’ wave events recorded on New Zealand lakes: 1846–2022

Date: **7 May 1846**

Lake(s): Taupō / Taupomōana

Wave type: Tsunami

Generation: Subaerial landslide into lake (natural dam failure) caused by heavy rainfall (e.g., Massey et al. 2009)

Effects: Although no specific wave records exist, evidence provided by the 21 March 1910 landslide tsunami event in the same vicinity (see below), and Māori oral history, make it reasonable to presume a subaerial, landslide-generated tsunami, most likely occurred[8]. The *New Zealand Spectator and Cook’s Straight Guardian* (1 July 1846; p. 6) reported that: *“The natives say that afterwards the taniwa* (taniwha) *fled across the lake … they saw the splash of his tail as he crossed the lake”*. In traditional Māori history, large waves, storm surges, and tsunamis were commonly explained as the work of a taniwha (King et al. 2007). In the NZTD, this tsunami (ID 18) has a validity rating of ‘Probable’ and it is stated: *“… it is likely that the taniwha in the lake after the landslide in 1846 represents a tsunami”*.

Massey et al. (2009) concurred with this as their landslide-generated wave modelling for the same site produced similar wave paths, to those described in Māori oral history. Massive water displacement can also be inferred in a diary entry made by the Rev. Richard Taylor, a day or so after the landslide, stating: *“We were about half a mile from Te Rapa, I noticed that the lake was still discoloured with the vast quantity of mud which had flowed into it”* (*New Zealand Herald*, 23 March 1910, p. 8).

Validity: Probable

Date: **23 January 1855**

Lake(s): Rotoiti (North Island)

Generation: Earthquake (Wairarapa). Epicentre 41.20°S, 175.20°E. Magnitude M_{WF} 8.2–8.3. Depth 33 km (Downes & Dowrick 2014)

Wave type: Seismic seiche

Effects: Grapes (2000) mentions Lake Rotoiti as the northern-most lake in which seiching occurred during this earthquake (see lakes Wairarapa and Onoke, below).

Validity: Definite

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[8] The landslide that caused the 1846 tsunami, destroyed the village of Te Rapa (Little Waihi) and killed 64 people, whilst the landslide that generated the 20 March 1910 tsunami (in very close proximity), destroyed Waihi village, and killed one person (e.g., *Auckland Star* 21 March 1910, Lowe 1910, Massey et al. 2009). The lake waves themselves were not responsible for the fatalities. Lowe (1910) erroneously states the landslide date as 27 March 1910.

Date: **23 January 1855**

Lake(s): Unnamed (1): Whanganui

Generation: Earthquake (Wairarapa. See above)

Wave type: Seismic seiche

Effects: Downes and Grapes (1999) quote an anonymous author from *Chapman's New Zealand Monthly Magazine* (October 1862): *"A small but deep lake near Whanganui, on which the writer was then living, surged backwards and forwards many times in a remarkable manner, and was covered the next morning with masses of raupo, torn up from a depth of several feet in the swampy heads of the bights into which the lake runs"*.

Validity: Definite

Date: **23 January 1855**

Lake(s): Unnamed (2): Whanganui

Generation: Earthquake (Wairarapa. See above)

Wave type: Seismic seiche

Effects: Continuing from the unnamed lake (1) event, above, *Chapman's New Zealand Monthly Magazine* (October 1862) states: *"Another sheet of water, in the same vicinity, broader and shallower than the above, spread so suddenly over the low flat land at its lower end, that a man … who was riding out from the town of Whanganui, and was about half-way across the level just named, found his horse suddenly knee deep in water, and checked her hurriedly, thinking she must have mistaken the road and be walking straight in to the lake … The water retreated as suddenly as it appeared…"*.

Validity: Definite

Date: **23 January 1855**

Lake(s): Wairarapa & Onoke

Generation: Earthquake (Wairarapa, see above). Associated faulting, uplift and tilting of lake basin

Wave type: Tsunami

Effects: Although a lake wave was not reported, it is implied that a vast amount of water had to have been displaced by the massive uplift around Lake Wairarapa and 28 000 acres of lake becoming dry. Menteath and Pownall (1871), the lawyers acting for local Māori, regarding ownership of the two lakes, wrote: *"In 1855 severe earthquakes raised the land and lowered the lake, and on the western side the land was upheaved nine feet and approximately 27 692 acres of land was reclaimed … and now approximately 28 000 acres around the margin of the lakes has become dry, by the earthquake of 1855"*. Specific detail of uplift around the lake, and lake margins becoming dry, is provided in Mackay (1891). It is also reasonable to presume that a lake tsunami occurred, as one of New Zealand's largest oceanic tsunamis was generated from the coastal area immediately adjacent to lakes Wairarapa and Ōnoke (e.g. de Lange & Healy 1986; Fraser 1998; Downes et al. 2017; GNS 2021), and Grapes (2000), noted that seiching occurred in lakes and rivers as far north as the Waipā River and Lake Rotoiti in the upper North Island, and as far south as the Waimakariri River in the South Island. However, Grapes (2000) does not name all the individual lakes affected and searches of newspapers failed to find mention of other lake waves.

Validity: Probable

Date: **Pre 10 November 1863**

Lake(s): Rotoroa (South Island)

Generation: Undetermined – possible subaerial or subaqueous mass movement

Wave type: Undetermined

Effects: Higgin (1863, see below) reported this was the first time he had witnessed Lake Rotoroa becoming suddenly agitated, for no apparent reason.

Validity: Possible

Date: **10 November 1863**

Lake(s): Rotoroa (South Island)

Generation: Undetermined – possible subaerial or subaqueous mass movement

Wave type: Undetermined

Effects: Higgin (1863) reported the following curious phenomenon at Lake Rotoroa: *"There was no wind or rain at the time, yet at two o'clock p.m. it thundered a little as if at a distance, when all at once Roto-roa became most violently agitated, the waves rose to a height dangerous for a canoe to attempt to cross the lake. The whole again became calm and smooth as a mirror, in an hour or so. This is the second time it has occurred since I have been in the district; there was no sensation of an earthquake felt by any person in the neighbourhood"*.

Validity: Possible

Date: **24 June 1869**

Lake(s): Wakatipu

Generation: Earthquake – classed as a *"smart shock"* (Hector 1869)

Wave Type: Seismic seiche

Effects: Up to three severe earthquake shocks occurred around 11:00 am and: *"The lake was greatly disturbed"* (*Otago Daily Times*, 25 June 1869, p. 2). The earthquake was reported in many newspapers across the country. The *Evening Star* (24 June 1869, p. 2) reported the earthquake was violent, felt most strongly in the Queenstown area and that: *"The waters of the lake* (Wakatipu) *and the Shotover* (River) *were very much agitated"*.

Validity: Definite

Date: **24 June 1869**

Lake(s): Hayes (Waiwhakaata)

Generation: Earthquake (See above)

Wave type: Undetermined

Effects: A reporter from the *Dunstan Times* (2 July 1869, p. 3) was standing on the terraces that overlook Lake Hayes (Waiwhakaata), when the earthquake struck and reported: *"I looked about to see if (---) cliffs had fallen into the lake (---) the water was placidly still, with the exception of a long rolling wave which followed the direction of the earthquake"*. The dashed lines (---) indicate obliterated text in the scanned newspaper, making it impossible to determine if landslides from the cliffs did fall into the lake and generate the reported wave (tsunami), or if it was a seiche caused by seismic shaking.

Validity: Probable

Date: **19 April 1871**

Lake(s): Wakatipu

Generation: Earthquake – classed as *"Severe"* in Queenstown (Hector 1871)

Wave Type: Seismic seiche

Effects: An earthquake was felt over southern New Zealand. The shock at Queenstown (3:58 pm) was more severe than in other areas (*Evening Star* 19 April 1871, p. 2). A passenger on a sailing boat, of 4–5 tons, who was crossing the lake when an earthquake struck, reported that: *"… a sudden upheaval of our little craft took place, the stern seemed to be lifted right out of water, and the bow dipped slightly under it, after the manner of a duck when it perceives some sub-aqueous attraction. At this terrible moment a feeling came over me of being drenched with water from the waist downwards, and with something to the effect of a drowning man, I 'froze' to the mast … I never again wish to experience an earthquake on the water"* (*Lake Wakatip Mail*, 17 May 1871, p. 2).

Validity: Possible

Date: **5 December 1881**

Lake(s): Sarah

Generation: Earthquake (Castle Hill, North Canterbury) and probable gas-expulsion. Epicentre 43.13°S, 171.77°E. Magnitude M_{WI} 6.0. Depth 12 km (Downes & Dowrick 2014; Geonet 2021)

Wave type: Tsunami

Effects: Enys (1882) wrote: *"The author wishes to place on record the following facts which occurred after the earthquake of 6th* (sic) *December. The manager of Grassmere Station, about two hours after the shock, or about a quarter to ten, rode past Lake Sarah, … He was astonished to see about two to three chains from the shore, two mounds of water being thrown up about four feet above the surface of the lake, and two hours after on his return past the same place these fountains were still playing. I have known the manager, Mr H. Carson for about eighteen years and can* *fully trust his evidence and think the fact worth recording. I can offer no explanation of the occurrence, unless it be the escape of gas".*

The timing of the earthquake at 7:37 a.m. (Anon. 1881, p. xxii) is consistent with Enys's (1882) report on when the station manager rode past the lake, and Hogben (1890; p. 469) stated: *"The occurrences reported to have been witnessed at Lake Sarah ... can very well be explained as secondary effects of the earthquake".*

Validity: Probable

Date: 27 August 1883

Lake(s): Taupō / Taupōmoana

Generation: Atmospheric forcing (coupling) associated with the Krakatoa (Indonesia) volcanic eruption

Wave type: Tsunami

Effects: *The Thames Star* (15 September 1883, p. 2) reported: *"Coincidental with the recent tidal disturbances all over the world, the water of Lake Taupo fell 18 inches for half-an hour, and then slowly rose to their old level".* Anon. (1883, p. 556) observed the connection between oscillations in the barograph and recent oceanic disturbances from the Krakatoa eruption, and that: *"Dr. Hector also read a letter from Major Scannell, Inspector A. C.*(Armed Constabulary), *(stationed at Taupo), giving an account of marked oscillation in the level of Taupo Lake, amounting to a vertical rise and fall of 18 inches, which was repeated several times at intervals of 20 minutes at about noon on the same date that the tidal disturbance was felt on the coast, viz., on 28th August; affording clear evidence of the passing of waves through the lake, due to a motion of the land, probably produced by the unusual periods of the tidal inequalities of pressure on either coast".*

de Lange and Healy (1986, pp 125–126) suggested an atmospheric forcing mechanism because it was unlikely that this oscillation could be directly generated by the Krakatoa eruption. Lowe and de Lange (2000, p. 402) also noted the occurrence of lake waves from the Krakatau (Krakatoa) eruption on Lake Taupō / Taupōmoana, stating: *"They were also recorded on 600 km^2 Lake Taupo in New Zealand where the maximum wave height during seiching reached 0.5 m".*

Validity: Definite

Date: 5 September 1883

Lake(s): Taupō / Taupōmoana

Generation: Earthquake – described as '*Slight*' at Taupō / Taupōmoana, in many newspapers

Wave type: Seismic seiche

Effects: At 5:00 pm a slight earthquake was felt in Taupō / Taupōmoana. The *Hawkes Bay Herald* (7 September 1883, p. 2, and other papers) reported: *"A few minutes after the shake, the lake fell eighteen inches for about half-an-hour, when the waters slowly rose to their old level".* This account, and that of *Thames Star* (15 September 1883) above (and other newspapers), for the 27 August 1883 event, are very similar, so doubt is cast as to whether they are separate events, several days apart, or if delayed newspaper reporting (as was common at the time) for the 27 August event, has confused the timing of the event(s). The *Hawkes Bay Herald* (and other newspapers) also noted heavy westerly gales, thunder, and hailstorms, so this could have been a wind generated seiche.

Validity: Possible

Date: **9 April 1886**

Lake(s): Crater Lake

Generation: Volcanic and ice-collapse

Wave type: Tsunami

Effects: Cussen (1886, p. 378) reported on his trigonometrical surveying expedition to Crater Lake, and observations of increased volcanic activity at Mount Ruapehu. He noted: *"... the water appeared now and then to assume a rotary motion, eddies and whirlpools, passing from the centre to the sides, and steam flashing up from the eddies, leaving little doubt in my mind, that the water was in a boiling state"*. Also, a portion of icy mass surrounding the lake broke away and crashed into the lake below.

Validity: Definite

Date: **c. 2 June 1886**

Lake(s): Tarawera

Generation: Undetermined (probably associated with increased volcanic activity and the Mount Tarawera volcanic eruption on 10 June 1886)

Wave type: Undetermined

Effects: The *Auckland Star* (10 June 1886a, p. 3) reported that about a week before the Mount Tarawera eruption on the 10th: *"At Lake Tarawera it was observed that the water rose and fell in a rapid manner such as had never been witnessed before, and a like phenomenon was to be seen on Lake Rotomahana. On one occasion as a party of tourists were landing from a boat, the water of the lake rose like a tidal wave, and those who had not landed had to wait till the wave subsided before they could do so"*. A tour guide noted: *"... a tidal wave, some two feet high, had rolled across the surface of the lake about a week previously"* (*New Zealand Herald* 12 June 1886a, p. 5). Other newspapers reported similar stories.

Pond and Smith (1886, p. 338) provided further detail: *"About week prior to the eruption, a wave was noted on Lake Tarawera, causing the water to rise about 2 feet above the ordinary level, which broke on the shores, washing the boats out of the sheds, and causing some alarm among the Maoris, who, apparently, had never witnessed anything of the kind before"*. The *Lyttelton Times* (15 June 1886, p. 5) also reported the 'tidal wave' and boats being washed out of a boat shed, but stated it occurred a fortnight before the eruption and the wave was three feet high.

Validity: Definite

Date: **c. 2 June 1886**

Lake(s): Rotomahana

Generation: Volcanic – probably associated with the Mount Tarawera eruption on 10 June

Wave type: Tsunami

Effects: The *Auckland Star* (10 June 1886b, p. 3) reported that about a week before the Tarawera eruption, Lake Rotomahana also rose and fell in a similar fashion to Lake Tarawera (see above). Pond and Smith (1886, p. 349) stated: *"At the same date, some visitors to Rotomahana found that the Pink Terrace had been in eruption, throwing mud for several yards around, an occurrence which had never been noted before"*. Classed as a tsunami based on mud being ejected into the lake at the time the lake level fluctuations were reported.

Validity: Definite

Date: 8 June 1886

Lakes(s): Rotomahana

Generation: Volcanic (associated with the Mount Tarawera eruption on 10 June)

Wave type: Tsunami

Effects: The *Auckland Sun* (8 June 1929, p. 6), recounted the 1886 eruption and stated that at Rotomahana: *"… fumaroles and hot springs were unmistakeably agitated, and on the morning of June 8 two waves rushed across the lake surface"*.

Validity: Possible

Date: 10 June 1886

Lake(s): Rotoiti (North Island)

Generation: Earthquakes between 10–24 June associated with Mount Tarawera eruption on the 10th; numerous and severe (Anon. 1886)

Wave type: Seismic seiche

Effects: This wave was first reported in the *Taranaki Herald* (25 June 1886, p. 2) as: *"A telephone message from Roto-Iti states that a tidal wave rose to the stable of the Fraser Hotel at Teheki., seven yards distant. The difference of the level is three feet. The residents did not see the wave advancing, but on rushing out saw it receding"*. The story was repeated in many other newspapers although there is confusion over the distance of Fraser's Hotel from the lake shore. For example, the *Christchurch Star* (25 June 1886, p. 4, and others), states: *"107 yards distant"*, whilst the *South Canterbury Times* (25 June 1886, p. 2; and others) states the hotel was *"170 yards off"*. Most newspapers concur with 107 yards distance.

Validity: Definite

Date: 10 June – 12 July 1886

Lake(s): Rotorua (North Island)

Generation: Earthquakes (associated with Mount Tarawera eruption)

Wave Type: Seismic seiche

Effects: Pond and Smith (12 July 1886, pp. 353–354) reported that: *"The level of Rotorua lake oscillated somewhat on the 10th June, but to no great extent. At 7 a.m. it fell 1 inch; at 9 a.m. it rose 6 inches, and fell again at noon 3 inches and remained there all day, falling on the night of the 10th June, 5 inches, since when the oscillation has been continuous, but to no very great extent"*. The same story was reported in the *New Zealand Herald* (13 July 1886b, p. 6), and many other newspapers.

Validity: Definite

Date: **14 June 1886 (Event 1)**

Lake(s): Taupō / Taupōmoana

Generation: Earthquakes associated with the Mount Tongariro eruption

Wave type: Seismic seiche

Effects: An ash eruption occurred on Mount Tongariro (GNS 2021b). The *Auckland Star* (15 June 1886, p. 2) and other papers reported: *"At four o'clock yesterday morning an explosion was heard in the direction of Tongariro, followed by a muffled rumbling noise. The waters of Lake Taupo were greatly agitated, and rose considerably, rushing up the beaches in tremendous surf, and pouring through the head of the outlet at the head of the Waikato River in a deafening roar. There was not a breath of wind and the country was enveloped in a thick fog. At daylight the water was smooth and tranquil and had resumed its normal level, but the water marks were still plainly discernible high near the shores"*.

Validity: Definite

Date: **14 June 1886 (Event 2)**

Lake(s): Taupō / Taupōmoana

Generation: Earthquakes associated with the Mount Tongariro eruption

Wave type: Seismic seiche

The *Daily Telegraph* (15 June 1886, p. 3) noted: *"Lake Taupo yesterday afternoon rose to an alarming height very suddenly, but subsided gradually without doing any damage"*. The same or similar stories and details of the eruption were produced in newspapers around the country (e.g., *Evening Post* 15 June 1886, p. 3; *Oamaru Mail* 15 June 1886, p. 3; *Nelson Evening Mail*, 15 June 1886, p. 2; *Kumara Times* 16 June 1886, p. 3). Although the newspapers implied an association between the sudden lake level rise and increased volcanic and earthquake activity from Mount Tongariro, no direct evidence of a lake wave (such as high-water marks or 'roaring surf') was provided, as in Event 1, above.

Validity: Probable

Date: **15 June 1886**

Lake(s): Tarawera

Generation: Subaerial landslide (earthquake series associated with Tarawera volcanic eruption)

Wave Type: Tsunami

Effects: An official rescue party were boating across Lake Tarawera and: *"After starting from the landing place at Wairoa for Moura … they were accompanied by avalanches of land falling from the cliffs on the right, which fell into the lake with terrible velocity, the weight causing the lake to make a series of pulsations"* (*New Zealand Times,* 1 June 1886, p. 2). Reported in many other newspapers.

The *New Zealand Herald* (13 July 1886c, p. 5) commented further on the landslips into the lake, when a group of geology professors, who were examining the lakes in the area, post eruption, noted that: *"The cliff from which the gallant party* (above) *had embarked was nowhere to be seen, all that part having subsided into the lake"*.

Validity: Definite

Date: **March 1890 (day unknown)**

Lake(s): Crater Lake

Generation: Volcanic and ice-calving

Wave type: Tsunami

Effects: Hill (1891, p. 619) reported on the increased volcanic activity of Mount Ruapehu and upon ascending the mountain, noted that now and then, masses of ice gave way from the 250 ft high ice cliffs and crashed into the boiling lake. The lake was in constant motion, moving from west to east, in regular pulsations: *"After every pulsation … I noted large cavern-like recesses below the icewall … as if the water had subsided somewhat, but these slowly disappear as the maximum movement of the water approached"*.

Validity: Definite

Date: **9 April 1894**

Lake(s): Whakaari / White Island

Generation: Volcanic

Wave type: Tsunami

Effects: A reporter on an excursion tour to Whakaari / White Island described the crater lake as: *"… towards the remote interior of the crater, the water boils furiously a huge dome thereof being constantly lifted four or five feet high and dashed in waves over the surface of the lake"* (*Bay of Plenty Times*, 9 April 1894, p. 2).

Validity: Definite

Date: **17 August 1895**

Lake(s) Taupō / Taupōmoana

Generation: Earthquake (17th; 6:27 pm), officially classed as a '*smart*' shock (Anon. 1895). Also, subaerial (and possible subaqueous) landslides in the lake. Epicentre 38.80°S, 176.00°E. M_{WI} 6.0. Depth 12 km (Downes & Dowrick 2014).

Wave type: Tsunami

Effects: A series of earthquakes on the 17–18 August in the Taupō / Taupōmoana area. Numerous 'immense landslips' were reported in the region. The Post Office telegraphist messaged that: *"The earthquake on Saturday affected the lake sufficiently to produce a wave two feet high"* (*Colonist*, 20 August 1895, p. 2). The same story is repeated in many of the country's newspapers.

Downes and Dowrick (2014; p. 71), stated: *"A small tsunami (60 cm) occurred in Lake Taupo, possible causes being landslides, subsurface slumping or vertical deformation"*. The NZTD gives this tsunami (ID 256) a validity of 'Definite', and notes that numerous large landslides fell into the lake, within 10 km of Taupō / Taupōmoana settlement, and these were the most obvious sources of the tsunami.

Validity: Definite

Date: **26 January 1903**

Lake(s): Te Anau (Te Anau-au)

Generation: Earthquake – '*Severe*' in Queenstown; lasted nearly half a minute (*Evening Star*, 26 January 1903, p. 4)

Wave type: Undetermined

Effects: At about 1:45 pm two distinct earthquake shocks were felt (several seconds between the shocks) in the Te Anau (Te Anau-au) – Milford region. The *Southland Times* (3 February 1903, p. 3) reported, *"Where the mountains are composed of friable rocks some stones rolled down, but very few were shifted in the solid granite country. The surface of the lake was considerably agitated"*. The shocks were reported across much of the South Island, in many newspapers with reported intensities ranging from slight to severe.

Note: Classed as 'Undetermined' because no specific mention of rockfalls entering the lake directly were found, although this was possible.

Validity: Probable

Date: **8 March 1904**

Lake(s): Crater Lake

Generation: Ice-calving

Wave type: Tsunami

Effects: George Allen (registered surveyor), surveyed much of the central North Island and he gave a detailed account of his descent into Mount Ruapehu's crater in 1904. Allen (1907, p. 11) reported that the lake level was about 200 ft below the crater rim (highest peak = 9 170 ft above mean sea-level, at the time) and the ice-cliffs were about 40 ft high. Water in the crater lake was described as: *"It was not hot, but probably tepid for it had deeply undermined the ice-cliffs, vast blocks which frequently fell off into the lake, creating great waves, and disturbing the sulphur-scum, with which about half the water was covered"*.

Validity: Definite

Date: **9 August 1904**

Lake(s): Taupō / Taupōmoana

Generation: Earthquake, (Cape Turnagain) and subaerial landslides into lake. Epicentre 40.40°S, 176.40°E. Magnitude M_S 6.8, $\hat{M}_W$ 6.7–6.8, M_{WI} 7.0–7.2. Depth 16–40 km (Downes & Dowrick 2014)

Wave type: Tsunami

Effects: Landslides falling into lake were reported from several sources. *"The earthquake yesterday was very severe round the eastern shore of Lake Taupo, and between the Waitahanui and Hatape rivers the high pumice cliffs were shaken down, and the lake's surface is covered with a deep deposit of pumice, extending for a couple of miles off shore. At Tokaanu the shock was not so severe, but the surface of the lake was greatly agitated, and it being a flat calm at the time, the change was easily observed"* (*Auckland Star* 10 August 1904, p. 2; *Thames Star* 11 August 1904, p. 2).

Validity: Definite

Date: **9 August 1904**

Lake(s): Rotomahana

Wave type: Seismic seiche

Generation: Earthquake (Cape Turnagain; see above)

Effects: *"The water suddenly rose two feet, and a considerable commotion was observed in the centre of the lake"* (*Poverty Bay Herald* 17 August 1904b, p. 1). The same paper went on: *"There was a violent commotion on the water at Lake Rotomohana and the guide in charge of the boats had his hand badly injured endeavouring to hold the boat against the jetty"* (*Poverty Bay Herald* 17 August 1904a, p. 3). Downes (1995), Downes and Dowrick (2014) and GNS (2021) also noted seiching in several North Island rivers, Lake Rotomahana and a possible oceanic tsunami at Mohaka.

Validity: Definite

Date: **August 1908 (early)**

Lake(s): Taupō / Taupōmoana

Generation: Undetermined

Wave type: Undetermined

Effects: The *New Zealand Herald* (11 September 1908; p. 4), reported that: *"The rise occurred about a month ago, and it was stated on good authority that this vast volume of water rose 13in in 10 minutes. The lake receded, rose again about 7in, and eventually went back to its former level"*. The same story is reported in other newspapers and because of its newsworthiness, the event is not considered as the regular occurring, wind-generated seiche on the lake.

Validity: Possible

Date: **23 March 1909**

Lake(s): Gunn (Ōtāpara)

Generation: Earthquake, with associated subaerial landslides, probable subaqueous landslides, and gas-expulsion. Described in Queenstown as: "*An earthquake of great violence and long duration*" (*Lake Wakatip Mail* 23 March 1909a, p. 4)

Wave type: Tsunami(s)

Effects: A severe earthquake struck the Fiordland area and lake waves were witnessed by a tramping party, although newspaper reports are conflicted as to whether the tramping party were on the shore of Lake Gunn (Ōtāpara) or Lake Te Anau (Te Ana-au) (located closely together): Lake Gunn (Ōtāpara) appears the most likely, based on reported details.

The *Lake Wakatip Mail* (30 March 1909b, p. 4) stated: *"It was when skirting the shores of Lake Gunn that the severe earthquake of Tuesday morning was felt. So violent was it in those parts that the ground literally heaved up and the waters of the lake appeared to rise up, as it were upon an* (sic) *heap"*. The same paper (27 April 1909c, p. 5) went on: *"Those who were in view of the lake* (Gunn) *were bewildered seeing the calm waters all of a sudden bubble furiously in all directions and a big wave pass from shore to shore"*. Widespread landsliding around and into the lake was also reported.

Conversely, the *Evening Star* (27 March 1909, p. 6) reported that tramping party was close to the edge of Lake Te Anau (Te Ana-au) when the earthquake struck. The lake: *"… did not have* *a ripple, when suddenly the water became agitated and bubbles rose to the surface, giving the resemblance of a boiling lake. Seven distinct shocks were counted, the lake being agitated in each case. Landslips occurred and added to the general commotion, the party having to take to the bush on account of the danger involved in keeping in proximity to the lake".*

Validity: Definite

Date: 23 March 1909

Lake(s): Waimumu dredge pond

Generation: Earthquake (see above)

Wave type: Seismic seiche

Effects: A worker on the Waimumu gold dredge: *"… was looking into the water when, to his surprise, the water heaved. He could not understand the phenomenon until he had heard of the earthquake"* (*Southland Times*, 26 March 1909, p. 4).

Validity: Possible

Date: 20 March 1910

Lake(s): Taupō / Taupōomoana

Generation: Subaerial landslide into lake, probably generated by geothermal eruption (e.g., Massey et al. 2009)

Wave type: Tsunami

Effects: The *Auckland Star* (21 March 1910) provided the first details of a massive landslide occurring the previous morning, that overwhelmed Waihi village and entered Lake Taupō / Taupōmoana, although no mention was made of the subsequent tsunami. The *New Zealand Herald* (22 March 1910, p. 5) and other newspapers reported that: *"… the* (land) *mass was rushing head-long down the slope, and at last it reached the lake, into to which it precipitated itself. The consequent agitation of the waters resulted in the formation of a tidal wave, about 10 ft high, which swept across the lake to the opposite shore. On this some children were playing, and they were caught by the wave and swept off their feet. Fortunately, a number of adults were on hand, and with some difficulty the children were rescued. So great was the force of the wave that all the boats and canoes on the shore were washed away. The wall of water swept across the bay to the Tokaanu wharf, over which it washed, to the peril of a youth named Robinson, who was on the wharf at the time, but had some difficulty remaining there. The wave rolled down the foreshore by Tokaanu, and there subsided".*

The *Dominion* (28 March 1910, p. 7) reported an eyewitness account stating the landslip extended 250 yards into Lake Taupō / Taupōmoana and created about 16–18 acres of new land above lake level. *"The tidal wave which followed the slide washed up huge quantities of carp, which now strew the road for hundreds of yards".* A man walking along the road, ran to what he thought was a safe position, but *"… when the land slipped into the lake a tidal wave six feet high pursued him. Another sprint, and the pedler* (sic) *was at last safe, for though the water did overtake him it reached only up to his knees".*

Lowe (1910, p. 43.) made no mention of lake waves in his official landslide report but significant water displacement can be presumed, by his statement that debris went 120 chains into the lake and that: *"10 acres of new land has been formed above the waters of the lake. Huge quantities of debris were shot out into the deep water for many chains".*

Massey et al. (2009) examined the landslide risk at Waihi and stated that the 1910 landslide originated on the Waihi Fault scarp, about 300 m to the north of the 1846 failure: the debris volume of c. 3×10^6 m^3, was larger than that of 1846 event and flowed two kilometres into the lake, at the southern shore, producing a wave about 3.0 m high, at its source. Where the wave reached the opposite side of the lake, the NZTD (ID 265) states: *"The height of the surge needs to be at least 0.5 metre to have caused the children problems, but probably no more than 1–1.5 m, otherwise there would have been greater impact"*. The NZTD gives a validity of 'Definite'.

Validity: Definite

Date: 24 April 1915

Lake(s): Wakatipu

Generation: Earthquake

Wave type: Seismic seiche

Effects: The *Lake Wakatip Mail* (27 April 1915, p. 5) reported that the effects of a severe earthquake in the Queenstown district (11:15 am) were more noticeable on the lake than on land, and that: *"The lake before the shock was calm and still but afterwards the surface became disturbed by several large ripples which ran north and south, thus creating a high wave against the shore"*.

Validity: Probable

Date: February 1925 (day unknown)

Lake(s): Crater Lake

Generation: Ice-calving

Wave type: Tsunami

Effects: Visitors to Crater Lake, Mount Ruapehu, in February witnessed: *"… a portion of the ice wall fell which sent a wave across the lake…"* (*Evening Post,* 31 March 1925, p. 9).

Validity: Definite

Date: 9 March 1929

Lake(s): Sumner (Hokakura)

Generation: Earthquake (Arthur's Pass), subaerial slide, liquefaction. Epicentre 42.84°S, 171.83°E. Magnitude M_S 7.1, M_W 7.0, $\hat{M}_W$ 7.0 (Downes & Dowrick 2014)

Wave type: Tsunami

Effects: A local resident stated that: *"The quake was so severe that it raised a wave about ten feet in height on the lake, and tossed a boat with an outboard motor high and dry over a fence onto adjoining land. The 'quake caused a portion of shingle bank to fall into the lake"* (*Hokitika Guardian,* 2 April 1929a, p. 3). The report is repeated in many other newspapers.

Speight (1933, p. 177), reported on land-surface damage caused by the Arthur's Pass earthquake and noted that: *"It is true, when the earthquake occurred, according to reports from reliable observers, the water of the lake was much disturbed, and settlings of the shore are reported with small discharges of water from earthquake craters …"*

Downes and Dowrick (2014, p. 9) also noted this wave, occurring to the northeast of the fault rupture, but: *"An MM intensity cannot be assigned at Lake Sumner, where there was a surge in the lake, as this could be attributed to a number of sources, including a small tsunami generated by slumping into the lake"*.

Validity: Definite

Date: **17 June 1929**

Lake(s): Nelson reservoir dam

Generation Earthquake (Murchison a.k.a. Buller). Epicentre 41.70°S, 172.20°E. Magnitude M_S 7.8, M_W 7.3, $\hat{M}_W$ 7.7. Depth 20 km (Downes & Dowrick 2014; Geonet 2021)

Wave type: Seismic seiche

Effects: The Nelson City engineer inspected the city reservoir ('*The Big Dam*') after the Murchison earthquake and noted: *"At the dam there was considerable wave action as a result of the shock, and water was thrown over the wall"* (*Nelson Evening Mail* 18 June 1929b, p. 5).

Validity: Definite

Date: **17 June 1929**

Lake(s): Rotoroa (South Island)

Generation: Earthquake (Murchison. See above)

Wave type: Tsunami

Effects: This event was reported in most of the country's newspapers, such as *The Nelson Evening Mail* (19 June 1929a, p. 7), which stated: *"Lake Rotoroa rocked from side to side like a huge basin of water being tipped about … Half an hour an hour after the main shake, the water receded from the hotel shore of the lake and exposed the lakebed for about 50 yards. It then came back in a series of large waves. The bridge over the Gowan* (River) *at the lake was torn from its piles and banks of the river and was hurled upstream. The wrecked structure was carried still further by the Gowan waters, which were temporarily flowing back into the lake. The water then turned again to its normal course and carried the bridge against the piles … the jetty has been smashed and the Lake Hotel…is badly damaged"*. Fissures and landslips were also reported between the Gowan River bridge and the lake.

Note: Classed as a tsunami, based on descriptions of lake waters receding and returning over a long period (30 mins), and ground disturbances (fissures and slips) between the bridge and lake, although Hancox et al. (2016) identified few landslides around Lake Rotoroa, from this earthquake but many around Lake Rotoiti. Many newspapers also reported huge landslips into Lake Rotoiti (adjacent catchment to Rotoroa), but have confused the subsequent lake wave accounts, at least, with Lake Rotoroa (e.g., *Press* 20 June 1929, p. 9), as the Te Kauparenui / Gowan River discharges from Lake Rotoroa, not Rotoiti, and the hotel was on the shores of Lake Rotoroa. Ignoring the erroneous accounts, no verified lake waves were reported on Lake Rotoiti.

Validity Definite

Date: **17 June 1929**

Lake(s): Brunner / Moana

Generation: Earthquake (Murchison. See above)

Wave type: Tsunami

Effects: Reported in many of the country's newspapers. During the earthquake, workers at Moana, on the northern shore of Lake Brunner / Moana, observed that: *"...the centre of Lake Brunner ...was seen to fall in rapidly, so quick, in fact, that it was as if a piece of solid ground had fallen from the centre. Then, a fraction of a second later, the remainder of the water commenced to fall into the gap. The bottom of the lake rose again, and a huge column of water shot high into the air, setting up waves, such as are only seen during a fierce gale"* (*Auckland Star* 19 June 1929, p. 9). The same article mentions that timber-workers at Te Kinga, on the western shore of Lake Brunner, witnessed a huge crevasse, estimated at two-chains wide, opening and closing on the lake's swampy margins.

Similarly, the *Otago Daily Times* (22 June 1929, p. 13), reported that: *"Lake Moana sank down in the middle, then came up like a typhoon"*. A local farmer had a narrow escape, described by *The Hokitika Guardian* (21 June 1929b; p. 6): *"The centre of the lake sank into a great cavity, and then the waters rose in a terrifying fashion, and a great wave swept towards the edges. His boat was thrown clean out of the water and over the slip. There was a great commotion in the lake for some time afterwards"*.

Note: Classed as a tsunami, based on length of occurrence, apparent scale of waves, and ground disturbances (fissures) on lake margins.

Validity: Definite

Date: **17 June 1929**

Lake(s) Victoria

Generation: Earthquake (Murchison. See above)

Wave type: Seismic seiche

Effects: Mr H.F. Skey (Director and Seismologist of the Christchurch Magnetic [Seismological] Observatory) was passing Victoria Lake, in Hagley Park, when the Murchison earthquake struck. He observed that the earthquake began at 10:19 a.m., and: "*A minute later the trees began to sway, the motion apparently being from east to west. The next thing was that the wild ducks rose from the lake, being disturbed by little waves that ruffled the lake. When he measured the waves they were half an inch high*" (*Christchurch Star* 17 June 1929a, p. 1). Mr Skey further suggested that the waves were not sufficient to alarm the ducks: *"...which must therefore have been raised by the impulses arising from the bed of the lake"* (*Christchurch Star* 17 June 1929b, p. 10). Besides the witness, this account is also given some credibility as lake waves were recorded elsewhere (see above), and at the time of occurrence, the weather was fine, calm, and frosty, so the small waves cannot have been wind generated.

Validity: Possible

Date: **3 February 1931**

Lake(s): Old open reservoir (Hamilton city)

Generation: Earthquake (Napier a.k.a. Hawke's Bay). Epicentre 39.30°S, 177.00°E (Dowrick & Smith 1990). Magnitude M_S 7.8, M_W 7.4–7.6, $\hat{M}_W$ 7.8. Depth 20 km (Downes & Dowrick 2014)

Wave type: Seismic seiche

Effects: The *Waikato Times* (4 February 1931, p. 8) reported that water in the Hamilton municipal baths spilled over and: *"A quantity of water in the old open reservoir on the lake hill also spilled over the side as a result of the shake"*.

Validity: Definite

Date: **3 February 1931**

Lake(s): Waikaremoana

Generation: Earthquake (Napier, see above)

Wave type: Seismic seiche

Effects: The *Poverty Bay Herald* (4 February 1931a, p. 12) reported that: *"At the lake the water was thrown up about 15 ft"* and the next day (5 February 1931b, p. 12) described Lake Waikaremoana as being *"greatly agitated"* by the earthquake. Three people were crossing the lake when they thought their boat would be swamped by the agitated waters (*Poverty Bay Herald* (9 February 1931c, p. 12).

The *Horowhenua Chronicle* (20 Feb.1931, p. 5) described the event as: *"The lake waters rose 10ft at the jetty, lifting launches and boats and then carrying them far out as it receded"*.

Validity: Definite

Date: **3 February 1931**

Lake(s): Tūtira

Generation: Earthquake (Napier, see above). Probable subaerial landslides into lake

Wave type: Tsunami

Effects: The *Poverty Bay Herald* (6 February 1931d, p. 5.) reported that two locals set off on bicycles from Wairoa to Napier, encountering a landslide that had blocked the Tūtira road cutting, and: *"They found the road around Tutira considerably cracked. At one place the whole piece of road had slipped into the lake"*. A local farmer undertook a reconnaissance of earthquake damage in the area and noted that: *"The Tutira Lake had not been altered in level but a miniature tidal wave had stepped over the shore, but without causing any real damage"* (*Evening Post* 13 February 1931, p. 7; *Poverty Bay Herald* 17 February 1931e, p. 7).

Note: This tsunami could have also been generated by the 13 February 1931 earthquake (See Downes & Dowrick 2014) but based on the above report of the road slipping into the lake, it most likely was caused by the earthquake on 3 February.

Validity: Probable

Date: 26 March 1931

Lake(s): Ōpunake Lake (power-scheme lake)

Generation: Earthquake (Palmerston North) and liquefaction. Epicentre 40.00°S, 175.50°E. R-F 6 in Palmerston North, R-F 5 in Wanganui (Adams & Henderson 1933).

Wave type: Tsunami

Effects: The *Opunake Times* (31 March 1931a, p. 2) and other local papers reported a sharp earthquake at 10:20 pm that caused a curious phenomenon in the Opunake Power Board's lake. A small island appeared to be upheaved from the bottom of the lake. The depth of the water previously was about 10 feet, and the upheaved material was now at water level when the lake was full, but clearly visible at other times. The upheaved material was very soft, and the *Patea Mail* (6 April 1931) reported soft mud oozing out of the fissure in the island.

The Power Board engineer stated: *"... he had noticed the island and examined it at once. The lake bottom had certainly been disturbed, for roots and shingle were brought to the surface. At the centre of the mound a large hole appeared ... on the night of the earthquake he had noticed water in a tank had been disturbed in a manner which caused it to rush round as if it were being stirred. If the same had happened at the lake, which was probable, the debris would then collect at the centre of the lake where a miniature whirlpool would be formed"* (*Opunake Times* 21 April 1931b, p. 2).

Validity: Probable

Date: 1932 (day & month unknown)

Lake(s): Tarawera

Generation: Undetermined

Wave type: Undetermined

Effects: When reporting on the February 1933 Lake Taupō / Taupōmoana event (below), several newspapers stated: *"There was a pulsation on* (Lake) *Tarawera last year, but of short duration"* (e.g., *Auckland Star,* 21 February 1933, p. 8). No further information was found.

Validity: Possible

Date: 15–21 February 1933

Lake(s): Taupō / Taupōmoana

Generation: Undetermined

Wave type: Undetermined

Effects: This event was reported in many of the country's newspapers. The *Auckland Star* (21 February 1933, p. 8.) reported that at 10:00 am, 15 February, workers on the edge of Lake Taupō / Taupōmoana noticed the lake rose suddenly and that: *"The steady swelling of the waters continued for 13 minutes, the level of the lake rising almost 20in and then stopping. The waters then subsided, taking 9 minutes to regain the ordinary level. There was a pause for four minutes, when the waters again rose about 20in, taking the same time (13 minutes) to attain the maximum and another nine minutes to subside ... Since then, the movement has been regular, and has continued without interruption ... It was noted that when the strange movement began the rise of the waters was directly against the set of the wind that has been blowing fairly strongly, and later changed to across the wind".* Local Māori, and long-term European settlers, had never seen anything similar. Initially, thermal activity beneath the lake was thought to be the cause, but this was quickly dismissed.

The *Nelson Evening Mail* (23 February 1933, p. 6), reported that Professor Speight (Canterbury Museum curator), Dr Adams (government seismologist) and Dr Kidson (government meteorologist), all called the event a seiche although Speight speculated the event was caused by some form of mass-movement, stating: *"I think in the present case, that the seiche is possibly due to some earth movement round the lake or in the bottom of the lake, but that is merely speculation, and I don't know"*.

Note: Although called a seiche by the above people, the lake wave is classed here as undetermined, owing to the uncertainty of the generating mechanism.

Validity: Definite

Date: 20 December 1934

Lake(s): Crater Lake

Generation: Volcanic

Wave type: Tsunami

Effects: The *New Zealand Herald* (22 December 1934, p. 10, and other papers) reported on a climber's ascent to Crater Lake (Mount Ruapehu) and he: *"… found the lake in a very disturbed condition … The water was evidently very hot and boiling violently in places, presenting a remarkable contrast to the surrounding ice cliffs. There were no signs, however, of the water having risen above the ice cliffs on the surrounding snow"*.

Validity: Definite

Date: 15 July 1935

Lake(s): Taupō / Taupōmoana

Generation: Earthquake (Wairakei). Epicentre 38.70°S, 176.20°E. Intensity R-F 7.
(Hayes 1937; *Evening Post* 24 July 1935, p. 10)

Wave type: Seismic seiche

Effects: Severe shock about 11:20 pm followed by a succession of trembles. *"Loud rumblings continued through the night, and the uncanny effect was increased by the roar of surf beating on the lake shores, a weird contrast to the calm night … a few minutes after that following the first shake there had been a roar like a heavy sea in the lake. As the night was calm this could only be attributed to some seismic influence"* (*Waikato Times* 16 July 1935, p. 6).

"The shocks were accompanied by subterranean rumblings which seemed to proceed across the lake" (*Horowhenua Chronicle* 17 July 1935, p. 3).

The *New Zealand Herald* (17 July 1935, p. 12), also reported: *"Another very noticeable feature was that although there was no wind the waves breaking on the lake shore made more noise than usual"*, and that the Rev A. Laughton, who was travelling in the area, stated: *"… that following the first shake there had been a roar like a heavy sea in the lake. This could only be due to seismic influence, as otherwise the night was calm"*.

The earthquake was widely felt, with severe shaking in the Taupō / Taupōmoana area, along with *"… shaking down some cliffs … The shock occurred in the early hours of the morning, the* *night being a still one, and the ripples which it caused on the surface of the lake could be heard distinctly breaking on the shore"* (*Evening Post* 24 July 1935, p. 10).

Several newspapers reported landslides around Lake Taupō / Taupōmoana and over a wide area in the central North Island, blocking roads etc., but no reports were found of landslides entering the lake (direct observations of landslides or subsequent debris in the lake).
On this basis, the lake waves have been determined as a seismic seiche.

Validity: Definite

Date: 1937–1938 (Summer – date uncertain).

Lake(s): Wakatipu

Generation: Earthquake, with probable delta collapse and gas expulsion. Uncertainty of exact earthquake because of the vagueness of Brody and Irwin's (1970) account

Wave type: Tsunami

Effects: Brodie and Irwin (1970) reported: *"During the summer of 1937–38 a sharp earthquake shock was felt by a group on the Glenorchy wharf (Dr R. W. Willett pers. comm[9].) Within minutes, the surface waters of the lake a few chains distant, over the delta edge, became violently turbulent and discoloured by sediment; the disturbed area marked by extensive bubbling of gas. A slump had evidently been triggered by the earthquake"*.

Based on information in Hayes (1939, 1940), Dowrick and Smith (1990), Downes (1995), and Downes and Dowrick (2014), the most likely earthquake for generating this tsunami, was the Taiporoporo / Charles Sound earthquake, occurring on 17 December 1938, which was widely felt over the South Island, especially in the Otago, Southland, and Milford Sound / Piopiotahi areas.

Validity: Definite

Date: 2 February 1938

Lake(s): Virginia (Rotokawau)

Generation: Earthquake (Banda Sea, Indonesia). M_W 8.6 (Cummins et al. 2020)

Wave type: Seismic seiche

Effects: The *Evening Post* (5 February 1938, p. 10), reported that: *"The city gardener … reports a phenomenon which occurred at Virginia Lake on Wednesday morning, and which was no doubt the direct result of the great earthquake recorded at the same time. He was standing at 7:30 on the edge of the lake when suddenly the water commenced to roll with a semi-tidal effect. It receded at regular intervals, leaving a muddy foreshore, the maximum movement being about a yard. The movement continued until 7:40. The morning was dead calm, and there was no perceptible movement of the ground in the vicinity of the lake. The same morning, at 7:13, a distant earthquake was recorded on the instruments at the Dominion Observatory, Wellington"*.

Variations of this account were also reported in the *Auckland Star* (5 February 1938, p. 7), *Evening Star, New Zealand Herald, Press* and *Thames Star* (all on 7 February 1938). Reports of other lakes being affected were not found. This earthquake was recorded globally and Okal and Reymond (2003), stated that it was one of the 10 largest earthquake-moments ever recorded.

Validity: Possible

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[9] Dr R.W. Willet was in the New Zealand Geological Survey (Department of Industrial and Scientific Research).

Date: **24 June 1942**

Lake(s): Wairarapa

Generation: Earthquake (Wairarapa 1: 4 separate shocks) Main shock 11:16 pm, local time. Epicentre 40.96°S, 175.69°E. Magnitude M_L 6.5, M_S 6.2, M_W 6.9–7.2, $\hat{M}_W$ 7.1. Depth 12 km (Downes & Dowrick 2014)

Wave type: Tsunami

Effects: *The Evening Post* (30 June 1942, p. 3) and *Gisborne Herald* (6 July 1942, p. 5) reported that on the night of the earthquake, a flounder fisherman on Lake Wairarapa, had a most uncanny experience: *"From a state of calmness the waters of the lake became disturbed, the surface showing up as a mass of whirlpools. It was most unusual and he decided he would make for the shore. Progress in his small boat, however, was not easy, it being difficult to row against the swirling waters. He reached the shore some hundreds of yards from the intended landing place, near the Lake Ferry Hotel …"*. Many newspapers (e.g., *Evening Post* 30 June 1942, p. 3; *New Zealand Herald* 2 July 1942, p. 2) reported that *"… something in the nature of a tidal wave"* had occurred the lake, as boats had been shifted 200 yards during the disturbance.

The *New Zealand Herald* (2 July 1942, p. 2) also noted physical changes in the Lake Wairarapa area: in Lake Onoke, new islands developed, at the southern end of the lake, the gentle slopes had changed to a vertical drop, *"… and it is stated that the bed of the lake has been raised several feet"*. Severe ground-surface damage (landslides and liquefaction) in the Wairarapa area was recorded by Hayes (1942), Downes (1995), Downes et al. (1999), and Downes and Dowrick (2014), although several authors rejected Ongley's (1943) findings, that surface faulting had occurred.

Validity: Definite

Date: **24 June 1942**

Lake(s): Lake Rotoroa / Hamilton Lake

Generation: Earthquake (Wairarapa, see above)

Wave type: Seismic seiche

Effects: Residents adjacent to the lake, in Lake Crescent, noted whirlpools on the day of the Wellington (Wairarapa) earthquake. The *Auckland Star* (7 August 1942, p. 4) reported: *"Wellington and country districts experienced a very severe earthquake on Wednesday, June 24, and on the same day there were several whirlpools in the centre of the usually placid Hamilton Lake … the whirlpools were seen for about three-quarters of an hour"*.

Validity: Definite

Date: **2 August 1942**

Lake(s): Lake Rotoroa / Hamilton Lake

Generation: Earthquake(s), see above

Wave type: Seismic seiche

Effects: Following on from the 24 June 1942 Lake Rotoroa / Hamilton Lake earthquake event above, the *Auckland Star* (7 August 1942, p. 4), reported: *"Another series of earthquakes occurred in Wellington on Sunday morning* (2 August) *and again there was at least one whirlpool seen in*

Hamilton Lake, the time between 9 and 10 o'clock". This whirlpool occurring between 9:00 am and 10:00 am, must have been associated with an aftershock of the main earthquake on the 2 August, which occurred at 00:34 am (*Evening Star* 3 August 1942, p. 2; Downes & Dowrick (2014).

Validity: Definite

Date: **8 May 1943**

Lake(s): Wānaka

Generation: Earthquake (Lake Hāwea). Also, probable delta collapse and associated gas-expulsion. Possible rockfalls into lake. Epicentre 44.23°S, 169.37°E. Magnitude M_L 5.9. (Reyners 2005). Depth 50 km. Intensity MM7 in the Wānaka area (Downes & Dowrick 2014)

Wave type: Tsunami

Effects: The sharpest earthquake in living memory in the area. Widespread damage and land-sliding were reported in many newspapers (e.g., Reyners 2005). At the headwaters of Lake Wānaka, in the Makarora River catchment, the *Evening Star* (10 May 1943, p. 2) reported that: *"Residents in the Makaora district became alarmed when huge boulders were dislodged by the shocks hurtled down the sides of the Wilkin* (River) *Valley"*. The *Alexandra Herald and Central Otago Gazette* (12 May 1943, p. 4.) added: *"In the Makarora area the quake is said to have been particularly severe. Huge boulders hurtled down the hillside and the waters at the head of the lake* (Wānaka) *bubbled like a huge boiling cauldron for some minutes"*.

Validity: Probable

Date: **19–22 March 1945**

Lake(s): Crater Lake

Generation: Volcanic (eruption & lava bombs)

Wave type: Tsunami

Effects: Mount Ruapehu's increased activity was observed by crew on a RNZAF reconnaissance flight. They recorded a small, new island vent, in the crater lake, 50ft across and a few feet high above the water and that: *"The lake was considerably disturbed, and water was playing over the island … The rocks being ejected were fairly large and were thrown over 40ft before falling back into the lake"* (*New Zealand Herald* 21 March 1945, p. 6). Wave height and run-up elevation can be estimated, based on the air force flight observations, as the new island was estimated to be 6–8 ft high, above the lake surface (*Evening Star* 21 March 1945, p. 10).

A climbing party, including a mountain guide from the Chateau Tongariro, climbed Mount Ruapehu to witness the increased volcanic activity of the mountain. Rocks were thrown from a new island vent, in the centre of the lake, and fell back into the lake: *"From a peak to the south of the lake, Mr Mason and his party watched the activity for several hours. Rocks thrown up, he estimated, would be about 2cwt. The lake itself had become like a rolling surf as the rocks crashed into it"*. The new cone and lake were photographed, and aerial reconnaissance was also undertaken that morning (*Evening Post* 23 March 1945, p. 6).

Validity: Definite

Date: **24 March 1948**

Lake(s): Ōkataina

Generation: Earthquake

Wave type: Seismic seiche

Effects: The *Northern Advocate* (24 March 1948, p. 4) and the *Gisborne Herald* (24 March 1948, p. 6) both reported: *"Earth tremors which set launches swinging at their moorings and shook houses were felt at Lake Okaitaina* (sic) *at 3:30 and 6 o'clock this morning … Waves slapped against the shores of the lake and moored boats bumped the wharf"*.

Validity: Probable

Date: **1 May 1948**

Lake(s): Whāngioterangi / Echo Lake

Generation: Volcanic (Mount Ngauruhoe eruption)

Wave type: Tsunami

Effects: Two duck-shooters, in a small dinghy, went to retrieve their birds and decoys on the lake: *"… when the whole lake became agitated and waves lapped the shores while the waters rose about 6in and as rapidly subsided. As they pushed off into the water, they found the surface coated in an oily substance which made rowing difficult, but none of these indications of subterranean activity, which were undoubtedly associated with the Ngauruhoe outbreak remained long in evidence. The Tama lakes at the base of Mt Ngauruhoe, have both sunk about 4ft"* (*Northern Advocate* 3 May 1948, p. 4; *Gisborne Herald*, 4 May 1948, p. 6).

Note: Classed as a tsunami, based on presumption that some subaqueous lake-bed disturbance must have occurred to have produced the oily substance on the lake surface.

Validity: Probable

Date: **14 January 1953**

Lake(s): Rotoiti (North Island)

Generation: Earthquake. Just before 2:00 pm, one of the most severe earthquakes for years was felt around the Rotorua lakes area (*Press* 15 January 1953, p. 6). No other details found. Possible subaqueous mass movement and gas expulsion.

Wave type: Tsunami

Effects: *"At Lake Rotoiti, several campers saw a rift in what appeared to be boiling water break to the surface at the eastern corner of the lake, about 50 yards from the shore. The rift was about 200 yards long … The water frothed and bubbled for about an hour after the earthquake"*. Dead leaves and weed were floating on the lake surface and the water was (unusually) cold (*Press* 15 January 1953, p. 6).

Validity: Probable

Date: 14 January 1953

Lake(s): Rotomā

Generation: Earthquake (see above)

Wave type: Seismic seiche

Effects: *"On Lake Rotoma, a small wave moved across the lake when the earthquake occurred. Several big clumps of weed with earth adhering to them were later found on the surface"* (*Press* 15 January 1953, p. 6).

Validity: Probable

Date: 14 January 1953

Lake(s): Ōkataina

Generation: Earthquake (see above)

Wave type: Seismic seiche

Effects: *"There were big splashes out in the lake"* (*Press* 15 January 1953, p. 6).

Validity: Probable

Date: 3 March 1956

Lake(s): Taupō / Taupōmoana

Generation: Earthquake (Tokaanu) and probable delta collapse, with associated gas expulsion. Epicentre 38.90°S, 175.80°E. Magnitude M_L 5.3. Depth 12 km (Downes & Dowrick 2014)

Wave type: Tsunami

Effects: The *New Zealand Seismological Report* 1956 (Anon. 1960, p. 81) states: *"Officers of the N.Z. Geological Survey who visited the area reported that gas was 'boiling' from the bed of Lake Taupo near the village of Waihi. They attributed this to the liberation of methane gas which had been trapped in the sediment of the lake bed. A wave 3 ft high was reported at the delta of the Tongariro River"*.

The *Press* (5 March 1956, p. 10) reported a sharp earthquake at 10:45 am on 3 March and increased activity of thermal springs around and beneath Lake Taupō / Taupōmoana. At the Tongariro River delta and Waihi, Lake Taupō / Taupōmoana was said to have bubbled furiously, and: *"One fisherman at the delta was caught in a small cross tidal wave which drenched him at a spot where a few minutes earlier the water was only ankle deep. No difference was noted in the level of the lake but there was a noticeable increase in the activity of hot pools at the Tokaanu thermal domain"*.

Hayes (1957) noted the earthquake was the second severest in New Zealand in 1956, with intensities of MM 6–7, in the Tokaanu area. Downes and Dowrick (2014) concurred with such intensities. The NZTD (ID 387), gives a validity rating of 'Definite' and states: *"A small wave 0.9 m high was observed at the delta of the Tongariro River, in association with the 1956 March … Tokaanu earthquake at the southern end of Lake. The earthquake shaking was strong enough to cause minor structural damage and hence capable of causing slumping of the Tongariro Delta, only a few kilometres from the epicentre. Hence the small wave could have been caused by such slumping …"*

Validity: Definite

Date:	**4 June 1988**
Lake(s):	Te Anau (Te Ana-au)
Generation:	Earthquake (Te Anau [Te Ana-au]) and subaqueous delta collapse. Epicentre 45.12°S, 167.29°E (Mount Irene). Magnitude M_L 6.1, M_S 6.5, M_W 6.7; Depth 73 km (Clark et al. 2011; Downes & Dowrick 2014; Geonet 2021).
Wave type:	Tsunami
Effects:	Landslide caused a one-metre-high tsunami in North Fiord of Lake Te Anau (Te Ana-au) (Hancox et al. 2003). Numerous landslides in Fiordland. Downes (1995) reported a seiche, about one metre high, from North Fiord, Lake Te Anau (Te Ana-au). Forsyth et al. (2006) commented further on this wave: *"At the delta of Narrows Creek, Mr V. Thompson was thrown to the ground by the shaking. His boat was swallowed by a 'crater' in the water when the beach slumped into the lake, but popped back up again shortly afterwards and was cast up on the beach by a 'tidal wave'. The water was "heaving and bulging", and large waves smashed onto the beach. Many crevasses opened up in the delta, and much of the beach where Mr Thompson had been standing disappeared into the lake. The remaining beach was cracked and spongy where before it had been hard".*
Validity:	Definite

Date:	**2–3 May 1992 (Event 1)**
Lake(s):	Maud and Tekapo (Takapo)
Generation:	Rock avalanche (Mount Fletcher) and ice collapse (Maud & Grey Glaciers)
Wave type:	Tsunami
Effects:	The Civil Defence Officer's report (Dore 1992) states: *"After a series of rockfalls … a massive fall occurred during the night of 2–3 May dislodging thousands of tonnes of rock and triggering the dislodging of massive amounts of ice off the terminal faces of the Maud and Grey Glaciers into the ice melt lake at the foot of the two glaciers.* *This in turn displaced huge amounts of water creating a large wave estimated 20 metres high or more which overtopped the debris and river outlet at the southern end of the Glacier Lake and discharged down Godley Valley in a surge that from evidence covered most of the Valley floor and all the flood channels. Reports from Air Safari pilots and others the next day indicated large amounts of discoloured water discharging down the Valley and into Lake Tekapo….No doubt the length of the valley (28 kms from Lilybank Station to Separation Stream) dissipated most of the force of the flood wave by the time it reached the head of Lake Tekapo. Everywhere we travelled the ground was littered by shrubs and snow, tussocks torn out by the force of the water for most of the length of the valley …"* McSaveney (1992b, p. 100) described the rock avalanche event and the subsequent flood wave as: *"A great flood wave shot out of the lake and travelled 45 km down Godley River to Lake Tekapo, but it wasn't much of a flood beyond about 5 km".* More detail of the flood-wave was provided by McSaveney (2002), based on eye-witness accounts, field observations and modelling. The flood wave left icebergs stranded up to 20 m above the lake, near Godley Hut, and vegetation near the lake outlet was ripped out, over a width of c. 650 m across the valley. The braided bed of the Godley River was extensively scoured for several kilometres. *"The flood travelled 45 km to Lake Tekapo where it raised the lake level ~90 mm"* (p. 59). The water inflow into the lake was calculated to be 7.8×10^6 m^3 and the wave celerity was calculated at c. 8.0 km/h or 2.2 m/s. The fastest lake rise was 16 mm in 1.25 hours, which was equivalent to 300 m^3/s inflow and: *"Peak outflow from the point of impact would have been several orders of magnitude*

greater" (p. 60). If the wavelength was assumed to be 1.9 km long (based on the wave event of 16 September 1992, see below), the wave height could have been c. 10 m.

Hyde (2015) noted that: *"A large rock avalanche fell from Mt Fletcher and travelled down the Maud Glacier valley and into the small glacier lake. Eight million cubic litres of water were displaced generating a flood wave that travelled 45 kilometres down the Godley River to Lake Tekapo. The lake rose by 98 millimetres"*.

Validity: Definite

Date: 16 September 1992 (Event 2)

Lake(s): Maud and Tekapo (Takapo)

Generation: Rock avalanche and ice collapse (Mount Fletcher & Maud Glacier)

Wave type: Tsunami

Effects: Ice was stranded and snow blackened to a height of 7.0 m above the lake. The Maud Lake outlet was scoured over a width of 600 m. The rock avalanche and ice debris displaced 5×10^{6} m^{3} of water from Maud Lake, into Lake Tekapo (Takapo), across a front 780 m wide. The estimated wave dimensions were c. 1.9 km long and c. 7.0 m high. The volume of water that entered Lake Tekapo was less easy to calculate than for the May 1992 event because of lake level fluctuations associated with hydro-electricity generation and preceding rainfall (McSaveney 2002).

Validity: Definite

Date: 18–25 July 2004

Lake(s): Rotoehu

Generation: Landslides generated by earthquake swarm, coinciding with heavy, prolonged rainfall from 15–18 July

Wave type: Tsunami (called seiche by Hancox et al. 2004)

Effects: Hancox et al. (2004, p. 1) reported on the Lake Rotoehu earthquake swarm and noted that: *"The many landslides that fell into Lake Rotoehu may have caused or at least contributed to the ~600mm 'seiche' (wave) observed 8–10 m back from the lake shore"*. NIWA (2020) stated: *"The landslips were aggravated by an earthquake swarm of over 200 shallow earthquakes around Lake Rotoehu, coinciding with the flood impact"*.

Validity: Definite

Date: **10 February 2009**

Lake(s): Tasman

Generation: Ice-calving (Haupapa / Tasman Glacier)

Wave type: Tsunami

Effects: *"A giant slab of ice, estimated at 250 m long by 250 m wide and 80 m high, plunged into the lake. It sent a three-metre surge of water down the terminal lake. A second iceberg about a quarter of the size calved from the face shortly afterwards"* (Tollan 2010). The event was witnessed by tourists on a boat trip on the lake (Tourism New Zealand, 2009).

Validity: Definite

Date: **22 February 2011**

Lake(s): Tasman

Generation: Ice-calving (Haupapa / Tasman Glacier). Possibly induced by a combination of earthquake shaking (Christchurch earthquake), preceded by prolonged, heavy rainfall, higher lake levels, and warmer lake water temperatures (Dykes et al. 2017). Epicentre: Mw 6.2. 43.58°S, 172.68°E. Depth 5.0 km (Geonet 2021)

Wave type: Tsunami

Effects: The *Timaru Herald* (23 February 2011) reported the following: *"Glacier watchers on the Tasman Lake had an experience of a lifetime yesterday. Two guides and 16 passengers were on two boats on the lake when the 6.3 magnitude Canterbury earthquake hit, triggering tsunamis and causing a massive ice calving off the glacier. Aoraki-Mt Cook Alpine Village Ltd general manager of tourism, Denis Callesen said the guides were radioed from the village as soon as the earthquake was felt, so were able to prepare for the event. Mr Callesen said the boats endured 30 minutes of tsunamis, up to 3.5 metres high. Staff are trained for the event, knowing to turn the boats towards each tsunami and motor gently forwards. About 30 million tonnes of ice calved – 1200 metres across the face, 30 metres above the lake and more than 250 metres below the surface to the bottom of the lake and back for about 75 metres. Mr Callesen said it was either the third biggest, or second-equal biggest event in Tasman Lake's history"*.

Power (2013, p. 3) stated the ice-calving and subsequent tsunami were caused by the 22 February Christchurch earthquake, but it was debatable whether this was a true tsunami although no reason for the doubt was given. Dykes (2013) and Dykes et al. (2017) measured this tsunami with dataloggers, where it reached c. 3.1 m above the lake's water-level, at its southern shoreline. The event was also videoed and photographed with time-lapse cameras, confirming the wave occurrence, and enabling the ice-calving volume to be calculated at c. 4.5 x 106 m^3. The event happened about 30 minutes after the Mw 6.2 Christchurch earthquake, and: *"… while the temporal association with the earthquake remains intriguing, the effects of any preconditioning factors remain unclear"* (Dykes et al. 2017, p. 336).

Pararas-Carayannis (2019) reported on the February 2011 Christchurch earthquake and the subsequent Tasman Lake tsunami. Details were much the same as those repored in the *Timaru Herald* (2011; see above), although Pararas-Carayannis (2019, p. 148) stated: *"According to eyewitnesses* (sic) *reports the initial wall of water was 50 to 60 metres in height …"*. In researching the present paper, no other documentation was found to verify this.

The NZTD gives this event (ID 714) a validity of 'Probable', which is contrary to the fact that the tsunami was observed by many witnesses on the lake, as well as being instrumentally recorded and filmed. The NZTD also states that the: *"Lyttleton earthquake caused glacier to calve (30 Mt* [million tonnes] *ice)"*, which contrasts with Dykes et al. (2017) who cast doubt about the influence of the earthquake on the ice-calving event. Based on tsunami definitions such as those of Clark et al. (2011) and Power (2013), plus evidence of witnesses and Dykes et al. (2017), the event is classed here as a definite tsunami.

Validity: Definite

Date: 31 January 2012

Lake(s): Tasman

Generation: Ice-calving (Haupapa / Tasman Glacier)

Wave type: Tsunami

Effects: This event was also recorded instrumentally, with Dykes et al. (2017, p. 339) observing that although a greater volume of ice (c. 6×10^6 m^3) was involved than in the 22 February 2011 event, *"… this calving event was preceded by much more subtle variations in precipitation and lake-level changes than the 2011 calving event"*.

Validity: Definite

Date: 4 May 2015

Lake(s): Wānaka

Generation: Earthquake (Matukituki Valley). Epicentre 44.54°S, 168.84°E. M_W 5.8. Depth 4.0 km. (Halliday 2016; Geonet 2021)

Wave type: Seismic seiche

Effects: Halliday (2016, p. 1050) reported seismic *"… seiche waves with an estimated height of 0.5 m were observed at Wānaka* (township)*"*. Halliday (*pers. comm.*, E-mail 18 March 2022) stated: *"The seiche wave was reported to me by a digger driver who was excavating an elevated building site near the end of Mt Gold Rd, about 300m from the lakeshore of Beacon Point. He felt the Matukituki earthquake and climbed out of his digger. He subsequently noticed a series of waves advancing down the lake, which was flat calm at the time, from the direction of the Matukituki Valley. He estimated the height of the waves at 0.5 m, but this observation was from a site 50 m above lake level and 300 m from the shore"*.

Validity: Probable

Date: 2019 (day/month unknown)

Lake(s): Erskine

Generation: Avalanche (snow, ice)

Wave type: Tsunami

Effects: Morris (2021, p. 68) provides photographic evidence a large avalanche that entered Lake Erskine and reported: *"A wave was then generated and propagated outward from the impact zone as the wave travelled across the lake. It was reflected from the opposite shoreline"*. Morris stated that different patterns in the cracked lake-ice indicated the initial avalanche impact point and subsequent wave travel directions.

Validity: Definite

Date: **6 February 2019**

Lake(s) Tasman

Generation: Ice-calving (Haupapa / Tasman Glacier)

Wave type; Tsunami

Effects: George (2019) reported that ice-calving resulted in*: “A tidal surge up to 2 metres high smashed the jetty about and lifted a boat trailer upside down onto another trailer”*. This event was reported in many newspapers and verified by glacier-lake boat tour guides.

Validity: Definite

Date: **10 September 2021**

Lake(s): Hooker

Generation: Avalanche (snow, ice)

Wave type: Tsunami

Effects: Time-lapse video footage taken by the Mountain Research Centre, (University of Otago; Miller, *pers. comm*, 2021), shows a large avalanche from the Hayter Stream catchment entering Hooker Lake, disturbing the lake surface, and distributing avalanche debris right across the lake.

Validity: Definite

Date: **13 October 2021**

Lake(s): Hooker

Generation: Avalanche (snow, ice)

Wave type: Tsunami

Effects: Time-lapse video footage (cover photograph and Figure A1, following page) taken by the Mountain Research Centre (University of Otago; Miller, pers. comm. 2021) shows a large avalanche in the Hayter Stream catchment entering Hooker Lake at 06:51. Although the wave height is not determinable from the video, avalanche snow and ice were distributed directly across the c. 600m-wide lake in just over two minutes, indicating the wave celerity was around 18 km/h, or 5.0 m/s.

Validity: Definite

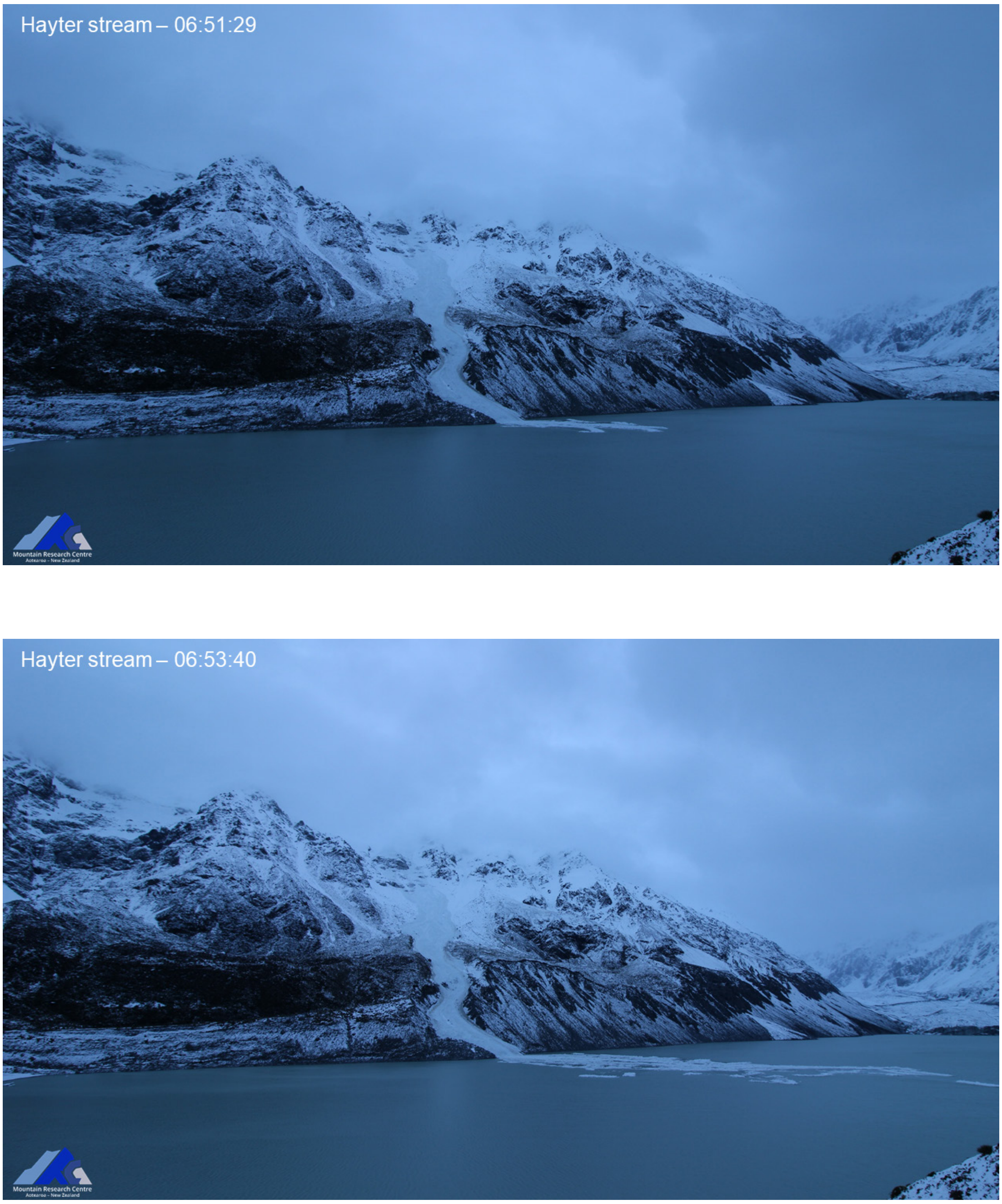

Figure A1. Hooker Lake, 13 October 2021. Time-lapse images showing an avalanche in the Hayter Stream catchment (centre) entering Hooker Lake and the subsequent tsunami distributing debris across the c.600 m wide lake in just over two minutes. Photographs: Aubrey Miller (Mountain Research Centre, University of Otago, Dunedin). Used with permission.

Date:	**30 November 2022**
Lake(s):	Taupō / Taupōmoana
Generation:	Earthquake. Epicentre 36.86°S, 175.96°E (c. 20 km south-west of Taupō). M5.7; M_L 5.3. Depth = 9.0 km. Strong shaking (Geonet 2022a). Probable combination of earthquake activity and ground deformation caused by magma and hydrothermal fluids moving deep beneath Taupō volcano, and subaerial/subaqueous landslides (e.g., Hutchinson 2022a; GNS 2022a, b, c)
Wave type:	Tsunami(s)
Effects:	Although the wave(s) was not witnessed because of the earthquake occurrence time (11:47 p.m., Geonet 2022a), substantial evidence validates the occurrence of the tsunami(s). Newspaper websites, the next day, published photographs of debris lines stranded many metres from the foreshore in grassed park areas; destroyed pleasure craft, ground deformation (cracks and subsidence) around the lake edge, and a severely eroded beach (e.g., Hewitt 2022; Hutchinson & Ward 2022; Hutchinson 2022a, b). Dr Emily Lane (NIWA, Hydrodynamic Scientist) posted a graph on social media (the next day), of water level recordings taken from the lake level gauges at Acacia Bay and Tokaanu, both of which showed an immediate (albeit small) increase in water levels at the time of the earthquake. The graph was presented in Hutchinson (2022b).

The most significant damage occurred in the Four Mile Bay area at Wharewaka, where the local coastguard skipper stated: *"In Four Mile Bay, at the southern end of Taupō township, the water had surged about 20–30 m up the beach, destroying two boats … ripping wooden bollards from a park area nearby and eroding about 2 m of soil away from the foreshore"* (Hutchinson & Ward 2002). The owners of the destroyed boats stated that the wave(s) uplifted the boats from the grassed area, pulled them back into the water, and destroyed them (Hewett 2022).

At the time of this publication, GNS Science, NIWA, and other agencies, were still analysing the earthquake and tsunami data, which was being updated regularly via the media, so published scientific information for inclusion in this report was limited. Nonetheless, Geonet (2022a, b, c) provided some quantitative data in relation to ground deformation, landslides, and tsunami run-up levels. At Horomatangi Reef, there was 250 mm horizontal movement towards the south-west, and 180 mm of vertical movement (the largest ever recorded at this location). At several onshore sites, horizontal movement was between c. 10–20 mm, but it was noted further analysis of the dataset was underway. Geonet (2022b) stated:

"Experts are assessing earthquake-related tsunami in the lake that occurred because of the M5.6 earthquake (since upgraded to M.5.7). This caused run up along the lakeshore at several locations, mostly focussed on the northern end of Lake Taupō. Our field teams have been using drone footage and surveying techniques to measure localised lake shore slumping and tsunami inundation. Locations of investigation have been guided by public information along the lake shore. The position of pumice strandlines at Wharewaka Point appears to show the largest tsunami inundation, measured at ~40 m inland. Wave action is likely the result of at least one tsunami, however, we are still assessing their causes".

Geonet (2022c) described the small tsunami as waves travelling across the lake and surging a few metres across many beaches, leaving behind some strands of pumice, sticks and sand. *"The larger surge at Wharewaka Point, where the beach is known to have retreated by some 20 m, may be associated with a possible underwater landslide. It is expected that models generated by our experts in the coming weeks will allow us to understand these details further"*. Surveyed tsunami debris was found almost one metre above the lake level, on the western shores at Kuratau, and on the east shore of the lake at Motutere. In places, the lakeshore had been undercut by waves and small areas had collapsed a metre or so back. Less impact was recorded on the northern lakeshores, as at Whakaipo Bay, where pumice debris was deposited less than 30 cm higher and less than a metre inland from the high-water mark. At Kinloch, Acacia Bay, and in the western bays, little or no change was recorded. The major changes occurred at Wharewaka

Point, where there a substantial amount of foreshore and beach was washed out, and pumice debris stranded to a maximum of about 40 m inland from the lake. Computer modelling was being undertaken to determine how the tsunami might have been generated and spread across the lake, and the specific cause of the effects at Wharewaka Point was also being investigated. Over 30 landslides had been recorded around the lake, with the largest being in the Whitecliffs area (7.0 km from the epicentre). Geonet (2022c) continued:

"Here, a several-hundred-meter-long (though relatively shallow) section of the cliffs collapsed into the lake, generating a large white plume of sediment that could still be seen stretching north along the coastline several days after the earthquake … It is possible an underwater landslide occurred at the location of the popular swimming beach (Wharewaka Point), causing 170 m of the shoreline to subside into the lake, with a maximum retreat of up to 20 m. Whilst still under investigation it is possible that the collapse of the beach into the lake drew water in behind it, generating the local tsunami that washed up onto the picnic area behind it".

Validity: Definite