ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 42 Number 3 2023

TSUNAMIS, SEISMIC SEICHES, AND UNDETERMINED WAVES ON NEW ZEALAND LAKES, 1846–2022: A NEW DATABASE, AND OVERVIEW.

John Benn
Department of Conservation
Private Bag 4715
Christchurch Mail Centre 8140
New Zealand
Email: jbenn@doc.govt.nz

ABSTRACT

A new database of tsunamis, seismic seiches and undetermined waves (collectively called lake waves) that occurred on New Zealand lakes between1846-2022 has been compiled and summarized. Based on an extensive literature review, photographic and field evidence, the investigation is the first to collate such information on a national scale. It increases the knowledge of a poorly understood natural hazard that has occurred throughout the country and provides a basis for further research.

Seventy-four lake waves were recorded, implying a much higher occurrence frequency than previously considered. Apart from meteorite impact, lake waves have been generated by all known mechanisms, from local to global scale. Eleven tsunamigenic categories were identified. Most (*n* = 48; 65%) have been associated with seismic shaking, either directly, or with co seismic processes. Lake waves have been recorded in all types of lakes, ranging from the country's largest to some of the smallest; some of the deepest to shallowest, and from the highest-altitude lake to those around sea level. The greatest wave height (c. 10 m), and run-up elevation (c. 20 m above the lake surface), was associated with the May 1992 Maud Lake tsunami. To date, lake waves have caused minimal property damage or personal injury, although the hazard and risk they present is predicted to increase, in association with intensifying lakeside developments and, possibly, with climate-change effects.

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

1. INTRODUCTION

New Zealand is prone to all known natural hazards (e.g., Spenden & Crozier 1984; Owens 2001), owing to its position across the active Australian–Pacific tectonic plate boundary, and its maritime location in the South Pacific Ocean (Figure 1). Yet, no research has been undertaken nationally, examining the historic occurrence of tsunamis, seismic seiches, or other undetermined waves (collectively termed lake waves) on the country's lakes, despite there being nearly 4,000 lakes greater than one hectare in area, with the eight largest each being greater than 100 km^2 (Schallenberg et al. 2013).

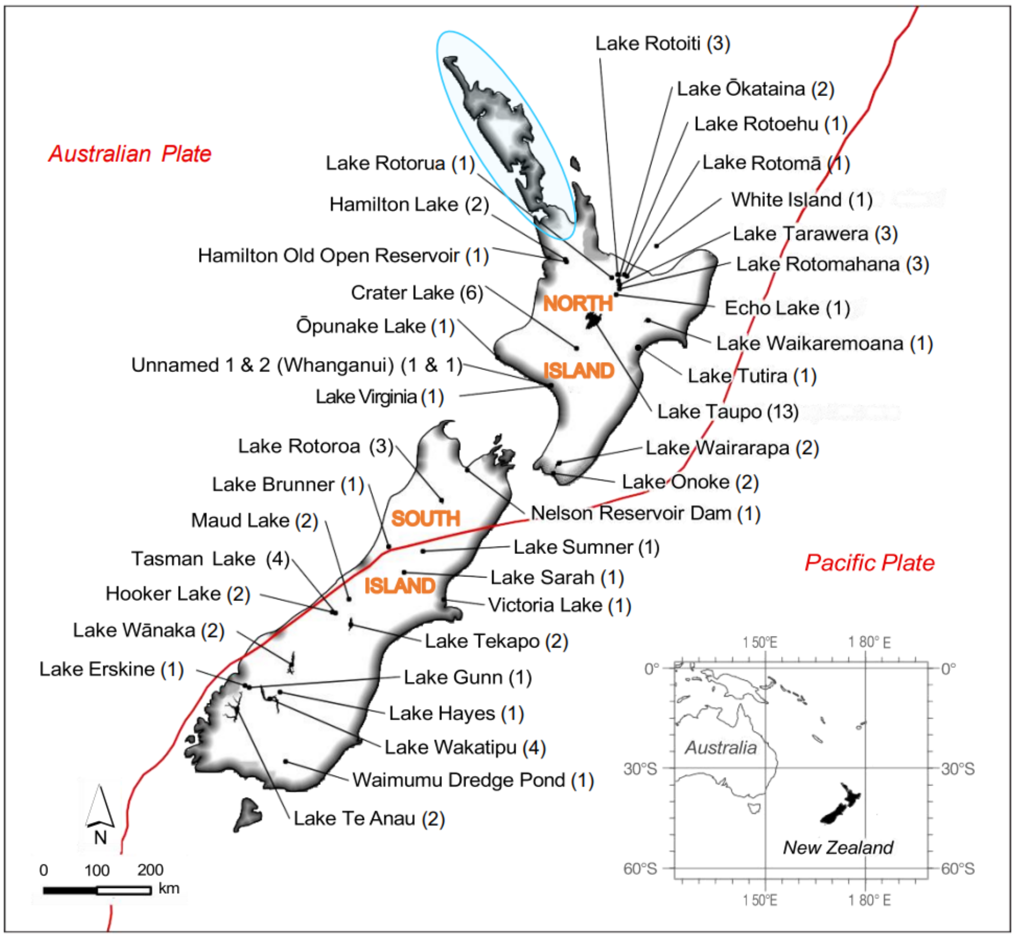

Figure 1. *New Zealand locations from where lake waves have been reported (and number of occurrences at each). Red line is the Australian-Pacific tectonic plate boundary. Blue-shaded area shows the Northland and Auckland regions, where no records were found.*

Recent lake wave research has been site-specific and focused on event prediction, based on return-periods of other natural hazards, that could be tsunamigenic (e.g., de Lange et al. 2002; Allen et al. 2009; Clark et al. 2011, Clark et. al 2015; Mackey 2015; de Lange & Moon 2016, Fraser & McMorran 2016; Brambus 2017, Mountjoy et al. 2019; Wang et al. 2020). Regarding historic lake waves, most literature has given them only a passing mention (excluding those generated by wind-forcing), as it has focused on initial generating mechanisms like seismic 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. Besides details of four historic lake tsunamis, presented by McSaveney (1992a, b, 1993, 2002), Dykes (2013), and Dykes et al. (2017), most information for such events is found in contemporary newspapers. Contrastingly, research for oceanic tsunamis is extensive and several national databases have been compiled - the most recent being the New Zealand Tsunami Database (Downes et al. 2017; GNS 2023).

To address this knowledge gap, the New Zealand government's Department of Conservation (which administers approximately one third of the country's land area) undertook an investigation to establish baseline information of historic lake waves, including locations, generating mechanisms, wave types, height and run-up elevations, frequency, and damage they have caused to life and property (Benn 2023). This complements predictive modeling and risk analyses recently undertaken by other government and external organizations, as commercial developments, recreation, and tourism activities intensify around many of the country's lake margins. Locations of reported lake waves are shown in Figure 1, with basic details for each event listed in Appendix 1.

2. METHODS

2.1 Information sources

An extensive desktop literature search was undertaken, combined with video/photographic, survey, field, and eye-witness evidence of lake wave occurrence, obtained via communications with others in similar fields of research. The Papers Past website (Papers Past | Newspapers Home (natlib.govt.nz)) provided most information (especially for the period 1846–1930s), as all New Zealand's newspapers have been scanned by the National Library, from each paper's first publication date up until at least 1920, and some major papers, up to the late 1980s. Parliamentary papers/reports/journals, personal letters and diaries, and other historic documents have also been scanned (ongoing and updated regularly). Other information sources included:

a) Earth-science journals,
b) New Zealand Tsunami Database (Downes et al. 2017; GNS 2023),
c) New Zealand Historic Weather Event Catalogue (NIWA 2023),
d) GNS landslide and earthquake reports for specific events,
e) Readily available natural hazard reports (councils and consulting companies),
f) Postgraduate theses,
g) General internet searches,
h) Miscellaneous history books,
i) Personal communications with other New Zealand-based earth scientists.

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, whirlpool, and specific locality names of known, or potential lake wave events, were searched.

2.2 Definitions

Accepted definitions for tsunamis (e.g., Sheppard et al. 1950; CERC 1984; Pararas-Carayannis 2000) and seismic seiches (e.g., Kvale 1955; McGarr 2020) were used. For this investigation, all waves caused by material falling into, or entering lakes and displacing water, were called tsunamis, regardless of the volume of the material involved (e.g., mass movement, small rockfalls). Undetermined waves (or oscillations) were those generated by unidentified processes but were known to have not been generated by wind forcing.

In cases when a generating mechanism like the February 1931 M_S 7.8 Napier earthquake (Downes & Dowrick 2014) produced a series of waves on unconnected lakes, the waves were defined as separate (multiple) lake waves. Conversely, in events such as the May 1992 Mount Fletcher rock avalanche/Maud Glacier ice collapse, which produced a single wave that travelled across multiple, connected lakes, the wave was defined as a single lake wave. In the database (Benn 2023), original reported units of measurement (imperial or metric) were maintained, as were earthquake magnitudes (M_W, M_{WF}, M_L, M_S, etc.) and intensities (MM, R-F) as defined by Downes and Dowrick (2014). Lake types listed in Table 1 are defined by Lowe and Green (1987).

2.3 Validity

For oceanic tsunamis, previous researchers have used a combination of numeric and descriptive methods to rank the validity of occurrence, ranging from the most detailed and reliable, to the vaguest and least reliable reports (e.g., Cox & Morgan 1977; de Lange & Healy 1986; Downes et al. 2017). Based on available evidence, lake wave validity classes for this investigation were defined in descending order as Definite, Probable, and Possible (Table 3, Appendix1). Further analysis may refine these, to align to the five validity classes established by Downes et al. (2017).

3. RESULTS

Seventy-four lake waves have been recorded on 38 lakes throughout New Zealand, between 1846 and 2002 (Figure 1; Appendix 1). Results are summarized in Tables 1–4, below.

Table 1. Lake waves recorded in New Zealand

Lake	Lake Type	Total Number of Waves	Wave Type & Number		
			Tsunami	Seismic Seiche	Undetermined
White Island	Volcanic	1	1		
Rotoroa / Hamilton	Peat	2		2	
Hamilton old open reservoir	Artificial	1		1	
Rotoehu	Volcanic	1	1		
Rotoiti	Volcanic	3	1	2	
Rotomā	Volcanic	1		1	
Rotorua	Volcanic	1		1	
Ōkataina	Volcanic	2		2	
Tarawera	Volcanic	3	1		2
Rotomahana	Volcanic	3	2	1	
Echo	Volcanic	1	1		
Taupo	Volcanic	13	7	4	2

Waikaremoana	Landslide	1		1	
Tūtira	Landslide	1	1		
Crater Lake	Volcanic	6	6		
Ōpunake Lake	Artificial	1	1		
Virginia	Dune	1		1	
Unnamed (1) Whanganui	Dune	1		1	
Unnamed (2) Whanganui	Dune	1		1	
Wairarapa & Onoke	Riverine & Bar	2	2		
Nelson reservoir dam	Artificial	1		1	
Rotoroa	Glacial	3	1		2
Brunner	Glacial	1	1		
Sumner	Glacial	1	1		
Victoria	Artificial	1		1	
Sarah	Glacial	1	1		
Maud & Tekapo	Pro-glacial & Glacial	2	2		
Hooker	Pro-glacial	2	2		
Tasman	Glacial	4	4		
Wānaka	Glacial	2	1	1	
Wakatipu	Glacial	4	1	3	
Erskine	Glacial	1	1		
Gunn	Glacial	1	1		
Hayes	Glacial	1			1
Te Anau	Glacial	2	1		1
Waimumu dredge pond	Artificial	1		1	
Totals		74 (100%)	41 (55%)	25 (34%)	8 (11%)

Notes: 1) Lakes listed from north to south - North Island lakes above red line, South Island lakes below; 2) Connected lakes are listed together, as individual lake wave events have affected the connected lakes simultaneously. Lakes Wairarapa and Onoke are connected via the Ruamahanga River; Maud Lake and Lake Tekapo are connected via the Godley River; 3) Blank spaces = no record.

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

Wave type and number				
Location	**Tsunami**	**Seismic Seiche**	**Undetermined**	**Total**
North Island	24	18	4	46 (62%)
South Island	17	7	4	28 (38%)
New Zealand	41 (55%)	25 (34%)	8 (11%)	74 (100%)

Table 3. Lake wave association with generating mechanisms. Note that the sum and percentages of waves are greater than 74 and 100%, respectively, as many lake waves were counted more than once, reflecting their association with multiple, simultaneous generating mechanisms.

Lake wave generating mechanism	Number (%) of lake waves associated with generating mechanisms
Seismic shaking	48 (65%)
Mass-movement (sub aerial/subaqueous slides)	18 (24%)
Volcanic/geothermal activity	14 (19%)
Ice-calving/collapse	10 (14%)
Gas-expulsion	6 (8%)
Rainfall	3 (4%)
Avalanche (snow, ice)	3 (4%)
Liquefaction	2 (3%)
Faulting/tilting (lakebed/margins)	1 (1%)
Atmospheric coupling	1 (1%)
Undetermined	6 (8%)

Table 4. Validity of lake wave occurrence.

Validity	Number (%) of lake waves
Definite	48 (65%)
Probable	16 (22%)
Possible	10 (13%)

4. DISCUSSION

4.1 Historic record and validity

It is acknowledged that the list of events recorded may be incomplete and may contain potential inaccuracies, for the following reasons. Many of New Zealand's lakes are remote from populated areas so numerous lake waves may not have been witnessed nor recorded. This concurs with findings by the likes of Kvale (1955), Roberts et al. (2013), and Clark et al. (2015). Similarly, many potential or actual tsunamigenic mechanisms have occurred at night, and again, eyewitness accounts may be absent.

Corresponding with a gap of digitized newspapers, comparatively little information was found for the period between the mid-1930s and early 2000s. Searching hard copy newspapers from this digital gap were outside the project's scope, as was searching for lake level data held by numerous organizations, which may have identified more events. However, real-time lake level data for most New Zealand's lakes do not exist, further increasing the possibility of lake waves being undetected. Lake wave research in New Zealand is a relatively recent occurrence, focused on modeling future events rather than documenting those past, so historical information is limited. Also, some records may have been overlooked in the literature search.

Accounts relying solely on historic (especially singular) newspaper reports may not be as accurate as others based on several independent sources of information (Munro & Fowler 2014), so details for some events listed in Tables 1–4 and Appendix 1 may change, as more information is found, and further analysis undertaken. Nonetheless, in similar investigations for oceanic tsunamis, Cox and Morgan (1977), de Lange and Healy (1986), and Downes et al. (2017), noted the importance of historic newspapers as an information source, which holds true for this investigation. Despite the recognized limitations, the events recorded provide a baseline for further research and allow the following initial observations to be made.

4.2 Distribution

Seventy-four lake waves have been recorded throughout New Zealand, from White Island's crater lake in the north, to the Waimumu gold-dredge pond in the south. However, no records were found for the Auckland or Northland regions, despite both regions having numerous natural lakes and artificial reservoirs (Figure 1; Table 1). Northland's lack of records is attributed to a possible absence of events and/or observation bias (being sparsely populated), whilst the most likely explanation for Auckland is event absence: Auckland is the most densely populated region in the country, making the probability of observation high, if any events had occurred. Almost two-thirds of lake waves have been recorded from the North Island (*n* = 46 [62%] in 21 lakes), compared to just over a third (*n* = 28 [38%] in 17 lakes) for the South Island (Table 2). This is also attributed to observation bias rather than environmental factors, as historically, many North Island lake-margins (such as Lake Taupo, with the highest recorded number of events; *n* = 13) have had much higher population densities than those of the South Island.

Lake waves have occurred on natural, modified, and artificial lakes, ranging in size from Lake Taupo, New Zealand's largest lake (616 km^2), 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 (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 altitude 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 the lowest lying, such as Lake Wairarapa at < 1.0 m above mean sea level (Livingston et al. 1986a).

4.3 Generating mechanisms

Lake waves in New Zealand have been generated by all known mechanisms except for meteorite impact, with eleven categories of tsunamigenic mechanisms identified: In many events, multiple, simultaneous trigger mechanisms were involved (Table 3). Most lake wave events (*n* = 48; 65%) have been associated with earthquakes, either as a direct consequence of seismic shaking (seismic seiches), or from secondary co seismic effects, like mass-movement, lakebed faulting, and liquefaction (tsunamis). Given New Zealand's high seismicity levels owing to its tectonic position, this result was not unexpected. The lowest earthquake magnitude found to be associated with lake wave generation was M_L 5.3 (1956 and 2022 Taupo tsunami events: Downes & Dowrick 2014; GeoNet 2022), although descriptive accounts for other events suggest it is probable that earthquakes of < M_L 5.3 have generated lake waves.

Records show that large-magnitude earthquakes and volcanic eruptions can generate more lake waves over a wider area than other tsunamigenic mechanisms, which tend to produce an individual wave at a specific site (Figures 2 & 3; Appendix 1). Eighteen lake waves (24%) have been attributed to some form of sub aerial or subaqueous mass-movement (Table 3). However, it is likely at least eight more (11%) were associated with this, in cases where landslides were recorded in the immediate vicinity of a lake wave event, but no reports were found of mass movements directly affecting the lakes. The generating mechanisms for six events (8%) could not be determined.

Geological controls produce broad tsunamigenic variances between the North and South Islands. 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 (Mount Ruapehu) - the only North Island lake with a permanent ice field adjacent to it. In the South Island, lake waves have been generated by most mechanisms, except volcanic activity (confined to the North Island) and atmospheric coupling, although the latter remains a possibility.

Lake waves in New Zealand have been generated by local, national, and remote, global-scale mechanisms (Figure 2). As examples, the May 1992 Maud Lake (unofficial, but common name) tsunami was generated by a local event – the Mount Fletcher rock avalanche/Maud Glacier ice-collapse (e.g., McSaveney 2002). On a national scale, Grapes (2000) noted the 1855 Wairarapa earthquake (M_{WF} 8.2, Downes & Dowrick 2014) caused seismic seiching in lakes and rivers between Lake Rotoiti (North Island) and Christchurch (South Island); an approximate range of 690 km (geodesic distance). At a global scale, the 1883 Krakatau eruption (Indonesia) caused a volcano-meteorological (atmospheric) tsunami on Lake Taupo (*The Thames Star* 15 September 1883; de Lange & Healy 1986; Lowe & de Lange 2000), 7, 900 km (geodesic distance) from the source. Similarly, the February 1938, M_W 8.6 Banda Sea earthquake in Indonesia (Okal & Reymond 2003; Cummins et al. 2020), was the apparent source for the seismic seiche reported on Virginia Lake (e.g., *Evening Post* 5 February 1938). Besides these two global-scale examples, all other reported lake waves (97%) were generated by mechanisms originating within New Zealand.

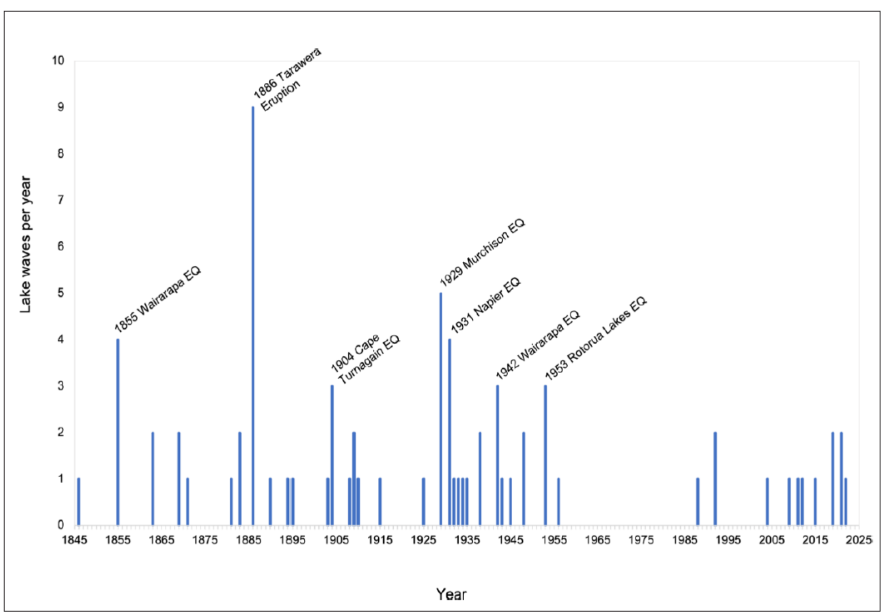

Figure 2. Lake wave occurrence, 1846–2022.

As illustrated by Figure 2, three or more lake waves generated by earthquakes were recorded. The tsunamigenic wave generating mechanisms of such earthquakes were dominated by the above listed, large-magnitude geological events, which produced waves on multiple lakes. The 1886 Mount Tarawera eruption is the dominant tsunamigenic 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 2000s, correlate with an absence of digitized newspapers, and prior to the early 1900s, many newspapers were not published daily, so some events may not have been reported. Prior to the early/mid 1900's, 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 the volcanic Lake Taupo in the North Island.

Figure 3. *Hooker Lake tsunami, Southern Alps, New Zealand (looking northwest to the Aroarokaehe Range): 7:00 a.m., October 13, 2021. The tsunami, generated by an avalanche in the Hayter Stream catchment (centre), crossed the 600 m wide lake in approximately two minutes (c ≈ 5.0 m/s or 18 km/h). Time-lapse photograph courtesy of Aubrey Miller (Mountain Research Centre, University of Otago, Dunedin, New Zealand).*

4.4 Wave height and run-up elevation

The greatest lake wave height to have been instrumentally recorded was the c. 3.1 m high tsunami on Tasman Lake, during the February 2011 Tasman Glacier ice-calving event (Dykes 2013; Dykes et al. 2017). However, wave heights presented for the May 1992 Maud Lake tsunami, have ranged from Dore's (1992) estimated > 20 m, to McSaveney's (2002) calculated 10 m (based on valley dimensions and iceberg/debris deposition levels). A tsunami height of c. 10 m appears most credible and comparable to the largest oceanic tsunamis recorded around the New Zealand coast (e.g., de Lange & Healy 1986; Fraser 1998; GNS 2023; NIWA 2023). McSaveney (2002) doubted a tsunami height of > 20 m, noting that icebergs stranded 20 m above the lake represented a combination of wave run-up and iceberg momentum, rather than wave height. If Dore's (1992) estimate were 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). Nevertheless, a tsunami run-up height of 20 m above the lake surface is comparable with modeling results by Clark et al. (2015), and Fraser and McMorran (2016), who calculated tsunami run-up heights of up to 25 m could result from large landslides entering the nearby glacial lakes of Tekapo, Pukaki, and Ohau.

Based on reliable evidence, the 1992 Maud Lake tsunami is most likely the largest terrestrial-based tsunami recorded in New Zealand during historic times, as from its source in Maud Lake, the wave travelled 45 km down the Godley River valley, and discharged c. 7.8 x 10^6 m^3 of water into Lake Tekapo, raising the 87 km^2 lake by c. 90–98 mm (Dore 1992; McSaveney 1993, 2002). At the opposite extreme, detailed surveying by GNS after the small November 2022 Lake Taupo tsunami, showed that relative to the lake's usual high-water mark, the maximum wave run-up elevation was 1.0 m and horizontal inundation distance was 40 m, respectively (GeoNet 2022; Appendix 1).

Reported wave heights for seismic seiches and undetermined waves (mostly based on visual observations), have ranged from as little as c. 12 mm on Victoria Lake (*Christchurch Star* 17 June 1929a, b) in the June 1929 M_S 7.8 Murchison Earthquake (Downes & Dowrick 2014), to 4.5 m at Lake Waikaremoana (*Poverty Bay Herald* 4 February 1931) in the 1931 Napier Earthquake. The upper limit is comparable to modeling results by Wang et. al. (2020), who showed that seismic seiche wave heights in the southern arm of Lake Tekapo during a M_W 8.2 Alpine Fault earthquake could reach c. 4.0 m. Where estimates for seismic seiche and undetermined wave heights are given in Benn (2023), most are less than 2.0 metres.

4.5 Duration

The longest observed period of seismic seiching was on Lake Rotorua, where continuous lake oscillations occurred for just over a month following the June 1886 Mount Tarawera eruption and associated earthquake swarm (Pond & Smith 1886). Another long period of lake oscillating, possibly caused by sub-aqueous mass-movement, occurred continuously for a week in February 1933, on Lake Taupo (e.g., *Auckland Star* 21 February 1933; *Nelson Evening Mail*, 23 February 1933). The longest recorded tsunami durations have been considerably shorter. McSaveney (2002) noted a rapid rise in Lake Tekapo's level from the arrival of Maud Lake tsunami (5.6 h after generation), which then declined exponentially over the next few days. Likewise, almost immediately after the February 2011 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). Where lake wave durations are known, most fall between a few minutes to a few hours (Benn 2023).

4.6 Frequency

It has been generally accepted that lake waves in New Zealand are rare, low-frequency events. When discussing large-scale rock avalanches in the Southern Alps, Hawley (1984) stated: *"A remote, but real possibility exists that one of these may fall into a lake (natural or "Hydro") and create waves of damaging proportions"*. More recently, Clark et al. (2015) 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"*. Similar statements by Painter (2004), Clark et al.

(2011), Ward et al. (2015), Mackey (2015), Dykes et al. (2017), and Mountjoy et al. (2019) are challenged here, as 74 lake waves over a 176-year period shows their occurrence in New Zealand has been far more frequent than previously considered. For example, the New Zealand Tsunami Database (GNS 2023) lists 128 tsunami events but only six of those are lake tsunamis.

Figure 2 shows the historic frequency distribution of lake wave occurrence. The frequency of tsunamis, especially in the South Island's glacial lakes, could increase in the future with predicted climate change increasing the frequency of landslides, avalanches, and ice-calving events around lake margins in the Southern Alps, as glaciers rapidly retreat. Warren and Kirkbride (1998) examined ice-contact lakes in the Southern Alps, noting that climate change had altered glacier behavior, which in turn, initiated ice-calving events. McSaveney (2002) reported on rock falls and rock avalanches in the Southern Alps, noting that over centuries, climatic warming and glacier-thinning had unloaded the toes of some exceptionally steep slopes, which had likely 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) examined possible climate change impacts on rock avalanches and other landslides in the Southern Alps 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"*.

4.7 Personal injury and near misses

The only reported case of personal injury caused by lake waves, was in the August 1904 Lake Rotomahana seismic seiche (M_S 6.8 Cape Turnagain earthquake, Downes & Dowrick 2014), where 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 1904; Downes 2006). Nonetheless, there have been several cases of people being swept away or knocked over by lake waves, or they have been in small watercraft when 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 Taupo (March 1910; March 1956), Lake Brunner (June 1929), Lake Waikaremoana (February 1931), Lake Wairarapa (June 1942), Echo Lake (May 1948), Lake Te Anau (June 1988), and Tasman Lake (February 2011).

4.8 Property and structural damage

Lake waves have caused minimal damage to private property or public infrastructure, primarily because most of the major events have occurred in both sparsely populated, and sparsely developed locations, at the time of occurrence. The most significant structural damage recorded, occurred near the outlet of Lake Rotoroa (South Island) during the 1929 Murchison earthquake, where a tsunami destroyed both the Gowan River bridge and lakeside jetty, and severely damaged the Lake Rotoroa Hotel (e.g., *Nelson Evening Mail* 19 June 1929). Lesser damage has included the washing-out of small sections of the vehicle access route to Godley Hut during the May 1992 Maud Lake tsunami (McSaveney 2002). On several occasions, small watercraft have been washed away from boatsheds, jetties, and moorings, as at Lake Tarawera (June 1886), Lake Taupo (March 1910, November 2022), Lake Sumner (March 1929), Lake Brunner (June 1929), Lake Waikaremoana (February 1931), and Lake Te Anau (June 1988).

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 May 1992 Maud Lake tsunami. Dore (1992) and McSaveney (1992a, b; 1993, 2002) described masses of ice and debris being deposited up to 20 m above the lake and widespread severe scouring of vegetation and sediment from the Godley River valley, many kilometers downstream of Maud Lake. The November 2022 Lake Taupo 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 (GeoNet 2022).

5. CONCLUSION

The most comprehensive database of historic lake waves in New Zealand has now been compiled, which has helped improve the understanding of these natural hazards. Furthermore, a baseline for further historical research has been established. Major findings were that lake waves have occurred at a much higher frequency than previously considered and have been generated by all known mechanisms (except meteorite impact); most being generated by, or associated with, seismic shaking. Lake wave magnitudes have ranged from barely detectable to catastrophic, and although lake waves have caused minimal damage historically, the hazard and risk they pose are expected to increase, with intensifying lakeside development and climate change effects. These findings, in conjunction with further research, may have implications for future lakeside planning and management.

ACKNOWLEDGEMENTS

Thanks are extended to the following contributors. The Department of Conservation (Eastern South Island Region, Christchurch) funded the project. Don Neale and Marie-Louise Grandiek (Department of Conservation) and two anonymous reviewers offered constructive comments on the draft manuscript. Aubrey Miller (Mountain Research Centre, University of Otago, Dunedin) provided the photograph of the 2021 Hooker Lake tsunami (Figure 3).

REFERENCES

Allen, G.F. 1907: Ruapehu and the other mountains of the Tongariro group. In: *Evening Star, 25 May 1907*: 11.

Allen, S.K.; Schneider, D.; Owens, I.F. 2009: First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand's Southern Alps. *Natural Hazards and Earth System Sciences 9*: 481–499.

Allen, S.K.; Cox, S.C.; Owens I.F. 2011: Rock avalanches and other landslides in the central Southern Alps of New Zealand: a regional study considering possible climate change impacts. *Landslides 8*: 33–48.

Auckland Star. 1933: *"Bosom Throbs"*. Lake Taupo waters. Strange movement ceases. Level rose every 4 minutes. *Auckland Star*, *21 February 1933*: 8.

Benn, J.L. 2023. Tsunamis, seismic seiches and undetermined wave events on New Zealand lakes, 1846-2022: a review. New Zealand Government. Department of Conservation, Wellington, New Zealand. *Science for Conservation 338*. 55 p. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sfc338entire.pdf

Brambus, O. 2017: The analysis of glacial retreat of selected mountain regions of New Zealand and natural hazards from GLOFs. Diploma thesis (Geography and Geoecology). Charles University. Prague. 146 p.

CERC. 1984. Shore protection manual, Vol. 1. Department of the Army, Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center (CERC). Washington D.C.

Christchurch Star. 1929a: Sway was from east to west: Mr. H.F. Skey says it was a severe one. *Christchurch Star, 17 June 1929*: 1.

Christchurch Star. 1929b: Greater than Arthur's Pass earthquake: Shocks too severe to be registered at the Observatory. *Christchurch Star, 17 June 1929*: 10.

Clark, K.; Hancox, G.; Forsyth, P.J.; Power, W.; Strong, D.; Lukovic, B. 2011: Identification of potential tsunamis and seiche sources, their size and distribution on Lakes Te Anau and Manapouri. Institute of Geological and Nuclear Sciences (GNS), Lower Hutt, New Zealand. *GNS Science Consultancy Report* 2011/96. 74 p.

Clark, K.; Upton, P.; Carey, J.; Rosser, B.; Strong, D. 2015: Tsunami and seiche scoping study for Lakes Tekapo, Pukaki, Ohau, Alexandrina and Ruataniwha. Institute of Geological and Nuclear Sciences (GNS), Lower Hutt, New Zealand. *GNS Science Report* R15/39. 82 p.

Cox, D.C.; Morgan, J. 1977: Local tsunamis and possible local tsunamis in Hawaii. Hawaii Institute of Geophysics. Honolulu. 124 p.

Cummins, P.R.; Pranantyo, I.R.; Pownall, J.M.; Griffin, J.D.; Meilano, I.; Zhao, S. 2020: Earthquakes and tsunamis caused by low-angle normal faulting in the Banda Sea, Indonesia. *Nature Geoscience 13*: 312–318.

de Lange, W.P.; Healy, T.R. 1986. New Zealand tsunamis 1840–1982: *New Zealand Journal of Geology and Geophysics 29(1)*: 115–134.

de Lange, W.P.; Magill, C.R.; Nairn, I.A.; Hodgson, K.A. 2002: Tsunami generated by pyroclastic flows entering Lake Tarawera. Conference presentation. *Eos, Transactions of the American Geophysical Union 83(22)*: Supplement – Conference abstracts.

de Lange; W.P.; Moon, V. 2016: Volcanic generation of tsunamis: Two New Zealand palaeo-events. In: Lamarche, G. et al. (Eds). Submarine mass movements and their consequences. *Advances in Natural and Technological Hazards Research, 41*: 559–567.

Donaldson, G.M. 2016: 1931 Waikari River tsunami: New Zealand's largest historical tsunami. Unpublished BSc thesis, University of New South Wales. 65 p.

Donaldson, G.M; Goff, J.; Chagué, C.; Gadd, P.; Fierro, D. 2019: 1931 Waikari River tsunami: New Zealand's largest historical tsunami. *Sedimentary Geology 383*: 148–158.

Dore, J.F. 1992: Mackenzie District Council Civil Defence Officer's report – Mt Fletcher rockfall and consequence: Godley Valley 2–3 May 1992. Mackenzie District Council, Fairlie. File Ref. j/rpt/cd-fletch. 1 p.

Downes, G.L. 1995: Atlas of isoseismal maps of New Zealand earthquakes. Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. *GNS Science Monograph 11*. 304 p.

Downes, G.L. 2006: The 1904 Ms 6.6, Mw 7.0–7.2 Cape Turnagain, New Zealand earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering 28(4)*: 183–207.

Downes, G.L.; Barberopoulou, A.; Cochran, U.; Clark, K.; Scheele, F. 2017: The New Zealand tsunami database: Historical and modern records. *Seismological Research Letters 88(2A)*: 342–353.

Downes, G.L.; Dowrick, D.J. 2014: Atlas of isoseismal maps of New Zealand earthquakes: 1843-2003. Second edition (revised). Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand (GNS). *GNS Science Monograph* 25. 769 p.

Dykes, R.C. 2013: A multi—parameter study of iceberg calving and the retreat of *Haupapa*/Tasman Glacier, South Island, New Zealand. PhD thesis (Geography). Massey University, Palmerston North, New Zealand. 273 p.

Dykes, R.C.; Brook, M.S.; Lube, G. 2017: A major ice-calving event at the Tasman Glacier terminus, Southern Alps, 22 February 2011. *Journal of the Royal Society of New Zealand 47(4)*: 336–343.

Evening Post. 1938: Sign of earthquake: Lake gives demonstration. *Evening Post, 5 February 1938*: 10.

Evening Post. 1945: More intense: Ruapehu's activity. *Evening Post, 23 March 1945*: 6.

Fraser, R.J. 1998: Historical tsunami database for New Zealand. Unpublished MSc thesis (Earth Sciences). University of Waikato, Hamilton, New Zealand. 86 p.

Fraser, J.; McMorran, T. 2016: MacKenzie lakes – landslide tsunami investigation. Report for Environment Canterbury. Golder Associates (Christchurch). Report No. 1546369_7407_002_R_Rev1. 35 p.

GeoNet. 2022. Taupo earthquake update. 14 December 2022. GeoNet News. Institute of Geological and Nuclear Sciences (GNS), Lower Hutt, New Zealand. https://www.geonet.org.nz/news/LuzOzDmQcQUUmdeiL67oX

GNS. 2023: New Zealand Tsunami Database: Historical and modern records. Institute of Geological and Nuclear Sciences (GNS), Lower Hutt, New Zealand. https://data.gns.cri.nz/tsunami/index. html

Grapes, R. 2000: The day the earth shifted. *New Zealand Geographic 46*. https://www.nzgeo.com/stories/the-day-the-earth-shifted/

Hancox, G.T.; Dellow, G.; McSaveney, M.; Scott, B.; Villarmor, P. 2004: Reconnaissance studies of landslides caused by the M_L 5.4 Lake Rotoehu earthquake and swarm of July 2004. Institute of Geological and Nuclear Sciences (GNS), Lower Hutt, New Zealand. *GNS Science Report* 2004/24. 21 p.

Hawley, J. 1984: Slope instability in New Zealand. In: Spenden I.; Crozier, M.J. (Eds). 1984. Natural hazards in New Zealand. Chapter 11: 88–133. Complied for the New Zealand National Commission for UNESCO, 1984. 500 p.

Hogben, G. 1890: The determination of the origin of the earthquake of 5th December 1881, felt at Christchurch and other places. Article LIV. *Transactions and Proceedings of the New Zealand Institute 23*: 465–470.

Irwin, J. 1975: Checklist of New Zealand lakes. New Zealand Oceanographic Institute, Wellington, New Zealand. *New Zealand Oceanographic Institute Memoir 74*. 161 p.

Kvale, A. 1955: Seismic seiches in Norway and England during the Assam earthquake of August 15, 1950. *Bulletin of the Seismological Society of America, 45(2)*: 93–113.

Livingston, M.E.; Biggs, B.J.; Gifford, J.S. 1986a: Inventory of New Zealand lakes; Part I - North Island. National Water and Soil Conservation Authority, Ministry of Works and Development. Wellington, New Zealand. 200 p.

Livingston, M.E.; Biggs, B.J.; Gifford, J.S. 1986b: Inventory of New Zealand lakes; Part II - South Island. National Water and Soil Conservation Authority, Ministry of Works and Development. Wellington, New Zealand. 193 p.

Lowe, D.J.; Green, J.D. 1987: Origins and development of the lakes. In: Viner, A.B. (Ed). Inland waters of New Zealand. New Zealand Department of Scientific and Industrial Research, Wellington, New Zealand. *Bulletin 241*: 1–64.

Lowe, D.J.; de Lange, W.P. 2000: Volcano-meteorological tsunamis, the c. AD 200 Taupo eruption (New Zealand) and the possibility of a global tsunami. *The Holocene 10(3)*: 410–407.

Mackey, B. 2015: Seismic hazard in the Queenstown Lakes District – August 2015. Otago Regional Council, Dunedin, New Zealand. 89 p.

McGarr, A. 2020: Seismic seiches. In: Gupta, H. (Ed). Encyclopedia of Solid Earth Geophysics. *Encyclopedia of Earth Science* Series.

McSaveney, M.J. 1992a: The Mt Fletcher rock avalanche of 2 May 1992: Immediate Report. Geology and Geophysics. Department of Scientific and Industrial Research, Christchurch, New Zealand. 20 p.

McSaveney, M.J. 1992b: The Mt Fletcher rock avalanche of May 2, and again on September 16. *New Zealand Alpine Journal 45*: 99–103.

McSaveney, M.J. 1993: Rock avalanches of 2 May and 16 September 1992, Mt Fletcher, New Zealand.
Landslide News 7: 2–4.

McSaveney, M.J. 2002: Recent rockfalls and rock avalanches in Mt Cook National Park, New Zealand. Geological Society of America. *Reviews in Engineering Geology 15*: 35–70.

Mountjoy, J.; Wang, X.; Woelz, S.; Fitzsimmons, S.; Howarth, S.; Howarth, J.D.; Orpin, A.R.; Power, W. 2019: Tsunami hazard from lacustrine mass wasting in Lake Tekapo, New Zealand. In: Linton, D.G. et al. (eds). 2019. Subaqueous mass movements. Geological Society, London. *Special Publications 477*: 413–426.

Munro, D.; Fowler, A. 2014: Testing the credibility of historical newspaper reporting of extreme climate and weather events. *New Zealand Geographer, 70*: 153–164.

Nelson Evening Mail. 1929: *"Like a tipping basin"*: Lake Rotoroa - Flow in stream reversed. *Nelson Evening Mail, 19 June 1929*: 7.

Nelson Evening Mail. 1933: Taupo's behaviour; Curious movement. Explanation by Professor Speight. *Nelson Evening Mail,* 23 February 1933: 6.

NIWA. 2023: New Zealand Historic Weather Events Catalogue. National Institute for Water and Atmospheric Research (NIWA), Wellington, New Zealand. https://hwe.niwa.co.nz/event/July_2004_Bay_of_Plenty_Flooding_and_Landslides

Okal, E.A.; Reymond, D. 2003. The mechanism of great Banda Sea earthquake of 1 February 1938: applying the method of preliminary determination of focal mechanism to a historical event. *Earth and Planetary Science Letters 216*: 1–15.

Owens, I.F. 2001: Chapter 23: Natural Hazards. In: Sturman, A; Spoken-Smith, R. (Eds). The physical environment – a New Zealand perspective: 427–446. Oxford University Press, Melbourne.

Painter, D. 2004: Chapter 45: Managing water-related risks. In: Harding, J.; Mosley, P.; Pearson, C.; Sorrell, B. 2004 (Eds). Freshwaters of New Zealand. New Zealand Hydrological Society and New Zealand Limnological Society. 702 p.

Papers Past. 2022. National Library of New Zealand, Wellington, New Zealand. Papers Past | Newspapers Home (natlib.govt.nz)

Pararas-Carayannis, G. 2000. Tsunami glossary. International Tsunami Information Centre; Intergovernmental Oceanographic Commission (of UNESCO); International Co-ordination Group of the Tsunami Warning System in the Pacific. Honolulu, Hawaii. 20 p. http://www.drgeorgepc.com/TsunamiGlossary.pdf

Pond, J.A.; Smith, S.P. 1886: Observations on the eruption of Mount Tarawera, Bay of Plenty, New Zealand, 10 June 1886. Article XLIV. *Transactions and Proceedings of the New Zealand Institute 19*: 342–371.

Poverty Bay Herald. 1904: The recent earthquake. *Poverty Bay Herald, 17 August 1904*: 3.

Poverty Bay Herald. 1931: Anxiety in Australia - avalanche of enquiries. *Poverty Bay Herald, 4 February 1931*: 12.

Roberts, N.J.; McKillop, R.J.; Lawrence, M.S.; Psutka, J.F.; Clague; J.J.; Brideau, M-A.; Ward, B.C. 2013: Impacts of the 2007 landslide-generated tsunami in Chehalis Lake, Canada. Conference paper. The Second World Landslide Forum. In: *Landslide Science and Practice:* 133–140. Springer (Berlin).

Schallenberg, M.; de Winton, M.D.; Verberg, P.; Kelly, D.J.; Hamill, K.D., Hamilton, D.P. 2013: Ecosystem services of lakes. In: Dymond, J.D. (Ed). 2013. Ecosystem services in New Zealand – conditions and trends: 203–225. Manaaki Whenua/Landcare Research Press. Lincoln, New Zealand. 539 p.

Sheppard, F.P.; Macdonald, G.A.; Cox, D.C. 1950. The tsunami of April 1,1946. *Bulletin of the Scripps Institution of Oceanography 5(6)*: 391-527.

Spenden, I.; Crozier, M.J. (Eds). 1984: Natural hazards in New Zealand: New Zealand National Commission for UNESCO, Wellington, New Zealand. 500 p.

Tait, S.U. 1977: Waikari Station 1840 to 1940. Hawkes Bay Regional Council (HBRC) Report No. AM15-16, HBRC Plan No. 4571.

Thames Star. 1883: Untitled. *Thames Star, 15 September 1883*: 2.

Wang, X.; Holden, C.; Power, W.; Lui, Y.; Mountjoy, J. 2020: Seiche effects in Lake Tekapo, New Zealand, in an Mw 8.2 Alpine Fault earthquake. *Pure Applied Geophysics*. 8 October 2020. 16 p.

Ward, H.; Morrow, F.; Ferguson, R. 2015: Taupo District flood hazard study: Lake Taupo foreshore. Report for the Waikato Regional Council and Taupo District Council. Opus International Consultants, Wellington, New Zealand. 112 p.

Warren, C.R.; Kirkbride, M.P. 1998: Temperature and bathymetry of ice-contact lakes in Mount Cook National Park, New Zealand. *New Zealand Journal of Geology and Geophysics 41(2)*: 133–143.