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Freshwater (paleo)tsunamis – A review

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Abstract

In freshwater systems (rivers and lakes), historical and recent tsunamis have been documented and their traces have been found in the geological record, but studies of paleotsunamis (prehistorical tsunamis) in such environments are still underrepresented. This contribution reviews paleotsunami studies with a focus on the post -2011 period and uses historical events to highlight some areas of research that have received little attention. In the past decade, the number of paleotsunami studies has increased and this includes those carried out over freshwater settings. However, studies of lacustrine paleotsunamis compared to studies on marine paleotsunamis are still rare and those for rivers are to our knowledge non-existent. Similarly, studies of historical tsunamis generated by meteorological disturbances have been carried out but there have been none for their paleotsunami counterpart. Thus, within this review, to cover all different aspects of tsunami generation processes in freshwater systems, we have used several historical examples, although there is a notable focus on lacustrine paleotsunamis. This review shows that future studies of freshwater paleotsunamis are necessary in order to better understand their causes, frequencies and hazard potential.

Keywords: paleotsunamis; lakes; rivers; meteotsunamis; earthquake; volcanic; mass movement

1. Introduction

Tsunami is a Japanese term for "harbor wave" (Darbyshire and Ishiguro, 1957; Goff et al., 2016). The current definition of the term 'tsunami' describes a series of propagating waves of extremely long wavelength and period, usually generated by sudden disturbances of the water column associated with earthquakes occurring below or near the ocean floor. Additional generating mechanisms include volcanic eruptions, subaerial and submarine mass-movements, and bolide or other impacts upon the ocean surface (Tsunami Glossary 2019). Tsunamis are invariably considered to be associated with marine settings and the earthquakes that cause them, a perception that has been reinforced by recent events such as the 2004 Indian Ocean and the 2011 Tohoku-oki events. While most marine tsunamis are most likely generated by plate displacements along sea-floor ruptures during megathrust earthquakes, recent events such as the 2018 Anak Krakatau tsunami (lateral collapse of Anak Krakatau volcano, Grilli et al., 2019; Takagi et al., 2019) indicate that this is by no means always the case.

Rapid displacement of large water masses can occur in any aqueous system. Worldwide historical documents and eyewitness reports have shown that tsunamis do not only occur in open oceans but also in confined fjords (e.g. 1958 Lituya Bay impulse wave in Alaska, US: Miller 1960; Fritz et al., 2009) and in freshwater systems such as rivers and lakes (e.g. Schnellmann et al., 2002; Fritsche et al., 2012; Kremer et al., 2012; Clark et al., 2015; Donaldson et al., 2019; Hu et al., 2020). These historical events allow us to document the existence, causes and consequences of such tsunamis. Unlike historical tsunamis, we only know about the occurrence of paleotsunamis (prehistorical tsunamis) through the traces that they have left behind in the geological record. We distinguish between direct traces that are the deposits of the tsunami itself on lake shores or backwash deposits on the lake floor (Dirksen et al., 2011; Freundt et al., 2006; Moore et al., 2006; Moore et al., 2014) and indirect traces of paleotsunamis that are reflected in the geological record of the causal mechanism (e.g. Schnellmann et al., 2002; Kremer et al., 2012; Bozzano et al., 2019). In the latter case, numerical modelling is used to support the hypothesis that a freshwater paleotsunami occurred and to assess the magnitude of the inferred event (e.g. modelling the tsunamigenic effects of large mass-movements in lakes; Kremer et al., 2014). In the former case, research on the geological traces of freshwater paleotsunamis is rare.

When searching for “paleotsunamis in lakes” (and its synonyms), around 13 to 1000 results are found on the “web of knowledge” and on “google scholar”, respectively. However, the majority of these results refer to marine tsunamis that are recorded in coastal lakes (e.g. Kempf et al., 2017). A review of the literature indicates that there are few publications with a specific focus on paleotsunamis generated in lakes (De Lange and Moon, 2016; Dirksen et al., 2011; Freundt et al., 2006; Kremer et al., 2014; Kremer et al., 2015; Leithold et al., 2019 Moore et al., 2006; Mountjoy et al., 2019; Nigg et al., submitted; Schnellmann et al., 2002; Strupler et al., 2018). There appear to be no publications referring specifically to river paleotsunamis or to paleo-meteotsunamis.

In this study, we use the following definition of a tsunami: “A series of waves that are formed by a sudden displacement of the water, caused in or adjacent to a freshwater system (lake and river) by subaerial and subaqueous mass-movements, volcanic activity, co-seismic fault displacement and meteorological effects” (Fig. 1). The preposition “paleo” refers to the prehistoric period where historical (written) documentation is absent. As the historical period varies between countries and cultures, we consider the definition used in the original publications (e.g. In Switzerland, historical documents describe natural hazards already in the 6th century (Gisler et al., 2007) while in New Zealand the first written records are dated around 1840 AD (Clark et al., 2015)). Historical events related to human activity, e.g. mass-movements triggered by construction and quarry works close to the shore, were not considered. In addition, historical wave events generated by e.g. ice avalanches in moraine-dammed proglacial lakes (e.g. Clague and Evans, 2000) were also not included. Many of these lakes have formed due to glacier retreat after the Little Ice Age and are therefore considered only short-term structures in geological terms.

Figure 1: Causes of freshwater tsunamis as mentioned in the definition used for this review.

The main objective of this study is to review the literature on paleotsunamis in freshwater systems (rivers, lakes). We focus mainly on the period since the devastating 2011 Tohoku-oki tsunami. In particular, we emphasize how increased tsunami awareness has led to a series of follow-up studies that also investigated the lacustrine realm. However, since the number of studies of freshwater paleotsunamis is limited, we also use historical case studies and pre-2011 literature to complete a review of the full range of processes that can generate these events. In the following, we briefly review the historical and prehistorical freshwater tsunami dataset with a focus on the paleotsunamis. We, then, discuss the advances made in paleotsunami research since 2011, the state of current research and propose future research ideas.

2. Historical studies

As noted, the number of paleotsunami studies is limited and not all processes are covered in the literature. We therefore use historical freshwater tsunamis to fill this gap. The historical case studies covered in this literature review are compiled within Fig. 2 and Table 1. From this dataset, the main processes causing freshwater tsunamis can be identified. These include fault displacement during earthquakes, mass-movements (subaquatic and subaerial) and volcanic processes, as well as meteorological effects.

The main traces of these historical case studies are the written records. In some cases, the cause of the tsunami has been found in the geological record (e.g. mass-movement deposits in Lake Lucerne in 1601 AD; Schnellmann et al., 2002). In some cases, the deposits laid down by the tsunamis themselves (e.g. Lake Owens in 1872; Smoot et al., 2000) is described (Table 1).

Figure 2: Map showing locations with reported/studied historical freshwater tsunamis. The numbers refer to the case studies listed in Table 1.

Table 1: Historical freshwater tsunamis studied/reported in literature. The numbers refer to their location on the map in Fig. 2.

Type of tsunami	**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
			Historical and recent reports	***Sedimentological***	***modelled***		
Fault-displacement tsunamis	Lake Patzcuaro (Mexico) (1)	1858	120 adobe houses destroyed by the wave; rising lake level by several meters	Reworked volcanic sands with lithoclasts and remains of ostracods		Fault displacement or island flank collapse	Garduno-Monroy et al., 2011

Type of tsunami		**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
				Historical and recent reports	***Sedimentological***	***modelled***		
		Lake Baikal (Russia) (2)	1861/1862	Several fatalities				Klyuchevskii et al., 2012; Didenkulova and Pelinovsky, 2006
		Owens Lake (southern California, US) (3)	1872	Wave height of 37 cm	Graded sands	55 cm	Earthquake	Smoot et al., 2000
Mass-movement tsunamis	Subaqueous	Lake Geneva (Switzerland) (4)	563	Destruction on the lake shore		3-12 m (modelled first wave arrival)	Rockfall	Kremer et al., 2012; Schoeneich et al., 2015
	Subaqueous	Lake Geneva (Switzerland) (4)	1584	"Stormy" waves; more than five feet water level change; damage and flooding of watersides			Earthquake - triggered subaqueous mass movement	Fritsche et al., 2012
	Subaqueous & subaerial	Lake Lucerne (Switzerland) (5)	1601	Up to 5 m wave height; outflowing river changed periodically flow direction; widespread damage; 9 fatalities		6 to >10 m wave height	Earthquake - triggered subaqueous mass movement	Hilbe and Anselmetti, 2015; Schnellmann et al., 2002; Cysat, 1601; Siegenthaler et al., 1987
Type of tsunami		**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
				Historical and recent reports	***Sedimentological***	***modelled***		
	Subaqueous	Lake Lucerne (Switzerland) (5)	1687	Up to 5 m wave height; two pulses with damaging backflow; inundation; damage mentioned		6 to > 10 m wave height	Spontaneous delta collapse	Hilbe and Anselmetti, 2015; Bünti, 1973

	Subaerial	Lake Lucerne (Switzerland) (5)	1801	Wave inundation in the village of Sisikon, 10 fatalities, several houses and stables destroyed			Rock avalanche	Heim, 1915; Huber, 1982
	Subaerial	Lake Lauerz (Switzerland) (6)	1806	15 m wave height, around 10 fatalities			Rockfall	Bussmann and Anselmetti, 2010; Zay, 1807
	Subaerial	Lake Taupo (New Zealand) (7)	1846	A tsunami is mentioned in Māori oral accounts			Mass movement	Clark et al., 2015
	Subaerial	Lake Loen (Norway) (8)	1905 & 1936	For both events, tens of metre wave height, many causalities and heavy destruction of houses and farms			Mass movement	Grimstad and Nesdal, 1991
	Subaerial	Lake Taupo (New Zealand) (7)	1910	3 m surge that reached the opposite shore; people swept off their feet and canoes washed away			Mass movement	Clark et al., 2015
Type of tsunami		**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
				Historical and recent reports	***Sedimentological***	***modelled***		
	Subaqueous	Lake Nahuel Huapi (Argentina) (9)	1960	2.5 m wave height; wave hit city of Bariloche; 2 fatalities			Earthquake-triggered mass movement	Barros, 1961; Parsons, 2002; Chapron et al., 2006;

								Beigt et al., 2016
	Subaerial	Lago Cabrera (Yate Volcano, Chile) (10)	1965	25 m wave height and 60 m run-up, three farmer houses destroyed, 27 fatalities	30–40 cm mud		15 days of unusual heavy rainfall before the mass movement	Watt et al., 2009
	Subaerial	Yanahuin Lake (Peru) (11)	1971	Several tens of meter wave height			Mass movement	Plafker and Eyzaguirre, 1979
	Subaerial	Lake Botnen (Norway) (12)	1978	5–6 m wave height; 15–25 m inland, damage in village			Mass movement	L'Heureux et al., 2012; Towson and Kaya, 1988
	Subaerial	Lake Spirit (USA) (13)	1980	Run-up of 260 m			Debris avalanches due to volcanic eruption of Mount St Helens volcano	Voight et al., 1981
	Subaqueous	Lake Brienz (Switzerland) (14)	1996	50 cm wave noticed by workers			Spontaneous delta collapse	Girardclos et al., 2007
	Subaerial	Lake Albano (Italy) (15)	1997	Less than 1 m wave height			Mass movement	Bozzano et al., 2009; Mazzanti and Bozzano, 2009
	Subaerial	Crater lake of Kasu Tephra Cone (Papua New Guinea) (16)	1999	15 m wave height, destruction of 2 houses, flattened vegetation; 11 injuries, 1 fatality			Mass movement	Wagner et al., 2003
Type of tsunami		**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
				Historical and recent reports	***Sedimentological***	***modelled***		

	Subaerial	Lake Coatepeque (El Salvador) (17)	2001	2 m wave; 5 fatalities			Earthquake-triggered mass movement	Bernard, 2009
	Subaerial	Chehalis Lake (Canada) (18)	2007	Extensive damage on the shoreline, camping grounds destroyed, 38 m run-up on the opposite shore		Max. wave amplitude 37 m	Mass movement	Roberts et al., 2013; Evers 2017
	Subaerial	Oeskjuvaten (Lake Askja, Iceland) (19)	2014	Several tens of meter wave height			Mass movement	Gylfadóttir et al., 2017
	Subaerial	Waikari River (New Zealand) (20)	1863		Thin gravel layer		Earthquake-triggered slope failure	Donaldson et al., 2019
	Subaerial	Waikairi River (New Zealand) (20)	1931	15 m wave height on a small area	River gravel fining inland, mixed with anthropogenic material (roof nails and crockery)	-	Earthquake-triggered slope failure	Donaldson et al., 2019
	Subaerial /Subaqueous	Tongario River (New Zealand) (21)	1956	0.9 m tsunami wave observed at the Tongariro River			Earthquake-triggered most probable delta collapse	Clark et al., 2015
	Subaerial	Totsukawa/Kumano River (Japan) (22)	2011	50 m run-up and destruction of Nagatono power plant			Rainfall-triggered mass movement (Typhoon Talas)	Chigira et al., 2013; Nagata et al., 2014 ; Fuchs et al., 2016
	Subaerial	Jinsha River (China) (23)	2018	Run-up traces, temporary landslide dam		50 m run-up on the opposite shore	Mass movement	Hu et al., 2020

Type of tsunami		**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
				Historical and recent reports	***Sedimentological***	***modelled***		

Volcanic tsunamis	Taal Lake, Luzon Island (Philippines) (24)	1716	Wave inundated southwestern shore up to 17 m inland			Sublacustrine eruption	Saderra Maso, 1904; 1911; Paris et al., 2014
	Taal Lake, Luzon Island (Philippines) (24)	1749				Phreatomagmatic eruption	Saderra Maso, 1904; 1911; Paris et al., 2014
	Taal Lake, Luzon Island (Philippines) (24)	1754	Waves on the western shore			Pyroclastic flow	Saderra Maso, 1904; 1911; Paris et al., 2014
	Taal Lake, Luzon Island (Philippines) (24)	1911	Western shore hit by 3 m high waves and 20-50 people were drown			Pyroclastic flow or atmospheric shock waves due to strong explosions	Saderra Maso, 1904; Paris et al., 2014
	Taal Lake, Luzon Island (Philippines) (24)	1965	190-355 fatalities as wave capsized boats of fleeing residents - waves inundated areas up 4.7 above lake level			Phreatomagmatic eruption	Moore et al., 1966; Paris et al., 2014

Type of tsunami	**Lake**	**Date (AD)**	**Evidences of tsunami**			**Cause**	**References**
			Historical and recent reports	***Sedimentological***	***modelled***		
	Lake Karymskoye (Russia)(25)	1996	2 to 30 m wave height	Finely laminated layers of up to 35 cm thickness composed of sand and gravel mixed with pebbles, plant and soil			Belousov and Belousova, 2001; Belousov et al., 2000; Falvard et al., 2018; Torsvik et al., 2010

					fragments	
Meteotsunamis	Data of the historic and recent meteotsunamis are compiled in Bechle et al., 2016	Great lakes (Lake Michigan, Lake Superior, Lake Huron, Lake Erie, Lake Ontario) (26)	1822 - 2015	m-scale (data are available for most events), damages have been noted in most cases; fatalities in some cases		Bechle et al., 2016 and references therein

2.1 Fault-displacement tsunamis

Co-seismic tectonic movements along a fault that crosses a lake can generate a tsunami. An historical example may have well occurred in Lake Owens in 1872 AD (Smoot et al., 2000). The reported wave height has been estimated at 37 cm and a graded sand layer has been found in the lake deposits as the evidence of this earthquake triggered tsunami. Another example happened in Lake Baikal during the 1861/1862 AD Tsagan earthquake (Didenkulova and Pelinovsky, 2006; Klyuchevskii et al., 2012; Lunina et al., 2012) that is thought to have caused a tsunami that led to several casualties (Klyuchevskii et al., 2012). However, other studies suggest that this tsunami might have been generated by an earthquake-generated mass-movement (Didenkulova and Pelinovsky, 2006). In Lake Patzcuaro (Mexico), a sedimentary unit identified in a trench is attributed to a resedimentation of lake deposits and is interpreted as being related to a tsunami generated in 1858 AD. However, as with the study in Lake Baikal, the tsunami-generating mechanism is not straightforward and could be related to either fault movement on one of the E-W faults that cross the lake or by the failure of the southwestern flank of the island of Janitzio (Garduno-Monroy et al., 2011; Fig. 4; Table 2). If Lake Baikal's and Lake Patzcuaro's tsunamis were generated by earthquake-triggered mass movements, then these events fall under Section 2.2.

2.2 Mass movement-induced tsunamis

The term “mass movement” is used here for any type of natural gravity-driven mass-movements mobilizing soil, rock, lava, pyroclastic material, ice, and snow (Hungr et al., 2001). Historical reports and recent observations indicate that subaerial and subaqueous mass movements have generated tsunamis in several lakes around the world (Fig. 2, Table 1). These mass-movements have been generated by a suite of mechanisms such as earthquakes, heavy rainfall, “spontaneous causes” such as over steepening or overloading, and volcanic processes such as avalanches or flank collapses. The majority of the reported historical tsunamis have been caused by subaerial as opposed to subaqueous mass-movements (Fig. 2).

Mass movements can also generate tsunami-like waves in rivers. Their occurrence is demonstrated in some historical examples (Table 1). The largest historical tsunami wave height in New Zealand was the result of a tsunamigenic slope failure into Waikari River in Hawke’s Bay, New Zealand in 1931 AD. The reported wave height in 1931 AD was 15 m although its areal extent was small, extending only 150 m length along the river bank and 66 m inland (Donaldson et al., 2019; Tait, 1977).

The 1931 AD slope failure occurred in unconsolidated uplifted loess and marine Plio-Pleistocene sediments that form a 120 m high hill on the western bank of the Waikari River. It was generated by severe ground shaking associated with the 1931 AD Hawke’s Bay earthquake (M_w 7.8) that, amongst other things, caused widespread landsliding in the region’s river catchments that most probably produced numerous local tsunamis (Davison, 1934; Smith, 1978). Rare historical documents give only general details about the resultant tsunami in the Waikari valley, although it is noted that buildings on the eastern side of the river (Waikari Station) were destroyed by the event (Auckland Star, 1931; Tait, 1977). The ~1.7 x 10^6 m^3 landslide fell into the river, displacing the water and causing a large impact wave that inundated Waikari Station. According to the landowner “*it also lifted the waters of the river onto the top terrace, surrounding the homestead and washing some of the outbuildings a chain* [22 yards/~20 m] *or so away*" (Tait, 1977, p. 78). The deposit consists primarily of river gravels that fine inland and become mixed with anthropogenic material such as roof nails and crockery (Donaldson et al., 2019). A thinner gravel layer beneath the 1931 AD deposit indicates repeated events have occurred in the area (Fig. 3).

Figure 3: Waikari River: a) Location on east coast, North Island, New Zealand; b) Tsunami site showing failure scarp on the western bank and Waikari Station on the eastern side; c) Gravel and coarse sand layer of 1931 AD tsunami; d) Coarse gravel layers related to the 1931 AD and 1863 AD tsunamis (photos: J. Goff).

This earlier, possibly smaller event, was most likely related to a slope failure generated by the M_w 7.4 1863 AD Hawke's Bay earthquake centered about 100 km south of the Waikari River (Stirling et al., 1998). This evidence for repeated tsunamis suggests that these events occur relatively frequently in the region. Therefore, there is a high probability that numerous past events have occurred not only in this catchment but in regional catchments with similar geology. Adams (1981) reported a similar 1931 earthquake-generated slope failure scenario in the larger Mohaka catchment some seven km NE of the Waikari River. It occurred in an unpopulated area and while there were no eyewitnesses to any possible tsunami, the slope failure was noted soon after the earthquake because it dammed the river, and continued to do so for the next seven years.

2.3 Volcanic tsunamis

Volcanic tsunamis are also termed "volcanogenic" (e.g. Freundt et al., 2007) or "volcanism-induced" tsunami. Nishimura (2008) and Paris et al. (2014) discuss several definitions. One of these definitions states "a high wave or surge of water produced by a variety of eruptive and non-eruptive processes at volcanoes" (Begét, 2000). In this review, we use a modified version of this definition: "A high wave or surge of water produced by eruptive processes, mainly underwater explosions and pyroclastic flows". Other eruption-related processes, such as flank failure entering the water (Paris et al., 2014) are considered to behave similar to subaerial and subaqueous mass-movements and are thus considered in the concept of mass-movement tsunamis. Historical examples of volcanic tsunamis due to phreatomagmatic eruptions have been noted in Taal Lake (Luzon Island, Philippines) and Lake Karymskoye (Belousov and Belousova, 2001; Belousov et al., 2000; Falvard et al., 2018; Saderra Maso, 1904; Moore et al., 1966; Torsvik et al., 2010).

2.4 Meteotsunamis

Meteorological tsunamis (or meteotsunamis) are meteorologically generated water waves that have similar characteristics and behavior to classic tsunamis. They are induced by atmospheric perturbations of air pressure and wind (Nomitsu, 1935; Linares et al., 2016). On historical timescales, meteotsunamis have been increasingly recognized in the literature. As one example, Bechle et al. (2016) quantify meteotsunamis based upon seasonality, causes and consequences using the historical record available for the Great Lakes (Canada and USA) from 1822 to 2015. This dataset of Bechle et al. (2016), published in their supplementary material, shows that most of these meteotsunamis have been m-scale waves. The most severe event occurred in Lake Michigan in 1929, where a 6 m high wave caused 10 fatalities. The historical dataset of Bechle et al. (2016) demonstrates that most of the events in the Great Lakes occur from late-spring to mid-summer and are associated with convective storms. As Bechle et al. (2016) summarizes the historical meteotsunami dataset in lakes, these historical events are not listed in detail in Table 1. We rather refer to this publication for the individual case studies.

3. Paleotsunami studies

As noted, there are only a few studies that have been carried out on paleotsunamis that occurred either in or adjacent to lakes. These studies are summarized in Table 2 and Fig. 4 (De Lange and Moon, 2016; Dirksen et al., 2011; Freundt et al., 2006; Kremer et al., 2014; Kremer et al., 2015; Leithold et al., 2019; Moore et al., 2006; Schnellmann et al., 2002; Montjoy et al. 2019; Nigg et al., submitted; Strupler et al., 2018). The interpretation of the occurrence of a paleotsunami is based on either direct observations of their onshore and offshore deposits (Two-Yurts Lake, Lake Managua, Lake Tahoe, Owens Lake; Lake Tarawera; Lake Sils) and/or by modelling the effects of large subaqueous and subaerial mass-movements (Lake Geneva, Lake Lucerne, Lake Tahoe, Lake Tekapo, Lake Crescent, Lake Sils).

Figure 4: World map showing location of lacustrine paleotsunami studies presented in this review (Table 2). Symbols in red represent studies where paleotsunamis have been found based on geological evidence, while blue symbols represent studies where potential paleotsunamis have been modelled based upon a probable generating mechanism. Studies published before 2011 are in grey, while post-2011 publication are in black font.

Table 2: Examples of lacustrine paleotsunamis found in literature and mentioned within this review. Locations are shown in Fig. 4.

Lake	**Date**	**Evidence**	**Wave height**	**Cause**	**Reference**
Owens Lake (USA)	Two events younger than 3000 cal BP	Poorly sorted, graded pebbly sand deposits	-	Fault displacement	Smoot et al., 2000
Lake Lucerne (Switzerland)	2420 cal BP	Consequences of large mass-movements	Up to 3 m (modelled)	Earthquake-triggered mass-movements	Schnellmann et al., 2002
Lake Geneva (Switzerland)	3683 cal BP	Consequences of large mass-movements (failure scar & deposit)	Up to 12 m (modelled)	Earthquake-triggered mass-movement	Kremer et al., 2014

Lake Geneva (Switzerland)	1920 cal BP 2185 cal BP 2650 cal BP	Consequences of large mass-movement deposits originating from the Rhône delta	1-2 m (modelled)	Subaqueous mass-movements (delta failures)	Kremer et al., 2015
Lake Zurich (Switzerland)	2210 cal BP	Consequences of large mass-movement deposits	1–2 m (modelled)	Subaqueous mass-movements	Strupler et al., 2018
Lake Tahoe (USA)	12000–21000 BP	Sandy, pebble sized gravels, erosion features due to strong current	Up to 50 m (modelled)	Subaqueous mass-movement	Moore et al., 2006; Moore et al., 2014
Two-Yurts Lake (Russia)	2100–2000 BP 2900 BP 4000 BP	Discontinuous layer of structure-less poorly sorted sands with rounded pebbles and organic material	Up to 10 m (field observation)	Subaerial mass-movement	Dirksen et al., 2011
Lake Sils (Switzerland)	141–770 cal AD	Fining-upward coarse sand overlying an organic-rich peat deposit in the off- and onshore realm	2–5 m (modelled)	Subaqueous mass-movement (delta failure)	Nigg et al., submitted
Lake Tekapo (New Zealand)	~1720 BP? (~1700 cal BP)	Consequences of subaerial/ sublacustrine mass-movements	Several meters modelled	Mass movements	Mountjoy et al., 2019; Upton and Osterberg, 2007
Lake Crescent (Switzerland)	3100 cal BP	Consequences of a large subaerial mass-movement	90–104 m following relationship of Clark et al. (2015)	Subaerial mass-movement	Leithold et al,. 2019
Lake Managua (Nicaragua)	3000–6000 BP	Massive, well sorted sand layer		Volcanic eruption	Freundt et al,. 2006
Lake Tarawera (New Zealand)	1314 AD	Sharp erosional contact on lacustrine silts and two fining upwards units	6–7 m (modelled with multiple closely spaced pyroclastic flows)	Pyroclastic flows	Magill, 2001; De Lange and Moon, 2016

3.1 Fault-displacement paleotsunamis

In Owens Lake (Southern California, USA), two deposits described as poorly sorted, graded pebbly sand layers were found in sediment cores from the lake floor and are dated to around 300 and 1500 BP, respectively (Smoot et al., 2000). The authors proposed that these deposits were caused by the erosion and redeposition of lake sediments because of a tsunami. As these deposits are associated with liquefaction structures and deformed bedding, the tsunamis may well have been caused by a fault displacement similar to an historical example in 1872 AD (with an earthquake of M_w 7.5–7.7 and a tsunami wave of about 55 cm). This hypothesis is supported by the identification of Holocene fault offsets along the Owens Valley Fault.

3.2 Mass-movement paleotsunamis

3.2.1 Lake Lucerne (Switzerland)

In Lake Lucerne, several coeval subaqueous mass movements were identified in reflection seismic data and interpreted as the effects of a paleo-earthquake dated to around 2420 cal BP (Schnellmann et al., 2002). These large coeval mass movements are interpreted as tsunamigenic. The consequences of a sudden water displacement due to one of the largest subaqueous mass-movement (total volume of 11 x 10^6 m^3, a run-out distance of 1.5 km and a 9 m high failure scar) of this event were modelled by Ward et al. (2001) using the linear water-wave theory. This modelling resulted in waves > 3 m high after 1 min after landslide initiation (velocity of 0.15 ms^{-1}) at the shore directly across from the subaquatic mass-movement (Schnellmann et al., 2002). Wave heights of 1–1.5 m reach the city of Lucerne (northwest of the subaqueous landslide location) ~ 4 mins after subaqueous landslide initiation. So far no onshore and/or shallow-water deposits have been found for this modelled paleotsunami scenario. Therefore, the consequences are solely based on the interpretation of reflection seismic data and results of the numerical modelling.

3.2.2 Lake Geneva (Switzerland)

In Lake Geneva, traces of a large subaqueous failure scar have been identified on the bathymetric map at a water depth greater than 80 m over a horizontal distance of ~5 km (Kremer et al., 2014). The failure escarpment reaches a height of up to 20 m (Fig. 5a). The mass-movement deposit has been imaged on reflection seismic profiles as a semi-transparent and chaotic seismic facies that is interpreted as a slide-evolved mass-flow deposit (Fig. 5b). The affected surface of this deposit is ~ 25 km^2 with a volume estimated at 130 x 10^6 m^3. In recovered sediment cores, the mass-movement deposit consists of deformed and folded sediments with mud clasts (Fig. 5c). The event is dated to 3683 ± 128 cal BP. As simultaneous mass-movements occurred along the same seismostratigraphic horizon throughout the lake, the most likely trigger for the mass-movements appears to be an earthquake. The consequences of such a large mass-movement on the water column have been simulated by numerically solving the shallow-water equation in two dimensions following the technique of Simpson and Castelltort (2006). The deposited volume of 130 x 10^6 m^3, the position of the failure scar, and the extent of the deposit constrained from the reflection seismic data were used as input parameter for the model. The velocity of the mass movement was calculated using the equation from Ward and Day (2002) with a slope gradient of 4° and a runout distance of 2.5 km (Kremer et al., 2014). The resulting first tsunami wave has been estimated to be between 4 and 6 m at Evian (southern slope) and Lausanne (northern slope) after 3 and 6 minutes, respectively (Fig. 5d). In Geneva (at the western end of the lake), wave heights of 1 to 2 m arrive 30 min after the initiation of the mass-movement. At two archeological sites (Preverenges and Morges/Les Roseaux, west of Lausanne), the first wave of 0.75 m is followed by several further waves of 1.7–1.8 m within 15 mins. These sites are characterized by pile dweller settlements that both show an occupation gap coinciding with the timing of the subaqueous mass-movement during the Early Bronze Age (Kremer et al., 2014). Thus, an earthquake-triggered mass-movement tsunami may well explain this time-gap in the pile-dweller occupation (Corboud, 2012; Kremer et al., 2014).

Furthermore, four additional prehistorical mass-movement deposits have been recorded in the reflection seismic data of Lake Geneva. These deposits are dated to around 2650, 2185 and 1920 cal BP (Kremer et al., 2015). The geographical distribution of these deposits suggest that they originated from slope failures of the Rhone Delta at the eastern tip of the lake. Simple modelling approaches have shown that the movement of these sediment volumes might have generated paleotsunamis with minimum wave heights > 1 m (Kremer et al., 2015). Two historically-documented delta failures, one in 1584 AD triggered by an earthquake (Fritsche et al., 2012) and the other in 563 AD triggered by rockfall and laterally consecutive delta failure (Kremer et al., 2012) have also generated tsunamis of different wave heights (Table 1). Thus, partial Rhone Delta collapses have produced at least six times tsunamigenic mass-movements over the past ~4000 years. The interpretation of the occurrence of paleotsunami events is based on the modelling of the effects of large mass-movement deposits recorded in the sedimentary archive.

Figure 5: 3683 ± 128 cal BP paleotsunami in Lake Geneva. (A) A former mass movement is recognized in the bathymetric map with traces of the associated headwall (white line). The thickness map is based on reflection seismic data (black lines) and indicates that the up to 15 m thick mass-movement deposit consists of deformed sediment packages. The bold black line marks the location of reflection seismic profiles shown in (B). (B) N-S oriented reflection seismic profile imaging a chaotic to transparent seismic facies that represents the mass-movement deposit. The rectangle shows the position of the sediment core shown in (C). (C) The sediment core shows deformed, mixed and homogeneous sediments interpreted as a slide-evolved mass flow topped by a homogeneous white layer (Kremer et al., 2014). (D) Simulated tsunami propagation assuming a 130 x 10^6 km^3 slide. Wave height and corresponding arrival times are indicated for selected cities around Lake Geneva. Digital elevation model provided by Geodaten © 2017 swisstopo (JD100042).

3.2.3 Lake Zurich (Switzerland)

Traces of basin-wide subaqueous mass movements have been detected in reflection seismic data of Lake Zurich. These are interpreted as earthquake-triggered events and have been dated to ~2210; ~11600 and ~13670 cal BP (Strasser et al., 2013). Strupler et al., (2018) modelled a tsunami scenario for all documented slides (cumulative volume of around 4 km^3) of the ~2210 cal BP event using GeoClaw (Berger et al., 2011). The strongest effects (run-up and inundation) were noted along the central basin of Lake Zurich with the largest wave heights of around 1.5 m generated 1 min after slide initiation (Strupler et al., 2018). Afterwards, the wave oscillated for the following 10 mins with peak amplitudes of around 0.5 m.

3.2.4 Lake Tahoe (USA)

Evidence of a paleotsunami has been found as a consequence of a large subaqueous mass-movement in Lake Tahoe (Nevada & California, USA; Moore et al., 2014). Moore et al. (2006) describes glacial boulders transported and sorted by strong currents to form a series of underwater ridges. Moreover, high-resolution bathymetry indicates underwater channels, which probably formed through lake-floor scouring at the same time (Moore et al., 2014). Furthermore, erosional surfaces that extend 1 km inland and 30 m above the lake level are overlain by sandy-pebble-sized gravels. It is suggested that the boulders, wave channels and erosional surface overlain by detrital sediment were caused by currents induced by a large tsunami triggered by the giant McKinney Bay landslide (12 km^3). The subaqueous landslide detached from the western wall into the deep Lake Tahoe basin during the late Quaternary, between 12000 to 21000 BP (Moore et al., 2014; Moore et al., 2006). The landslide debris is still visible as angular shaped blocks on the bathymetric map. Modelling suggests that rapid movement of the landslide may well have generated a giant tsunami with > 50 m wave height (Ward, 2013). Furthermore, the overtopping of the lake shore by this tsunami may have lowered the lake level by around 10 m (Moore et al., 2014).

3.2.5 Dvuh-yurtochnoe (Two-Yurts) Lake (Russia)

The Two-Yurts lake, formed by a landslide in the Late Pleistocene, was studied by Dirksen et al. (2011) with a focus on the tephrachronology of several Holocene landslide events. Along the eastern shore of the lake, Dirksen et al. (2011) observed a discontinuous layer of structure-less, poorly sorted sands with dispersed rounded pebbles (up to 1 cm in diameter) and reworked organic materials directly overlying landslide deposits, which has been dated to around 2900 ^{14}C BP (3100 cal BP). At another site, 2 km downstream from the lake, a depositional succession occurs that comprises a 10 cm thick structure less, poorly sorted sand layer with dispersed pebbles (up to 5 mm in diameter). This is overlain by a 20 cm thick layer of poorly stratified, moderately sorted sand that is capped by a 5–10 cm thick layer of poorly sorted sand and pebbles mixed with sand and charcoal. The authors concluded that this succession originated from a tsunami caused by a subaerial landslide. Moreover, the authors observed in another nearby smaller lake, a 3 cm-thick layer containing a diatom assemblage similar to that found in Two-Yurts Lake. The diatom assemblage is markedly different from those in the sediments directly below and above, indicating that this layer most likely consists of tsunami-reworked lacustrine sediments from Two-Yurts Lake. Two younger event layers of fine to coarse grained, poorly sorted sand with rounded pebbles are identified and also interpreted as tsunami deposits. These date to between 2000–2100 ^{14}C BP (1970–2120 cal BP). A further probable landslide-generated tsunami deposit is dated to ca. 4000 ^{14}C BP (4500 cal BP) indicating that at least four events have occurred between 4500 to 1970 cal BP (Dirksen et al., 2011).

3.2.6 Lake Sils (Switzerland)

A partial collapse of the Isola Delta with a total estimated depositional volume of 6.5 x 10^6 m^3 has been dated to around 474–770 cal AD (Blass et al., 2005). This is considered to have generated a significant tsunami in Lake Sils. Based on sedimentological core analysis, reflection seismic data and numerical modeling using MassMov2D (version 0.91; Beguería et al., 2009) and GeoClaw (version 4.6.3; Berger et al., 2011), Nigg et al. (submitted) proposed a basin-wide tsunami with run-up heights of 3-4 m and an inundation distance of 200 m on the lake shore. The modelled maximum tsunami height at the shoreline generally reached around 2.5–3.5 m, although they notably exceeded 5 m along the steep shoreline directly opposite the mass movement and in the source area around the shore of the collapsed delta. Sediment cores taken along an onshore-offshore transect provide evidence for this proposed scenario. An unusual coarse, fining-upward, sand was identified in the shallow-water setting of two apparently separated sub-basins and along the lake shore. The up to 20 cm thick sandy deposit overlies an organic-rich peat with a sharp erosional contact. Towards deeper water, the deposit transforms into a thicker sediment package with multiple fining-upward sequences as well as massive gravel deposits that are considered to have been laid down by pulse-like backwash currents (Nigg et al., submitted). This deposit is topped by a clay capping deposited out of suspension in both the shallow and deeper water settings. This event deposit is in turn overlain by organic-rich deposits that have been radiocarbon dated to 225–419 cal AD (Nigg et al., submitted) which immediately postdates the delta collapse (Blass et al., 2005).

3.2.7 Lake Tekapo (New Zealand)

Several stratigraphic units with coeval mass-movement deposits have been reported from reflection seismic data (Upton and Osterberg, 2007). Mountjoy et al. (2019) modelled the consequences of different mass-movement scenarios and showed that even relative small events with estimated volumes < 0.05 x 10^6 m^3 can generate m-scale tsunamis (Mountjoy et al., 2019). Based on sedimentation rates, an approximate age for one of these horizons has been estimated to around 1720 BP. This suggests that several paleotsunamis may well have occurred at Lake Tekapo, although further dating is needed to better constrain the ages of these events (Mountjoy et al., 2019).

3.2.8 Lake Crescent (USA)

At least four large megaturbidites are recorded in the sedimentary record of Lake Crescent (Leithold et al., 2019). The youngest is dated to around 3100 cal BP and has been linked to the large Sledgehammer Point rockslide which has an estimated volume of 12 x 10^6 m^3. The proposed tsunami generated by this rockslide had an estimated wave height of between 82 and 104 m (Leithold et al., 2019). This estimation is based on the relationship between subaqueous and maximum observed vertical shoreline run-up height using data from historical landslide tsunamis in lakes and fjords proposed by Clark et al. (2015). It was suggested that this rockslide had been triggered by an earthquake. The older turbidites may well indicate that further earthquake triggered rockslide-tsunamis have occurred (Leithold et al., 2019).

3.3 Volcanic paleotsunamis

3.3.1 Lake Managua (Nicaragua)

A sub-plinian to plinian eruption from a vent on the northwestern shore of Chiltepe Peninsula in Lake Managua , 3000–6000 BP, is recorded by a dacite to andesitic tephra (“Mateare Tephra”). A massive dark gray, well-sorted sand layer, the “Mateare sand”, has been found at elevations well above beach levels. The geographically widespread distribution of this layer excludes a fluviatile origin and, thus, has been interpreted as a tsunami deposit (Freundt et al., 2006). This tsunami layer has been explained as being generated by pulses of eruption during the initial phase of volcanic activity (Freundt et al., 2006). This pre-2011 study provides a context for the paleotsunami studies carried out since 2011 (Fig. 3; Table 2).

3.3.2 Lake Tarawera (New Zealand)

New Zealand has a short written-history (since ~1840 AD; Clark et al., 2015), thus in this context an event in 1314 AD is a paleo event. In 1314 AD, multiple pyroclastic flows emitted from Mt Tarawera during the Kaharoa eruption entered Lake Tarawera. This eruption coincides with the earliest evidence for human settlement in New Zealand (Hogg et al., 2003) and thus, represents a key dating event (De Lange and Moon, 2016). A paleotsunami deposit is described composed of two fining upward sequences overlying with a sharp, erosional basal contact with lacustrine silts. These fining upward units consist of cobbles and gravels originating from beach deposit. Based on the threshold velocities for the entrainment of the different clasts in these units, these layers were interpreted as being the result of two waves of 7 and 1 m high, respectively (Magill, 2001; De Lange and Moon, 2016). De Lange and Moon (2016) showed that multiple, but closely-timed, flows entering the lake were needed to generate the 6–7 m wave height.

4 Discussion

4.1 Causes of freshwater tsunamis

The above-mentioned examples of paleotsunamis in lakes show that different causal mechanisms can be distinguished: fault displacements, mass movements and volcanic processes (Figs. 1A to C). However, these studies do not cover meteotsunamis (Fig. 1D) as a further possible mechanism capable of triggering freshwater tsunamis. Indeed, prehistoric examples of meteotsunamis are yet to be reported. Similarly, mass movement-induced tsunami-like waves in rivers have only been reported in the historical record (Table 1). River tsunamis appear to only affect a small geographical area and are deposited in highly dynamic riverine systems. If these historical examples are indicative of the nature and extent of such events, then it is highly likely that evidence for their prehistoric counterparts may well have been eroded. However, evidence for the large slides that caused them may well be preserved in the landscape since they can block entire valleys and create landslide dams. The preservation of these landslides in the environment may well provide a way forward for numerical modelling assessment.

4.2 Advances in freshwater paleotsunami research since 2011

This literature review of paleotsunamis in freshwater systems shows that the number of studies has increased since 2011. Pre-2011 studies notably described single events (e.g. Schnellmann et al., 2002), while post-2011 work contains at least two examples that have shown repeated tsunamis in freshwater systems. Although the recurrence rate is low with around one event per 1000 years (Dirksen et al., 2011; Kremer et al., 2015), these studies show that the hazard related to tsunamis should not be underestimated. Over the past decade, paleotsunami studies modelling the effects of large mass-movements have increased, most probably related to computational advances. Additionally, since 2011 the first tsunami-hazard assessment studies have also now been carried out based on the knowledge of freshwater paleotsunamis (e.g. Lake Zurich, Strupler et al., 2018; Lake Tekapo, Mountjoy et al., 2019).

4.3 State of current research on freshwater paleotsunamis

There are still only a few lake paleotsunami studies in the literature and none for rivers. The paleotsunami studies found in the literature are from Lakes Owen, Crescent, Managua, Lucerne, Geneva, Zurich, Sils, Two Yurts, Tekapo, Tarawera and Tahoe (Fig. 3 and Table 2) (Smoot et al., 2000; Schnellmann et al., 2002; Freundt et al., 2006; Moore et al., 2006; Dirksen et al., 2011; Kremer et al., 2014; Kremer et al., 2015; Leithold et al., 2019; De Lange and Moon, 2016; Strupler et al., 2018; Mountjoy et al., 2019; Nigg et al., submitted). Six studies report tsunami deposits in the sediments on lake shores (Lakes Managua, Tarawera and Sils) or within the basin (Lakes Owens, Two-Yurts and Tahoe) with the sedimentary evidence differing between study sites. Poorly sorted sands containing pebbles were identified in the Owens Lake and Two Yurts Lake studies while in Lake Managua a well sorted sand layer was observed. In the investigations at Two-Yurts Lake, organic remains and charcoal were also found in the deposit layers.

In Swiss lakes, besides the documentary evidence for historical tsunamis, paleotsunamis are inferred based on the modelling of the consequences of large prehistoric subaqueous mass-movements on the water column. Deposits corresponding to these inferred paleotsunamis have only been proposed at Lake Sils (Nigg et al., submitted), whereas layers around the other lake shores or in the lake basins are so far missing. It seems reasonable to suggest that the best way forward here is to use modelled inundation data to identify the most likely lake-shore sites for preferential preservation of such deposits. For potential backwash deposits, a study of historically-documented events may serve as a useful guide for the identification of discrete units in sediment cores. Equally, reference to submarine data from equivalent historically-documented marine events such as the 2011 Tohoku-oki tsunami may provide guidance on the characteristics of backwash deposits (e.g. Goto et al., 2014).

The fact, that tsunami deposits in freshwater settings are rarely described may be explained by two major differences when compared to their marine counterparts. The first difference arises from geomorphological disparities. In the marine setting, coastal plains are generally much more extensive compared to lacustrine or riverine environments. Deep lakes often have a higher slope gradient along their shores and therefore, the tsunami deposition potential is reduced as no accommodation area is available. Furthermore, sandy beaches around lakes are often restricted in size and associated with fluvial embayments. Thus, the identification of lacustrine tsunami deposits is challenging. The toolkit for the identification of tsunami deposits has mainly been developed on marine tsunamis (Chagué-Goff et al., 2011). There marine microfossil species and saltwater chemistry are often used in the identification of tsunami deposits, all criteria that are absent in the freshwater environment.

Some advances are being made, and like the archive of marine tsunamis in coastal lakes (Bondevik et al., 1997; Hutchinson et al., 1997; Kempf et al., 2017), freshwater tsunamis (e.g. lake tsunamis) have been recorded in bays or smaller nearby lakes or wetlands, as shown in the case of Two-Yurts Lake. As there is a need in fostering the research on freshwater tsunami deposits, we have adapted a conceptual model from Einsele et al. (1996) to indicate the potential areas where tsunami deposits might be trapped and recorded in and adjacent to lacustrine environments (Fig. 6).

Figure 6: Settings for potential tsunami deposits in lacustrine environments (modified from Einsele et al., 1996)

Preliminary estimates of the frequency of lacustrine paleotsunamis have also been proposed for both Lake Geneva and Two Yurts Lake (Dirksen et al., 2011; Kremer et al., 2015). For Lake Geneva, six tsunamis (historical and prehistorical) have been identified within the past ~ 4000 years indicating that the tsunami hazard should not be ignored (Kremer et al., 2015). Although all of the tsunamis in Lake Geneva are related to subaqueous mass-movements, their causes are diverse. The initial triggers of the mass movements are earthquakes, rockfalls, and aseismic delta failures (Kremer et al., 2012; Kremer et al., 2014; Kremer et al., 2015). In Two-Yurts Lake, four tsunami deposits have been recorded within 2000 years, with wave heights between 5 and 10 m (Table 2; Dirksen et al., 2011). All were caused by subaerial mass-movements (Dirksen et al., 2011).

4.4 Future research strategies

Overall, studies of freshwater paleotsunamis are rare, although it is known through historical examples that tsunamis represent a recognized natural hazard that should not be underestimated. For tsunami hazard assessment, it is necessary to know the causes, frequencies, sizes, magnitude, and impacts of tsunamis (Clague et al., 2003 and references therein) and therefore, there is a growing need to carry out further paleotsunami studies. Such studies are of particular importance because some paleotsunamis have been reported from lakes with no historically-documented occurrences (e.g. Lake Managua; Two-Yurts Lake; Lake Tahoe).

Our review indicates that the study on freshwater paleotsunamis is challenging and that more sedimentological studies are needed. Current limitations stem from the fact that at least one of the following conditions need to be fulfilled: (1) tsunami deposits need to be preserved in the sedimentary record and to be distinguished from other type of deposits (such as storms, floods etc..) and/or (2) the traces of the paleotsunami cause needs to be preserved in the geological record so that it can be used for tsunami modelling. Unfortunately, palaeotsunami deposits and even evidence for their generating mechanisms are becoming harder to find on increasingly populated lake shores making it difficult to reconstruct the nature of past events.

To date, hazard assessments around lakes and rivers have only been conducted for the earthquake mass movement-generated tsunami hazard around Lake Zurich, Switzerland (Strupler et al., 2018) and mass movement-triggered tsunami hazard in Lake Tekopa (Mountjoy et al., 2019). Since there are many other lake and river shorelines where residential populations continue to grow, there is an urgent need for tsunami hazard assessements in order to foster awareness and understand the potential risks. In the case of the Lake Zurich study, the subaqueous landslide progression, wave propagation and inundation were calculated with a combination of open source codes including a probabilistic approach. This type of study allows first-order estimations of wave heights to be calculated and tsunami-prone areas to be identified (Strupler et al., 2018). Current work includes a workflow for a rapid screening for tsunami hazard potential on the basis of previous case studies that will be extrapolated using key characteristics (Strupler et al., 2020). These codes and concepts can be readily applied towards other exposed coasts and should be included in future state-of-the-art tsunami hazard assessments.

5 Conclusions

Paleotsunamis have been recorded in several lakes around the world. These paleotsunamis have been generated by fault displacements, mass movements (subaerial and subaqueous) and volcanic eruptions. Data from historical tsunamis in freshwater systems have shown that events caused by meteorological disturbances are missing from paleotsunami research. However, most freshwater paleotsunamis appear to be related to subaerial and subaqueous mass-movements, an observation that is supported by historical data.

This review provides first compiled datasets of historical and prehistorical freshwater tsunamis and that, although freshwater tsunamis are rare, they represent a natural hazard that should not be underestimated and that needs to be assessed. Data on the causes, frequencies and extent of freshwater tsunamis are needed in order to assess the tsunami hazard. Given the relative rarity of such events it is therefore crucial that further research is carried out on paleotsunamis in freshwater systems in order to provide a reasonable temporal coverage.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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