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Invited research article

A global assessment of the societal impacts of glacier outburst floods

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ABSTRACT

Glacier outburst floods are sudden releases of large amounts of water from a glacier. They are a pervasive natural hazard worldwide. They have an association with climate primarily via glacier mass balance and their impacts on society partly depend on population pressure and land use. Given the ongoing changes in climate and land use and population distributions there is therefore an urgent need to discriminate the spatio-temporal patterning of glacier outburst floods and their impacts. This study presents data compiled from 20 countries and comprising 1348 glacier floods spanning 10 centuries. Societal impacts were assessed using a relative damage index based on recorded deaths, evacuations, and property and infrastructure destruction and disruption. These floods originated from 332 sites; 70% were from ice-dammed lakes and 36% had recorded societal impact. The number of floods recorded has apparently reduced since the mid-1990s in all major world regions. Two thirds of sites that have produced >5 floods ($n = 32$) have floods occurring progressively earlier in the year. Glacier floods have directly caused at least: 7 deaths in Iceland, 393 deaths in the European Alps, 5745 deaths in South America and 6300 deaths in central Asia. Peru, Nepal and India have experienced fewer floods yet higher levels of damage. One in five sites in the European Alps has produced floods that have damaged farmland, destroyed homes and damaged bridges; 10% of sites in South America have produced glacier floods that have killed people and damaged infrastructure; 15% of sites in central Asia have produced floods that have inundated farmland, destroyed homes, damaged roads and damaged infrastructure. Overall, Bhutan and Nepal have the greatest national-level economic consequences of glacier flood impacts. We recommend that accurate, full and standardised monitoring, recording and reporting of glacier floods is essential if spatio-temporal patterns in glacier flood occurrence, magnitude and societal impact are to be better understood. We note that future modelling of the global impact of glacier floods cannot assume that the same trends will continue and will need to consider combining land-use change with probability distributions of geomorphological responses to climate change and to human activity.

1. Introduction and rationale

Glacier outburst floods, or 'jökulhlaups', are sudden releases of large amounts of water from a glacier. These floods typically have hydrograph characteristics of dam break floods since they are often initiated by failure of ice, moraine or landslide dams impounding glacial lakes (Tweed and Russell, 1999). They also include a subset of floods generated near-instantaneously by subglacial volcanic or geothermal activity and by heavy rainfall routed through glacier catchments (Roberts, 2005).

Glacier outburst flood occurrence and hydrograph characteristics are linked to climate via glacier downwasting and consequent meltwater production (Haeberli and Beniston, 1998). The formation and evolution of ice- and moraine-dammed lakes are related to environmental factors which are, in turn, heavily dependent on climatic conditions (Carrivick and Tweed, 2013). In particular, the attributes of some glacier outburst floods including timing (date of initiation) and peak discharge can be controlled by climate (e.g. Ng et al., 2007; Kingslake and Ng, 2013, respectively).

Present global deglaciation is increasing the number and extent of glacial lakes around the world (e.g. Paul et al., 2007; Gardelle et al., 2013; Wang et al., 2011; Carrivick and Tweed, 2013; Carrivick and Quincey, 2014; Tweed and Carrivick, 2015). There is a causal relationship between deglaciation and volcanic activity (e.g. Maclennan et al., 2002; Tuffen, 2010; McGuire, 2013) and volcanic activity beneath ice masses can generate glacier outburst floods both through the near-instantaneous melting of ice and from the drainage of meltwater temporarily stored as a water pocket or glacier lake.

Glacier outburst floods have been recorded for many centuries, particularly in Iceland and in Europe where there are records from the 1500s onwards. The societal impact of glacier floods most obviously includes direct destruction and damage to infrastructure and property, disruption to communities and loss of life, as has been reported from Iceland (e.g. Thorarinsson, 1939, 1974; Rist, 1984; Ives, 1991;

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Tómasson, 1996; Björnsson, 1976, 2003), the European Alps (e.g. Haeberli et al., 1989a, 1989b; Raymond et al., 2003; Huss et al., 2007), South America (e.g. Carey, 2005; Iribarren Anacona et al., 2015) and the Himalaya (e.g. Mool et al., 2001; Ives et al., 2010). Repeated glacier outburst floods from Lac du Mauvoisin, Switzerland, which killed hundreds of people and destroyed houses and infrastructure (Tufnell, 1984; Woodward, 2014), have been recognised as influencing the direction of scientific thinking on glacial geology and geomorphology, thus developing modern science. Firstly, in 'Principles of Geology', Lyell (1830) effectively challenged catastrophism and paved the way for scientific theory that recognised the former existence of ice ages and therefore a changing climate. Secondly, Ignaz Venetz was an engineer asked to drain water from Lac du Mauvoisin in Switzerland; he was subsequently asked to make the first survey the glaciers of the Alps. His ground-breaking field work, alongside that of Jean de Charpentier, Jens Esmark, William Buckland and ultimately Louis Agassiz, explored the links between glacial fluctuations and environmental change.

Recent major studies of glacier outburst floods have concerned the conceptualisation of sources, triggers and mechanisms (e.g. Tweed and Russell, 1999; Björnsson, 2003), physical mechanisms governing meltwater generation and routing through a glacier (e.g. Roberts, 2005; Kingslake, 2013, 2015; Flowers, 2015) and landscape impacts (e.g. Shakesby, 1985; Maizels, 1991, 1997; Carrivick et al., 2004a, 2004b; Carrivick, 2007; Russell et al., 2006). Whilst these and other regionally-focused research papers (see citations in Table 1) frequently refer to the impacts of glacier outburst floods as being an important rationale for research, there has not yet been a comprehensive global assessment of the impacts of glacier outburst floods on communities and economies.

The aim of this study is to provide the first global analysis of the societal impacts of glacier floods. We focus primarily on descriptive statistics of glacier floods and of their relative impact, because as it will be shown, a precise definition of the absolute impact of most events is impossible given the nature of existing records. In this study we define 'societal' as 'of or relating to the structure, organisation or functioning of human communities (AHD, 2011). We also shorten 'glacier outburst floods' to glacier floods for simplicity hereon in this text.

2. Data sources and methods

We created our own database of glacier floods by initially extracting data from published glacier flood inventories (see citations in Table 1). These flood inventories have generally focused on timing and to a lesser degree on magnitude and whilst both are interesting from a phenomenological perspective, the 'date' and 'peak discharge' attributes reported in the literature are not consistently recorded or calculated, as will be discussed below. In this study, we used several physical attributes *together* with societal impact attributes primarily to estimate the first-order global societal impact of glacier floods, but also to recognise linkages between physical characteristics and thus to assist correct interpretation of the potential landscape and societal responses to climate and land use change (Pelletier et al., 2015).

Physical and societal impact data was compiled from published literature and available regional/national reports, with guidance from a number of key research experts, to whom we are indebted for their helpful advice and assistance (Table 1). Overall we have compiled records of 1348 glacier floods (Fig. 1; Table 2). This is the biggest single compilation of the occurrence and characteristics of glacier floods to date. Of this total, 9% were in Scandinavia, 22% were in the European Alps, 6% were in South America, 16% were in central Asia, 25% were in north-west America, 20% were in Iceland and 2% were in Greenland. Definition of these global regions was informed by the most recent and most comprehensive global glacier mapping project by Pfeffer et al. (2014).

We stress that our study is based on records of events that we were able to identify and access and for which attributes are available. We acknowledge that there will be events that: (i) we have not been able to capture due to lack of data recording and/or availability, and (ii) we are aware of, but for which attributes are either missing or inconsistent. For example, we know of a few glacier outburst floods that have

Table 1
Key data sources used for the compilation of physical and societal impact attributes of glacier outburst floods. Other major sources that were not region-specific included Evans (1986) and Walder and Costa (1996).

Major region	Countries	Key publications for physical attributes	Key source of societal impact data	Acknowledgement of personal assistance
Scandinavia	Norway	Kjøllmoen and Engeset (2003); Kjøllmoen et al. (2010); Liestøl (1956); Knudsen and Theakstone (1988); Tvede (1989); Jackson and Ragulina (2014)	Jackson and Ragulina (2014)	Miriam Jackson
	Sweden	Klingbjer (2004)		Per Holmlund
Iceland	Iceland	Hákonarson (1860); Askelsson (1936); Thorarinsson (1939, 1958, 1974); Rist (1973, 1976, 1984); Preusser (1976); Ives (1991); Sigurðsson et al. (1992); Sigurðsson and Einarsson (2005); Björnsson (1976, 1988, 2003); Björnsson et al. (2000, 2001, 2003); Roberts (2002); Roberts et al. (2001, 2003); Rushmer (2006).	Veðurstofa Íslands (2016)	Matthew Roberts
North-west America	Canada	Jackson (1979); Mathews and Clague (1993); Rickman and Rosenkrans (1997); Clague and Evans (2000); Geertsema and Clague (2005);		John Clague
	Alaska, USA	Stone (1963); Post and Mayo (1971); Mayo (1989); Capps et al. (2010); Wolfe et al. (2014); Wilcox et al. (2014)	Stone (1963); Post and Mayo (1971)	
	Other USA	Driedger and Fountain (1989); O'Connor and Costa (1993)		
South America	Peru Chile Argentina	Lliboutry (1956); Harrison and Winchester (2000); Harrison et al. (2006); Dussaillant et al. (2010); Emmer and Vilımek (2013); Vilímek et al. (2014); Iribarren Anacona et al. (2015)	Carey (2005); Peru and Chile and Argentina in UNISDR (2015): DI-Stat; Guha-Sapir et al. (2015): EM-DAT	Vít Vilímek, Christian Huggel
Central Asia	Tibet Bhutan Nepal India Pakistan Kyrgyzstan KazakhstanTajikistan	Mason (1929); Hewitt (1982, 1985); Feng (1991); Xiangsong (1992); Yamada and Sharma (1993); Watanbe and Rothacher (1996); Richardson and Reynolds (2000); Mool et al. (2001); Ghimire (2004); Campbell and Pradesh (2005); Ng et al. (2007); Ng and Liu (2009); Chen et al. (2010); Glazirin (2010); Hewitt and Liu (2010); Ives et al. (2010); Narama et al. (2010); Shrestha et al. (2010); Komori et al. (2012); Liu et al. (2014)	Richardson and Reynolds, 2000; Iturrizaga, 2005; Komori et al., 2012; Nepal and Uttar Pradesh (India) both in UNISDR (2015): DI-Stat reports; Guha-Sapir et al. (2015): EM-DAT	Jürgen Herget Feliz Ng
European Alps	France Austria Switzerland Italy	Hoinkes (1969); Bachmann (1979); Haeberli (1983); Raymond et al. (2003); Richard and Gay (2003) (and GRIDBASE); GAPHAZ; Huss et al. (2007); Flubacher (2007); Vincent et al. (2010); Kämpfer (2012)	Richard and Gay, 2003 and GRIDBASE, GAPHAZ	Christian Huggel, Andreas Kaab