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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

36 note that future modelling of the global impact of glacier floods cannot assume that the same trends
37 will continue and will need to consider combining land-use change with probability distributions of
38 geomorphological responses to climate change and to human activity.

39

40 **Key words:** jökulhlaup; GLOF; glacier lake; proglacial; hazard; risk

41

42 **Highlights:**

- 43 • 1348 floods from 332 sites, and 36 % of these sites have recorded societal impact
- 44 • Over 12,000 deaths recorded globally due to glacier floods
- 45 • Recurrence intervals calculated based on volume, discharge and damage
- 46 • Damage type and index determined per event, per country and per major world region

47

48 **1. Introduction and rationale**

49 Glacier outburst floods, or ‘jökulhlaups’, are sudden releases of large amounts of water from a
50 glacier. These floods typically have hydrograph characteristics of dam break floods since they are
51 often initiated by failure of ice, moraine or landslide dams impounding glacial lakes (Tweed and
52 Russell, 1999). They also include a subset of floods generated near-instantaneously by subglacial
53 volcanic or geothermal activity and by heavy rainfall routed through glacier catchments (Roberts,
54 2005).

55

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

62

63 Present global deglaciation is increasing the number and extent of glacial lakes around the world (e.g.
64 Paul et al., 2007; Wang et al., 2011; Gardelle et al., 2013; Carrivick and Tweed, 2013; Carrivick and

65 Quincey, 2014; Tweed and Carrivick, 2015). There is a causal relationship between deglaciation and
66 volcanic activity (e.g. Maclennan et al., 2002; Tuffen, 2010; McGuire, 2013) and volcanic activity
67 beneath ice masses can generate glacier outburst floods both through the near-instantaneous
68 melting of ice and from the drainage of meltwater temporarily stored as a water pocket or glacier
69 lake.

70

71 Glacier outburst floods have been recorded for many centuries, particularly in Iceland and in Europe
72 where there are records from the 1500s onwards. The societal impact of glacier floods most obviously
73 includes direct destruction and damage to infrastructure and property, disruption to communities
74 and loss of life, as has been reported from Iceland (e.g. Thorarinnsson, 1939, 1974; Rist, 1984; Ives,
75 1991; Tómasson, 1996; Björnsson, 1976, 2003), the European Alps (e.g. Haeberli et al., 1989;
76 Raymond et al. 2003; Huss et al., 2007), South America (e.g. Carey, 2005; Iribarren Anaconda et al.,
77 2015) and the Himalaya (e.g. Mool et al., 2001; Ives et al., 2010). Repeated glacier outburst floods
78 from Lac du Mauvoisin, Switzerland, which killed hundreds of people and destroyed houses and
79 infrastructure (Tufnell, 1984; Woodward, 2014), have been recognised as influencing the direction of
80 scientific thinking on glacial geology and geomorphology, thus developing modern science. Firstly, in
81 ‘Principles of Geology’, Lyell (1830) effectively challenged catastrophism and paved the way for
82 scientific theory that recognised the former existence of ice ages and therefore a changing climate.
83 Secondly, Ignaz Venetz, who was an engineer asked to drain water from Lac du Mauvoisin in
84 Switzerland, and was subsequently asked to make the first survey the glaciers of the Alps. His ground-
85 breaking field work, alongside that of Jean de Charpentier, Jens Esmark, William Buckland and
86 ultimately Louis Agassiz, explored the links between glacial fluctuations and environmental change.

87

88 Recent major studies of glacier outburst floods have concerned the conceptualisation of sources,
89 triggers and mechanisms (e.g. Tweed and Russell, 1999; Björnsson, 2003), physical mechanisms
90 governing meltwater generation and routing through a glacier (e.g. Roberts, 2005; Kingslake, 2013,
91 2015; Flowers, 2015) and landscape impacts (e.g. Shakesby, 1985; Maizels, 1991, 1997; Carrivick et
92 al., 2004a,b; Carrivick, 2007; Russell et al., 2006). Whilst these and other regionally-focused research
93 papers (see citations in [Table 1](#)) frequently refer to the impacts of glacier outburst floods as being an

94 important rationale for research, there has not yet been a comprehensive global assessment of the
95 impacts of glacier outburst floods on communities and economies.

96

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

103

104 **2. Data sources and methods**

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

114

115 Physical and societal impact data was compiled from published literature and available
116 regional/national reports, with guidance from a number of key research experts, to whom we are
117 indebted for their helpful advice and assistance ([Table 1](#)). Overall we have compiled records of 1348
118 glacier floods ([Figure 1](#); [Table 2](#)). This is the biggest single compilation of the occurrence and
119 characteristics of glacier floods to date. Of this total, 9 % were in Scandinavia, 22 % were in the
120 European Alps, 6 % were in South America, 16 % were in central Asia, 25 % were in north-west
121 America, 20 % were in Iceland and 2 % were in Greenland. Definition of these global regions was

122 informed by the most recent and most comprehensive global glacier mapping project by Pfeffer et
123 al. (2014).

124

125 We stress that our study is based on records of events that we were able to identify and access and
126 for which attributes are available. We acknowledge that there will be events that: (i) we have not
127 been able to capture due to lack of data recording and/or availability, and (ii) we are aware of, but
128 for which attributes are either missing or inconsistent. For example, we know of a few glacier
129 outburst floods that have occurred in New Zealand (e.g. Davies et al., 2003; Goodsell et al., 2005),
130 Svalbard (e.g. Wadham et al., 2001; Cooper et al., 2002), the Canadian high arctic (e.g. Cogley and
131 McCann, 1976) and on the Antarctic Peninsula (e.g. Sone et al., 2007), but these floods do not have
132 a full date (day/month/year) associated with them nor records of any other attributes and therefore
133 are not considered further in this study. We have not included glacier floods from supraglacial lakes
134 in western Greenland or from subglacial lakes in Antarctica for the same reason.

135

136 **2.1 Physical attributes**

137 Lake name, glacier name, location/region/river, country, latitude, longitude, date, volume, peak
138 discharge, trigger mechanism and dam type were recorded in this study. It was difficult to
139 discriminate glacier flood records from other 'floods' in publically-available natural hazards
140 databases, so cross-checking attributes of date and place and '*name*' was vital. In a minority of cases,
141 extra cross-checking was required to make the correct definition of the attribute '*name*' because it
142 was not necessarily obvious if that name pertained to a lake or to a glacier, or perhaps even to a
143 catchment, valley river or region. Glacier floods that have been reported without an exact source
144 being known include those in Canada (Geertsema and Clague, 2005), and in the Shimshal region of
145 Pakistan (e.g. Iturrizaga, 2005), for example. Additionally:

- 146 • A single glacier can have multiple lakes that have drained;
- 147 • A single lake can drain multiple times: well-documented examples include Tulsequah Lake in
148 Canada (e.g. Marcus, 1960), Merzbacher Lake in Kyrgyzstan (Ng et al., 2007), Gornensee in
149 Switzerland (Huss et al., 2007) and Grímsvötn and Grænalón in Iceland (Björnsson, 1976;
150 2003);

- 151
- Large floods can have multiple outlets and inundate multiple rivers and this is probably more
- 152 common than apparent in the records due to a tendency to report from the largest river only.
- The same event can occur in different countries, because some events are trans-boundary,
- 153 originating in one country and routing into another.
- 154

155

156 We determined latitude and longitude for 77 % of our records ([Supplementary Information](#)), and

157 have converted the varying coordinate systems used in the literature to a standard (global latitude

158 and longitude in format of decimal degrees, geoid WGMS84). Regarding the 'date' attribute, the most

159 commonly reported format was simply 'year' but > 50 % also have month and day, which permits

160 analyses of seasonality and assists discrimination of multiple events from the same site within a single

161 year. Since glacier floods often span several days we usually remained uncertain as to whether the

162 day reported pertained to that of the flood onset at source, the time of peak discharge, or to the time

163 of any gauging or flood impact down valley. To give an indication of the spatial scales being

164 considered Mason (1929) reported a 21 m rise in river level at 300 km from source, and also

165 destruction of the village of Abadan 400 km from source in the 1926 Shyok floods in Pakistan.

166

167 We also encountered many cases where the timing of a glacier flood as reported in the literature had

168 been constrained for example via remotely-sensed images that bracketed the flood in time. Some

169 literature noted that some glacier lakes drained every year for several decades, but there were no

170 other details available (e.g. Vatnsdalsslón, Iceland reported in Thorarinsson, 1939; Glacier lake

171 Moreno had about 24 events registered between 1917 and 2012 and Glacier lake Colonia had floods

172 every summer between 1928 to 1958). Additionally, some glacier lakes are hydrologically connected

173 so that as one drains it causes another in the cascade to do the same, for example at Brady Glacier

174 (Capps and Clague, 2014) and in the Bhutanese Himalaya (Bajracharya et al., 2007). As well as cross-

175 checking dates between multiple literature sources, we converted all dates into the same date format

176 (day/month/year) and to further assist numerical analysis we also incorporated four columns of 'day',

177 'month', 'year' and 'Julian day of year'.

178

179 In assessing flood magnitude, the attribute *volume* was compiled and converted to units of M m³.
180 However, in most cases we have been unable to determine whether the reported volume is: (i)
181 measured outflow (with known lake bathymetry and lake drawdown) with consideration of any
182 coincident internal water release (e.g. Huss et al., 2007; Anderson et al., 2003), or (ii) reconstructed
183 from gauged (and separated baseflow) hydrograph analysis (e.g. Ng et al., 2007), (iii) pertaining to
184 water and sediment (e.g. if from a gauged stage record), or only a water fraction (e.g. if from an
185 empirical equation relating drained lake volume). Furthermore, if the *peak discharge* was gauged, we
186 then have to ask whether baseflow was considered. Additionally, if the peak discharge was
187 reconstructed or estimated, we could not necessarily determine whether the Clague-Mathews (1973)
188 relationship, or one of its derivatives was used (e.g. Evans, 1986; Walder and Costa, 1996; Ng and
189 Björnsson, 2003). We compiled all available details on the drainage mechanism and dam type for
190 individual glacier floods (Fig. 1).

191

192 **2.2 Societal impact data**

193 Societal impact recorded in this study were primarily sourced from the academic literature, but we
194 sought supplementary data from publically available natural hazards databases, specifically
195 Dartmouth Flood Observatory (2015): Masterlist, Guha-Sapir et al. (2015): EM-DAT, and UNISDR
196 (2015): DI-Stat. Securing societal data from a variety of sources was necessary to surmount the
197 common problems with acquiring such information, which in summary are as described above for
198 the physical attribute data; i.e. that records are not systematic, homogeneous, nor in compatible
199 format (e.g. Petrucci, 2012; UNISDR, 2015; Iribarren Anaconda et al., 2015). These natural hazards
200 databases yielded some extra societal impact data and most crucially, these data were quantitative
201 (such data is difficult to obtain) Overall 24 % of the glacier floods we have identified also had a
202 recorded societal impact (Table 2).

203

204 In this study, the societal attributes recorded were number of deaths, number of injured persons,
205 number of evacuees/displaced, total affected area, livestock lost, farmland lost, houses/farms
206 destroyed, total persons affected, road damage, bridges damaged, infrastructure damage and
207 financial cost. We also recorded positive impacts wherever available; for example tens of glacier

208 floods in Norway were noted to have contributed additional water into hydropower reservoirs
209 (Jackson and Ragulina, 2014). However, there was no single event for which we were able to populate
210 all of these societal attributes. With specific regard to the publically available natural hazards
211 databases, we found that many countries were not represented at all and we speculate that some
212 countries have not released such data. This could be due to lack of monitoring, recording and
213 communication of information or to the political sensitivity of particular locations.

214

215 Additionally, there are 'word-of-mouth' reports of glacier floods which are difficult to substantiate;
216 for example Vivian (1979) was told that several thousand people were killed when a huge flood was
217 generated from ice fall into a proglacial lake in Tibet (see Tufnell, 1984). In general, we encountered
218 problems in matching the societal records of glacier flood impacts to the physical data because the
219 date and place of an impact can be different to the date and place of flood origin. This 'mis-match'
220 meant that laborious manual cross-checking was the only way to compare the two sets of records.
221 Most commonly, if deaths, injuries, evacuees/displaced persons were reported, they were not
222 quantified. Similarly, 'livestock lost', 'farmland lost', 'houses'/'farms destroyed', and 'road damaged'
223 were mentioned quite frequently, for example in the Icelandic (e.g. Thorarinsson, 1939; 1958) and
224 central Asian (e.g. Hewitt, 1982; 1985) literature, but were often unquantified. Perhaps a village
225 name was given, but the size of this village was not, for example. In contrast 'bridges destroyed' and
226 'infrastructure damage' frequently named the bridge(s) or the infrastructure, which included
227 hydropower installations, irrigation canals, communal buildings, and tourist facilities, and thus a
228 rudimentary tally of impacts was more easily compiled. Costs reported were often costs of remedial
229 work, and sometimes whilst there was mention of elaborate emergency measures implemented,
230 such as helicopter evacuations of people and emergency pumping of water for example, no costs
231 associated with this emergency action were given.

232

233 ***2.3 Derivation of societal impact of glacier outburst floods***

234 Approaches to assessing glacier flood impacts usually disregard any socio-economic factors (Messner
235 and Meyer, 2006). Those few approaches that do exist to assess the direct impact of floods (and other
236 natural hazard phenomena) can be more or less complex, not least depending on data availability,

237 but also on the scale and intentions of the study. In this study, we were motivated to provide a
 238 quantitative comparison between glacier flood events; i.e. of their relative direct impact, rather than
 239 an attempt to precisely define the absolute impact of any individual event. Indeed the latter is
 240 probably not possible given the problems with reporting of this data as noted in [section 2.2 above](#).
 241 Therefore, we applied the simplest (and most clearly documented) societal relative impact
 242 classification present in the peer-reviewed literature, which can be employed at both local and
 243 regional scale, and which was performed by establishing *a priori* three damage levels (c.f. Petrucci,
 244 2012; [Table 3](#)).

245
 246 The total impact per glacier flood was then converted to a total impact per country, I_C , or per major
 247 geographical region (regions as in Figure 1), I_R as the sum of relative damage D_i caused, as based on
 248 the concept that relative damage is the product of relative value, V_i , of a damaged element and the
 249 relative level of loss, L_i , that it suffered (Varnes, 1984):

$$250 \quad I_R = \sum D_i$$

251 where:

$$252 \quad D_i = V_i \times L_i$$

253 where V_i and L_i values were derived using the criteria in [Table 3](#) and as adapted from Petrucci (2012).
 254 We added deaths to the quantification of impact most simply whereby one death was given a value,
 255 V_i of one and an level, L_i , of one. We gathered country area data (CIA, 2016), national population
 256 data (ESA, 2016) and national Gross Domestic Product (GDP) data (World Bank, 2016) in order to
 257 normalise D_i by both a population density and by a measure of economic wealth. Thus we provide a
 258 crude measure of national susceptibility and national capability to respond, respectively (c.f. Barredo,
 259 2009). We appreciate that, within national boundaries, regional differences will perturb these
 260 capacities and we also recognise that glacier floods are frequently transboundary, but we could not
 261 source consistent data to enable greater granularity in our assessment.

262

263 **2.4 Derivation of recurrence intervals**

264 We calculated a recurrence interval = $(n + 1 \setminus m)$, where n is the number of years on record and where
265 m is the ordered rank of the event being considered. In this study we considered ranks of volume,
266 discharge and damage.

267

268 **3. Results**

269 **3.1 Spatial distribution of glacier floods**

270 Historical and modern glacier floods occur worldwide (Fig. 1). 70 % of glacier floods are from ice
271 dammed lakes, 9 % are from moraine-dammed lakes, 16 % are from an unknown dam type/trigger,
272 and 3 % are triggered by volcanic activity (Fig. 1). The amount of available information on dam type,
273 trigger mechanism, volume and discharge varies considerably by major world region (Fig. 1). There
274 are spatial differences in the apparent susceptibility of society to the impacts of glacier floods,
275 because the number of events with recorded societal impact per country or per major world region
276 does not correspond with the total number of glacier floods. This discrepancy between the number
277 of floods and the number of floods with recorded impact is due to: (i) the fact that some glacier floods
278 occur far away from people, property and infrastructure (e.g. many glacier floods in British Columbia:
279 Canada, Alaska: USA, Iceland), (ii) some sites produce multiple floods and some yearly floods (Fig. 2),
280 (iii) inconsistent reporting between countries and major world regions regarding event occurrence
281 and physical attributes. We have partially addressed the latter issue by focusing on societal impacts
282 because records are more likely if there has been a preceding flood and more likely to be more
283 detailed if there was societal impact.

284

285 **3.2 Temporal distribution of glacier floods**

286 Glacier floods have occurred throughout recorded history (Fig. 3). It is useful to consider here for the
287 first time, both for each major region (Fig. 3A) and globally (Fig. 3B), the number of glacier floods on
288 timescales from centuries to days because: (i) it documents some of the raw data for our further
289 investigation of seasonality and recurrence intervals, (iii) it helps hint at process mechanisms, and
290 (iii) this will help future studies put glacier floods in the context of other natural hazards. Interestingly,
291 all major world regions (Fig. 3A) and Figure 3B show an apparent decline in the trend of the number
292 of glacier floods being recorded from the mid-1990s onwards and this is discussed below. There is a

293 predominance of glacier floods in summer months, and this temporal clustering is weaker in the cases
294 of Europe and South America, and more pronounced in the cases of Iceland and central Asia (Fig. 4).
295 Scandinavia is unusual for having a seasonally bimodal distribution, with many floods recorded in the
296 winter month of January (Fig. 4). We do not have a trigger mechanisms recorded for > 90 % of our
297 Scandinavia records, but we speculate that a possible reason for a peak in glacier flood activity in
298 January in Scandinavia is that is a time is when freeze-thaw cycles are pronounced and resultant
299 rockfalls could route into glacier lakes.

300

301 For sites that have produced more than three floods, the days of the year on which a flood from a
302 given site has occurred are presented in Figure 5. Figure 5 shows that most northern hemisphere
303 sites are experiencing floods earlier in the year and that in South America, whilst there are only a
304 couple of sites with multiple floods recorded in both of these cases, the day of the year on which a
305 flood occurs is apparently becoming later. This pattern is discussed below and may be partly
306 explained by the apparent (though not statistically significant) reduction in glacier floods from ice-
307 dammed lakes (Fig. 6).

308

309 **3.3 Glacier flood recurrence intervals**

310 Recurrence intervals are presented for each major world region in Figure 7 and were calculated with
311 consideration of flood magnitude, as defined either by volume (Fig. 7A) discharge (Fig. 7B) or a
312 damage index (Fig. 7C). These estimates of recurrence intervals are fits to past events and not
313 predictions of future ones. The lack of error margins on these graphs reflects our inability to define
314 the magnitude of likely inaccuracies in volume or peak discharge because the method of calculation
315 for these attributes is often not reported. For this reason it is the shape of these lines and the relative
316 placing of the lines pertaining to each major region that is most important rather than the absolute
317 values. For a given recurrence interval, north-west America experiences floods with the greatest
318 volumes (Fig. 7A), but the least damage (Fig. 7C). In contrast, for a given recurrence interval the
319 European Alps experience low volume (Fig. 7A) and low discharge (Fig. 7B) glacier floods, but
320 moderate to high damage is caused (Fig. 7C). If a damage index of ten is considered, which describes
321 impact such as a highway bridge destroyed, or a large village destroyed, or ten persons killed (Table

322 3), then in broad terms South America has experienced this level of impact on average every ten
323 years, central Asia every twenty years, the European Alps every forty years, Scandinavia every 50
324 years, Iceland every 60 years and north-west America every 1000 years (Fig. 7C). South America is
325 the most vulnerable region to glacier floods causing societal impact of up to a damage index of ~30,
326 and central Asia is the most vulnerable region to glacier floods causing societal impact > ~30 (Fig. 7C).

327

328 **3.4 Global impact of glacier floods**

329 The global impact of glacier outburst floods can be crudely assessed using the number of events
330 recorded per country and per major world region (Fig. 8A). Using this measure, north-west America
331 (mainly Alaska), closely followed by the European Alps (mainly Switzerland) and Iceland are the most
332 susceptible regions to glacier floods (Fig. 8A). However, since many floods occur repeatedly from the
333 same location, an assessment of the global impact should also consider the number of sites recorded
334 to be affected by glacier floods, per country and per major world region (Fig. 8B). Given these
335 conditions the European Alps is the most susceptible region, and Switzerland is the most susceptible
336 country (Fig. 8B). Canada, Chile, Tibet and Iceland are other countries that all have ~ 30 sites
337 producing glacier floods (Fig. 8B).

338

339 The only societal impact attribute with standardised quantitative reporting was number of deaths.
340 We could not find records of deaths due to glacier floods from Greenland, Scandinavia and north-
341 west America. From the records that we were able to access, glacier floods have directly caused at
342 least 7 deaths in Iceland, 393 deaths in the European Alps, 5745 in South America and 6300 in central
343 Asia. However, 88 % of these 12,445 recorded deaths are attributable to just two events: the 1941
344 Huaraz, Peru (Carey, 2005) and the 2013 Kedarnath, India (Allen et al., 2015) disasters. The same two
345 events account for 82 % of the total damage caused globally by glacier floods because of the
346 contribution to the damage index of these exceptionally high numbers of reported deaths (Fig. 8C).
347 Iceland and Canada are notable for having relatively high number of events, relatively high number
348 of sites, yet low levels of damage, whereas Peru, Nepal and India have relatively few events yet very
349 high damage (Fig. 8).

350

351 The totals by country of all other societal impact-related damage, excluding the exceptionally high
352 numbers of deaths associated with Huaraz in Peru and Kedarnath in India, reveal that Nepal and
353 Switzerland have the most recorded damage due to glacier floods with 22 % and 17 % of the global
354 total, respectively (Fig. 8C). If the major world regions are ranked by damage due to glacier floods,
355 central Asia is the most affected, followed by South America, then the European Alps, Iceland,
356 Scandinavia, north-west America and Greenland (Fig. 8C).

357

358 Societal impacts of glacier floods are relatively rarely recorded for floods in Scandinavia and north-
359 west America (Fig. 9A). These are both geographical regions that might be expected to have some of
360 the most detailed records due to their economic development and likely monitoring capability and
361 so this lack of impact is not likely to be an artefact of reporting bias. Where impacts were recorded
362 in Scandinavia and in north-west America, then they only constituted loss of farmland productivity
363 (50 % of events in Scandinavia), and loss of bridges, trails, tracks and other tourist-related
364 infrastructure (< 5 % of events in north-west America) (Fig. 9A). In contrast, < 10 % of all events in
365 the European Alps and in central Asia and < 15 % of all events in South America have produced
366 impacts across the spectrum of impact types (Fig. 9A).

367

368 If damage types are calculated as a proportion of the number of sites (Fig. 9B), in comparison to the
369 number of flood events: (i) the global severity of glacier floods apparently increases, and (ii) the type
370 of impacts recorded are more diverse, in comparison to calculations made as a proportion of all
371 events (Fig. 9A). For example, one in five sites in the European Alps has produced floods that have
372 damaged farmland, destroyed homes, and damaged bridges; 10 % of sites in South America have
373 produced glacier floods that have killed people and damaged infrastructure; 15 % of sites in central
374 Asia have produced glacier floods that have inundated farmland, destroyed homes, damaged roads
375 and damaged infrastructure (Fig. 9B).

376

377 Mapping the relative damage index reveals that susceptibility to glacier outburst floods has a global
378 coverage and that the highest levels of relative impact occur in all major world regions except north-
379 west America (Fig. 10a). Normalising Di by population density homogenises the global distribution,
380 and actually in comparison to the raw Di values (Fig. 10a) emphasises Alaska, Peru and Iceland and

381 diminishes the prominence of central Asian countries (Fig. 10b). This normalisation by population
382 density is a crude measure of vulnerability (c.f. Alcántara-Ayala, 2002). Italy and Norway, France,
383 Pakistan and Iceland all have a very similar relative damage index (~ 200), but are more (Iceland) or
384 less (Pakistan) vulnerable because of very high or low population density, respectively. Normalising
385 Di by country GDP (Fig. 10c) is a crude measure of the ability of a country to mitigate, manage and
386 recover from the impacts of glacier floods. Using this measure Iceland, Bhutan and Nepal are the
387 countries with the greatest economic consequences of glacier flood impacts (Fig. 10c).

388

389 **4. Discussion**

390 **4.1 Data recording**

391 Investigating, compiling and analysing the data in this study has revealed disparate detection and
392 monitoring of glacier floods and non-standardised data reporting via scientific, public and
393 governmental sources. These concerns are not unique to glacier floods, but potentially retard hazard
394 mitigation and emergency preparation (Lindell and Prater, 2003). Accurate, full and standardised
395 data on glacier floods is needed by regional governments and agencies to determine if external
396 assistance is necessary and, if so, how much and in what form(s). National governments and natural
397 hazards authorities need to estimate glacier flood damage to report to taxpayers and to identify
398 communities - often relatively isolated communities - that have been (or might be)
399 disproportionately affected. Planners need to develop damage predictions to assess the effects of
400 alternative hazard adjustments, to quantify expected losses and to understand the extent to which
401 those losses could be reduced, all in combination to implement cost-effective mitigation strategies:
402 for example, to protect hydropower installations on rivers fed from glaciated regions and to
403 safeguard valuable agricultural land. Road and rail transport requires rivers to be bridged, which are
404 then put at risk from glacier outburst floods; in locations where there are repeated floods, there is a
405 need to protect such communication routes (e.g. Mason, 1929; Stone, 1963; Bachmann, 1979;
406 Tufnell, 1984). Insurers need data on the maximum damage and the most likely damage. These issues
407 of data acquisition and sharing are nowhere more important than for less economically-developed
408 countries where: (i) most deaths from natural disasters occur (Alcántara-Ayala, 2002; Kahn, 2005),
409 (ii) where primary industries such as agriculture and fishing can represent a substantial part of a

410 nation's economy; for example some glacier floods in west Greenland discharge so much sediment
411 into the fjords and off the coastline that fishing, which is a mainstay of the local and national
412 economy, is severely disrupted (Adam Lyberth, pers. comm.), and (iii) where hydropower dominates
413 a nations' GDP and socio-economic development potential, such as for Bhutan (Tshering and Tamang,
414 2016). However, the monitoring of events has resource implications and in locations where such
415 resources are scarce, other priorities frequently and unsurprisingly take precedence.

416

417 Whilst several natural hazards databases (e.g. Dartmouth Flood Observatory, 2015: Masterlist, Guha-
418 Sapir et al. 2015: EM-DAT, and UNISDR, 2015: DI-Stat) purport long-term records, they are in reality
419 biased towards more recent events. For example, the EM-DAT database (Guha-Sapir et al., 2015) has
420 the first 'hydrological flash flood' event in Austria occurring in 1952, and the first for Iceland in 1974.
421 Yet the scientific literature confirms that there have only been a few glacier floods in Austria since
422 1947 and many tens of floods in Iceland before 1974. For Nepal, Whiteman (2011, page XXX)
423 comments that "historical records indicate that even during the four decades up to 1970 several
424 GLOFs occurred in Nepal, although a GLOF in 1977 in the Khumbu Himal seems to have been the first
425 to have received significant scientific study (Kattelmann, 2003)". Furthermore, natural hazards
426 databases can apparently report an 'aggregate' or 'composite' impact, for example there are
427 circumstances in which heavy rain triggers flash flooding over a catchment area, but only part of the
428 resulting flood is due to a glacier flood. This is suggested by some of the records in the EM-DAT
429 database (Guha-Sapir et al., 2015) in which an individual entry can span several weeks. Toya and
430 Skidmore (2007) mentioned that developing countries have an incentive to exaggerate damage to
431 receive higher amounts of international assistance and therefore data may not be entirely reliable.
432 However, as a generalisation less economically developed countries are perhaps less likely to have
433 agencies responsible for gathering damage data due to different priorities, resource constraints and
434 political settings, for example, as suggested earlier. In short, despite the comprehensive efforts we
435 have made to gather available records of glacier floods in this study, if a flood was not recorded it
436 does not mean there was no flood, and if no impact was recorded for a flood it does not mean that
437 there was no impact. Our global assessment, country totals and damage index are therefore minima.

438

439 Furthermore, even when physical attributes are reported, they are far more ambiguous than may be
440 immediately realised. Continuously-recording river stage gauges are not common (although a few
441 countries such as Iceland and Norway have relatively good coverage due to their national monitoring
442 programmes) and are often located many tens of kilometres down valley from a glacier. Furthermore,
443 gauging sites are often destroyed by larger discharges (Haeberli et al., 1989) so records are likely to
444 be biased towards events with lower flow. We suspect that the Clague-Mathews (1973) relationship
445 between drained lake volume and peak discharge has been used to determine many of the reported
446 'discharge' values. Whether a reported discharge was measured at a gauge, or reconstructed using
447 the Clague-Mathews (1973) relationship, it cannot be an accurate reflection of the peak discharge of
448 water released from the glacier because it ignores the evolution of a dam-break type flood
449 hydrograph with time/distance down valley (e.g. Russell et al., 2010; Carrivick et al., 2013). From the
450 records of glacier floods that we analysed, it was often unclear whether the 'discharge' of a reported
451 glacier flood included consideration of baseflow or of water already in the glacier hydrological
452 system, since both introduce difficulty when constraining the water balance of a glacier flood (e.g.
453 Huss et al., 2007). Very simply, we draw attention to the fact that uncertainty is almost always
454 unreported in both the volume and the discharge estimated for an individual glacier flood.

455
456 Mindful of these uncertainties in glacier flood attributes, it perhaps seems prudent to consider using
457 empirical hydrograph reconstructions (Herget et al., 2015) and stochastic simulations of inundation
458 (Watson et al., 2015). These approaches contrast with the detailed knowledge needed for
459 mechanistic modelling that preferably relies on lake level changes or else an input hydrograph, plus
460 down-valley observations of hydraulics, plus a high- resolution digital elevation model, plus expertise
461 to run the model (e.g. Carrivick et al., 2009, 2010). Morphodynamic models of glacier floods, which
462 could be more accurate than hydrodynamic-only models where there is widespread and intense
463 sediment transport (e.g. Staines and Carrivick, 2015; Guan et al., 2015), are even more
464 computationally demanding. Perhaps most importantly for quantifying socio-economic damage,
465 there are emerging modelling techniques to consider impacts on the scale of individual buildings (e.g.
466 Jenkins et al., 2015).

467

468 **4.2 Global impact of glacier floods**

469 The number of sites recorded and reported to have produced glacier outburst floods is very small in
470 comparison to the number of glaciers and the numbers of glacier lakes, whether on a global, regional
471 or country scale. For example, Wang et al. (2013) identified 1667 glacier-fed lakes $> 0.1 \text{ km}^2$ in the
472 Tian Shan and 60 of these as potentially dangerous at present, yet our study only found nine sites
473 that have ever been recorded to have produced glacier floods in this area. As a proportion of the
474 number of (individual mountain or outlet) glaciers in each major world region (Pfeffer et al., 2014),
475 just 5.6 % in Iceland have been recorded to produce glacier floods, and this figure falls to 2.2 % for
476 the European Alps, 0.8 % for Scandinavia, 0.3 % for South America and for Canada and US (0.04 % for
477 Alaska) and 0.2 % for central Asia. Globally, the percentage of glaciers that have been recorded to
478 produce glacier floods is 0.17 %. We consider all these percentages to be minima due to the issues
479 of detecting and publically recording glacier flood data, as outlined above.

480

481 An apparent decline in the number of glacier floods recorded from the mid-1990s onwards (Fig. 3) is
482 unlikely to be due to issues of detection, given that it is a global pattern and given that improvements
483 in earth observation and monitoring have gained spatio-temporal coverage. The apparent decline in
484 floods is conspicuous given the continued increase in number and size of glacier lakes worldwide
485 (Carrivick and Tweed, 2013). The apparent decline in reported glacier floods could speculatively be
486 ascribed to: (i) successful efforts to stabilise glacier lake moraine dams (e.g. Grabs and Hanisch, 1992)
487 but the number of corresponding engineering projects is very small compared to the number of
488 GLOFs reported, (ii) the fact that successive floods can 'armour' flood channels (Ferrer-Boix and
489 Hassan, 2015) and improve conveyance-capacity at the reach scale (Guan et al., 2016) thus enabling
490 a river channel to more efficiently accommodate subsequent similar, (iii) local populations becoming
491 more aware and more resilient (c.f. Carey, 2005), (iv) that over the last 50 years ice-dammed lakes
492 seem to be generating floods less often whereas there is no such trend for moraine-dammed lakes
493 (Fig. 6), nor is there such a trend in the occurrence of glacier floods from englacial water pockets or
494 from volcanic activity (not graphed).

495

496 It has been previously documented that some sites are experiencing floods earlier in the year (Fig.
497 5). Thorarinsson (1939), for example, noted that Vatnsdalslón in Iceland drained gradually earlier in
498 the summer season between 1898 and 1938. Other well-documented examples include Lake
499 Merzbacher in Kyrgyzstan (Ng and Liu, 2009) and Gornersee in Switzerland (Huss et al., 2007).
500 Diminishing flood magnitude with successive events is also typical of the late stage of a 'jökulhlaup
501 cycle' in settings that have ice dams (Mathews and Clague, 1993). In these circumstances, ice margin
502 retreat and/or thinning over time reduces the depth of the lake that can be impounded and
503 consequently the amounts of water that can be released on drainage (Evans and Clague, 1994).
504 However, Huss et al. (2007) noted that there was no pattern of peak discharge variation with
505 progression through a jökulhlaup cycle at Gornersee. In general, Tufnell (1984) suggested that three
506 types of periodicity could be identified, namely: (i) annually or sub-annually and associated with
507 retreating glaciers and ice-dammed lakes, e.g. Gornersee, (ii) irregularly, as associated with barrier
508 lakes from glacier advances such as Allalin, Vernagt and Rutor glaciers in Switzerland, and with
509 volcanogenic glacier floods, and (iii) isolated phenomena such as Tete Rouse, Switzerland in 1892. It
510 must be noted however that the periodicity of floods at a site can change: Stone (1963) identified
511 four stages of different periodicity in Alaskan ice-dammed lakes.

512
513 Cycles of floods from the same site, and flood periodicity, are dependent on trigger and drainage
514 mechanisms and in the context of societal impacts are important because to some degree they can
515 be dependent on climate and hence may become predictable (e.g. Kingslake and Ng, 2013). Most
516 obviously the key relationship is that between lake water depth and the thickness of damming ice,
517 as well as with hydrologic connections within the glacier (Clague and Evans, 1997; Tweed and Russell,
518 1999; Roberts et al., 2005; Walder et al., 2006; Carrivick and Tweed, 2013; Tweed and Carrivick,
519 2015). In contrast, floods from Aniakchak in Alaska (Waythomas et al., 1996) are produced by
520 geothermal and volcanic activity producing meltwater and so are independent of climate. In contrast,
521 floods from Grímsvötn in Iceland decreased in *volume* but increased in *frequency* from 1934 to the
522 mid-1970s (Preusser, 1976) because as ice thickness reduced, the threshold for ice-dam flotation
523 diminished: thus even glaciers floods that might be assumed to be independent of climate can be
524 controlled by glacier fluctuations and hence indirectly by climate.

525

526 The relative damage index is extremely heterogeneous whether considered on a global, world region
527 or country scale or per event (Fig. 8). The occurrence with which types of impact are recorded is also
528 very heterogeneous (Fig. 9). These two observations together with comparison of the recurrence
529 interval curves by volume, discharge and by damage index together highlight that there is no
530 relationship between the size (volume or peak discharge) of a glacier flood and the societal impact
531 of that flood, as measured by a relative damage index (Fig. 7). Simply, recorded damage is not a
532 function of the physical attributes of the flood. This lack of a relationship between flood size and
533 flood impact is perhaps not surprising because elements of risk are not uniformly distributed in space,
534 but additionally may be because the same material impact (e.g. footbridge or road washed away) can
535 have fundamentally different consequences, i.e. secondary or indirect losses, that depend on social,
536 political, cultural and economic contexts.

537

538 Damage also varies with multiple floods from the same site (Fig. 2) as physical and societal adaptation
539 or resilience develops. In terms of adaptation of the physical environment, two floods of similar size
540 (volume or peak discharge) can have different impacts depending on sediment concentration and
541 thus flow rheology, since the time since the last event conditions sediment availability due to
542 geomorphological responses such as collapse of undercut banks infilling the channel, subsequent
543 lower-magnitude flows infilling the channel with sediment, a channel becoming wider and straighter
544 due to erosion by the first event and thus of improved conveyance capacity (e.g. Staines et al., 2015;
545 Guan et al., 2015). Thus glacier floods can behave as a Newtonian fluid, or be of debris flow type (e.g.
546 Huggel et al., 2003; Breien et al., 2008) or exhibit transitional flow regimes (e.g. Carrivick, 2010;
547 Carrivick et al., 2009, 2010, 2011). The Jancarurish, Peru 1950 flood released 2 M m³ of water and
548 transported 3 M m³ sediment and the Tête Rousse 1982 flood generated 0.2 M m³ water and 0.8 M
549 m³ sediment (Liboutry, 1971; Vivian, 1974; Bachmann, 1979; Tufnell, 1984). Unfortunately the
550 sediment-water ratio is rarely measured in glacier floods.

551

552 In terms of human adaptation, activity such as progressive development of infrastructure and
553 livelihoods on a floodplain, or conversely relocation to higher ground or even permanent removal of

554 people, property or infrastructure from risk, will change societal impact for a second flood of the
555 same physical characteristics. The nature of these human activities also has a spatio-temporal
556 evolution. Engineered flood defences in distal locations including walls and bunds to protect villages
557 were common in European Alps even in the 18th Century (e.g. Venetz, 1823) but are only recently
558 being constructed in the central Himalaya (Ives et al., 2010). The walls and bunds in Europe are now
559 to a degree superseded by reservoir dams, sluice gates and check weirs in more proximal locations
560 (Kantoush and Sumi, 2010)

561

562 **5. Conclusions**

563 This study has highlighted considerable spatio-temporal heterogeneity in the style of monitoring and
564 reporting of glacier floods and of their associated societal impacts. Standardised reporting and
565 sharing of data globally has been started most prominently by GRIDBASE (2016) and GAPHAZ (2016)
566 and this study is a progression to a global analysis and data sharing, but there is still a problem that
567 some countries do not have the economic or infrastructural capacity to achieve the necessary
568 monitoring nor to prioritise it against other issues. This problem leads us to make key
569 recommendations that there needs to be accurate, full and standardised monitoring and recording
570 of glacier floods, in particular to preferably discriminate flood volume and peak discharge at source
571 rather than at some distance down valley. Otherwise the physical mechanisms responsible for
572 generation of the flood are masked by the effects of channel topography on flood evolution with
573 distance down valley.

574

575 With the available data analysed, our key over-arching findings are that:

- 576 • Of 1348 recorded glacier floods, 24 % also had a societal impact recorded.
- 577 • Of recorded floods from 332 sites, 36 % had recorded societal impact.
- 578 • Recorded glacier floods have predominantly occurred from ice-dammed lakes (70 % of all
579 recorded floods).
- 580 • The number of recorded glacier floods per time period has apparently reduced since the mid-
581 1990s in all major world regions, but the reasons for this apparent trend are unclear.

- 582
- Two thirds of sites that have produced > 5 glacier floods (n = 32) are doing so progressively
583 earlier in the year, which hints at a global climatic control. However, there was no relationship
584 found between timing and peak discharge of glacier floods
 - We have found records of ice-dammed lakes at 78 sites that have produced three or more
585 glacier floods, some annually, including Tulsequah Lake in Canada at > 100 floods and 23 other
586 sites with ten or more floods each.
 - North-west America experiences floods with the greatest volumes but with the least damage.
588 In contrast, the European Alps experience low volume and low peak discharge glacier floods,
589 but moderate to high damage.
 - South America is the most vulnerable world region to glacier floods causing high levels of
591 societal impact (of up a damage index of ~30), and central Asia is the most vulnerable region
592 to glacier floods causing extreme levels of societal impact (damage index > ~30).
 - Glacier floods have directly caused at least 7 deaths in Iceland, at least 393 deaths in the
594 European Alps, at least 5745 in South America and at least 6300 in central Asia. However, 88
595 % of these 12,445 recorded deaths are attributable to just two events: the 1941 Huaraz, Peru
596 (Carey, 2005) and the 2013 Kedarnath, India (Allen et al., 2015) disasters. Thus a single event
597 with a large impact can change the spatio-temporal pattern considerably.
 - Iceland and Canada are notable for having relatively high number of glacier floods and
599 relatively high number of sites, yet low levels of damage; whereas Peru, Nepal and India have
600 relatively few events, yet high levels of damage.
 - One in five sites in the European Alps has produced floods that have damaged farmland,
602 destroyed homes, and damaged bridges; 10 % of sites in South America have produced glacier
603 floods that have killed people and damaged infrastructure; 15 % of sites in central Asia have
604 produced glacier floods that have inundated farmland, destroyed homes, damaged roads and
605 damaged infrastructure.
 - Bhutan and Nepal are the countries with the greatest economic consequences of glacier flood
606 impacts.
- 607
- 608
- 609

610 In future work, it is the intention to add to the records of glacier floods compiled and analysed in this
611 study ([Supplementary Information](#)) because i) we invite correspondence from anyone with more
612 data to fill any gaps, and ii) more glacier floods will occur in the future. Other studies may wish to
613 include lake area and shape, since the hypsometry of a glacier lake is partly determined by the dam
614 type (e.g. Cook and Quincey, 2015) and has an effect on the rate of water efflux. More sophisticated
615 statistical analyses on the spatial and temporal attributes could be considered, such as by employing
616 non-stationary time-series methods and by normalising impact by spatial density of socio-economic
617 attributes such as building density, respectively. Comparison of our data to other records; of climate,
618 of glacier changes, of socio-economic development, for example could be instructive. Secondary or
619 indirect impacts such damage or disruption to utility services and local businesses, loss of revenue or
620 increase in costs and emergency assistance and recovery expenses are very rarely mentioned in the
621 scientific literature in connection with glacier floods. Neither is there ever any mention of intangible
622 losses, which might include psychological impairments caused by both primary and secondary losses
623 that people experience due to a flood. To our knowledge there has never been an assessment of
624 societal impact in terms of response to a glacier flood, i.e. comparing a socio-economic situation
625 immediately before and in the weeks and months after a flood (e.g. ECLAC, 2003).

626

627 Overall, combining glacier flood data with societal impact data recognises the interactions of a non-
628 linear physical system with a human system, both of which can behave in a linear or non-linear
629 manner and with threshold responses. Therefore if future studies attempt modelling of the global
630 impact of glacier floods, be it of geomorphology or of populations or infrastructure, then the
631 response of the Earth's surface to climate change and to land-use change must be combined with
632 probability distributions of possible geomorphological responses (e.g. Alcántara-Ayala, 2002) and of
633 human activity to statistically characterize risk (Pelletier et al., 2015).

634

635 **Supplementary Information**

636 Table of lake name, glacier name, date, lat/long, and indication if societal impact record.

637

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644

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A global assessment of the societal impacts of glacier outburst floods

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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, P., 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	Dreidger and Fountain, 1989; O'Connor and Costa, 1993		
South America	Peru Chile Argentina	Lliboutry, L., 1956; Harrison and Winchester, 2000; Harrison et al., 2006; Dussailant et al., 2010; Emmer and Vilímek, 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 Kazakhstan Tajikistan	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; Glazarin, 2010; Hewitt and Liu, 2010; Ives et al., 2010; Narama et al., 2010; Shresta 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

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).

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	Scandinavia	European Alps	South America	central Asia	north-west America	Iceland	Greenland	Global
Total records	118	301	86	216	335	270	22	1348
Events with recorded impact (%)	74	39	7	25	10	7	5	24
Total single locations	20	88	49	79	57	32	7	332
Events at single locations with recorded impact (%)	65	45	27	39	14	38	14	36

Table 2. Summary of the total number of records of glacier outburst floods compiled in this study and the number of those events with recorded societal impact.

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	Sub-type	Vi			Li		
		bridge	tunnel	road	Level 1 (1)	Level 2 (0.5)	Level 3 (0.25)
Road network	Highway	10	10	8	Prolonged road traffic interruption	Temporary road traffic interruption	Limited road traffic disruption but some road damage
	State road	8	8	6			
	County road	6	6	4			
	Municipal road	5	5	3			
	Track			1			
Railway network	State railway	10	10	8	Prolonged rail traffic interruption	Temporary rail traffic interruption	Limited rail traffic disruption but some rail damage
	Regional route	8	8	6			
	Service track	5	5	3			
Residential buildings	Isolated house	6			Building collapse	Building evacuation	No evacuation but some adverse effects
	Small village	8					
	Large village	10					
Public buildings	e.g. airport, train or bus station, religious building, town hall, school,	10			Building collapse	Building evacuation	No evacuation but some adverse effects
Service networks	e.g. irrigation or drainage canals, electricity lines, telephone lines,	5			Prolonged service interruption across large areas	Temporary service interruption across large areas	Limited service disruption but some damage in small areas
Productive activities	Agriculture and farming	4			Interruption of production, or loss of production system	Interruption of production and loss of products	Limited loss of products
	Commerce/business	5					
	Fishing	4					
	Other industry	8					
Other infrastructure: hydraulic works	Check dam or weir or sluice	4			collapse	Loss of efficiency	No loss of efficiency but some adverse effects
	Earth embankment	5					
	Retaining wall	6					
	Dam	10					
Tourist facilities and sports resorts	Hotel or resort complex	10			Interruption of activity and loss of facility	Temporary interruption of activity	No interruption of activity but some adverse effects
	campground	4					
	Car park	4					
Human fatality	Death of individual reported	1			1	-	-

Table 3. Types and sub-types of damaged elements. For each type and sub-type, the value considered for damage assessment is V_i . The Level, L_i are multiplying factors for assessing total glacier flood impact per event and per country, I , and are 1, 0.5 and 0.25 for levels 1, 2 and 3, respectively. Adapted from Petrucci (2012), Petrucci and Gullà (2009, 2010).

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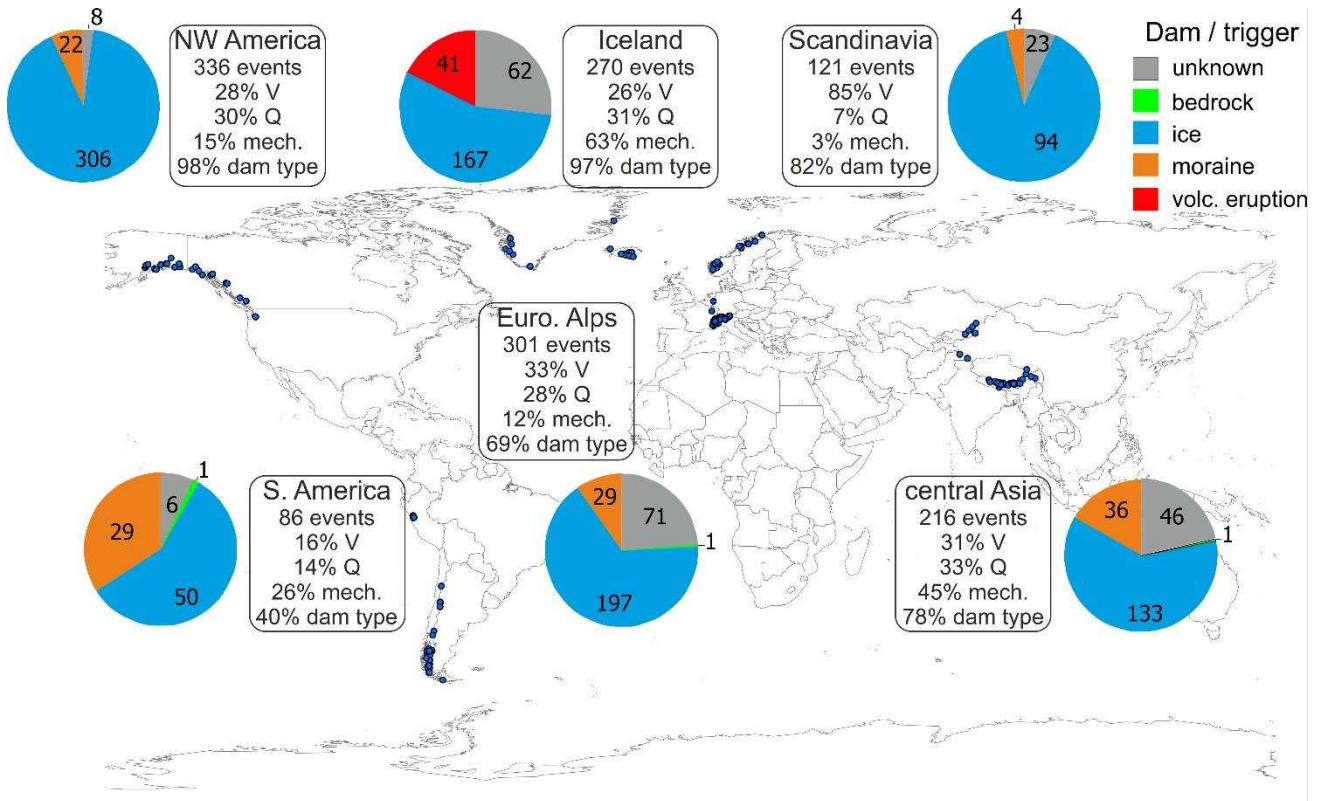


Figure 1. Overview by major region of the proportion of the glacier outburst flood records compiled in this study that include physical attributes; namely volume, V, discharge, Q, flood water release and/or routing mechanisms, and dam type. Note that ‘ice’ includes subglacial, ice-marginal and supraglacial situations, and that ‘volc. eruption’ includes (i) instantaneous outburst of meltwater derived from ice melt due to volcanic activity, (ii) release of water that was temporarily stored having been generated by ice melt due to volcanic activity, (iii) geothermal activity. Numbers on pie charts are the number of floods per dam type/trigger.

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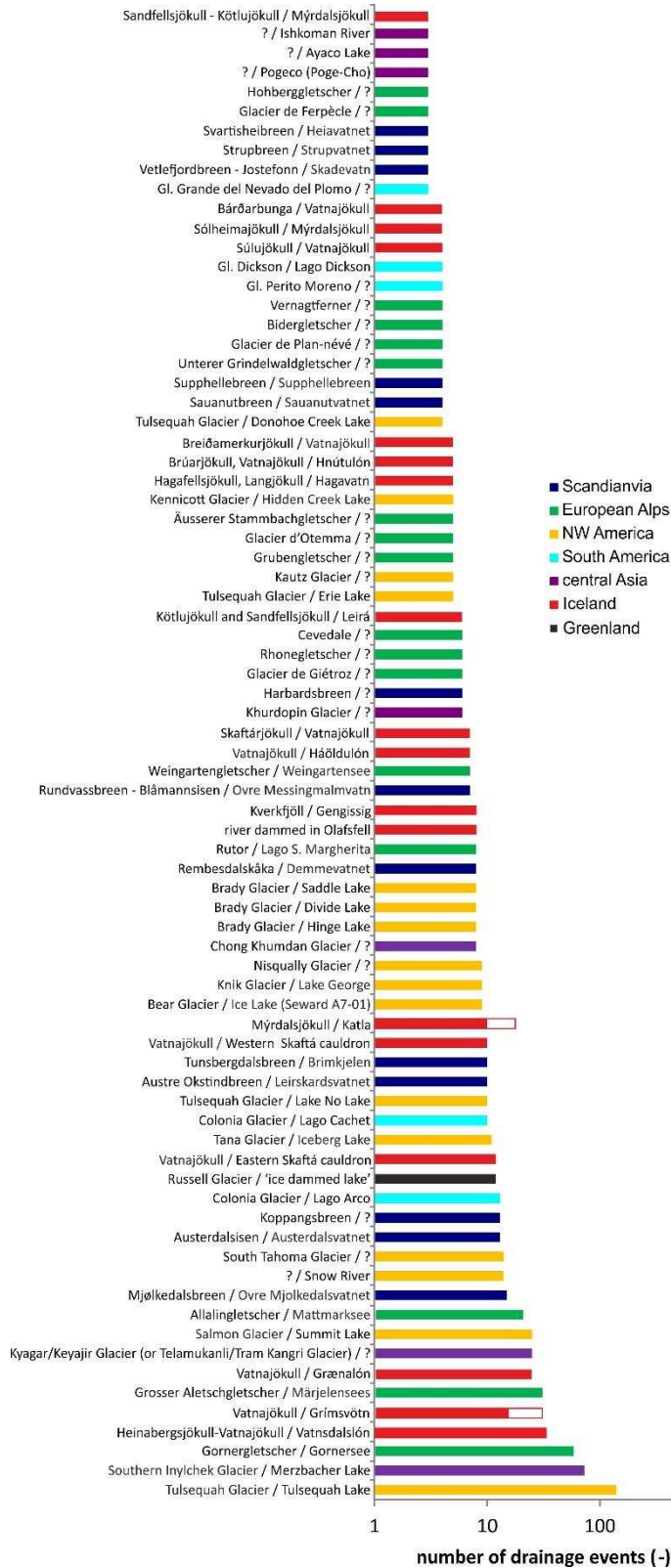
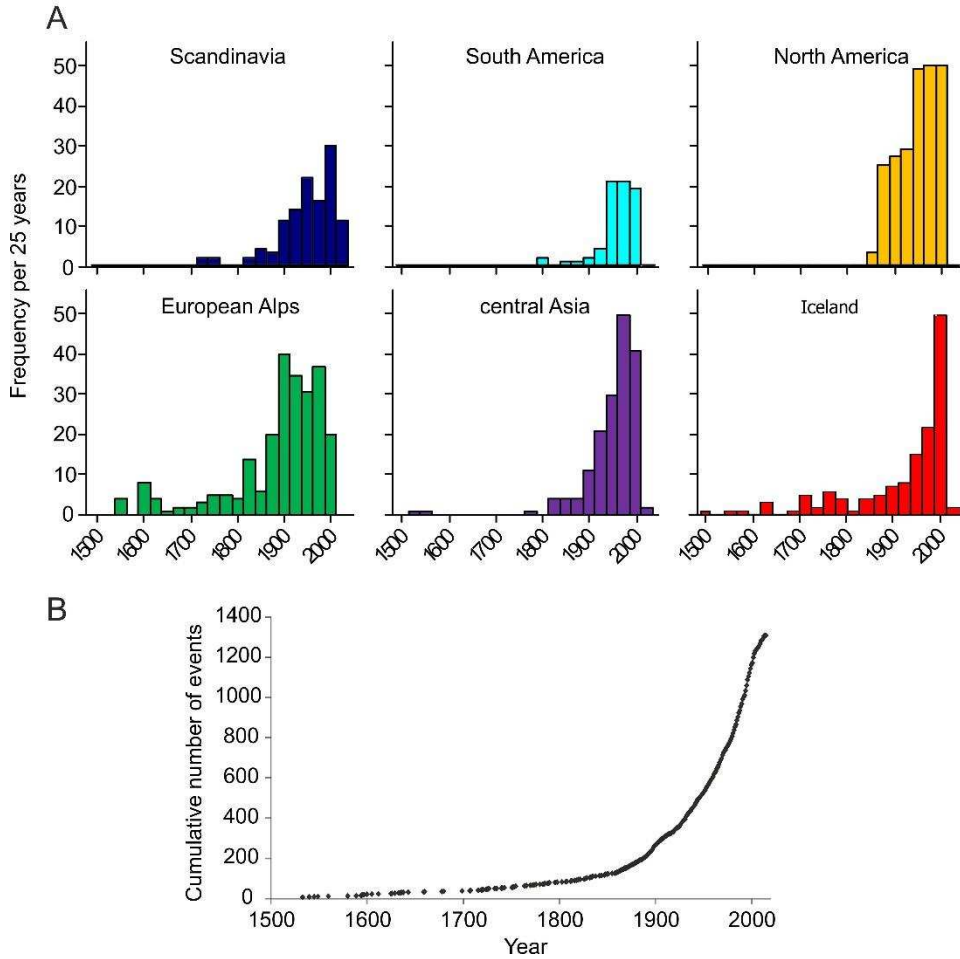


Figure 2. Glacier outburst floods that have originated from the same source three times or more. Note that '?' refers to missing information usually because there was no visible/named lake (e.g. if subglacial or englacial 'water pocket'). White parts of bars denote documented but unconfirmed sources of floods.

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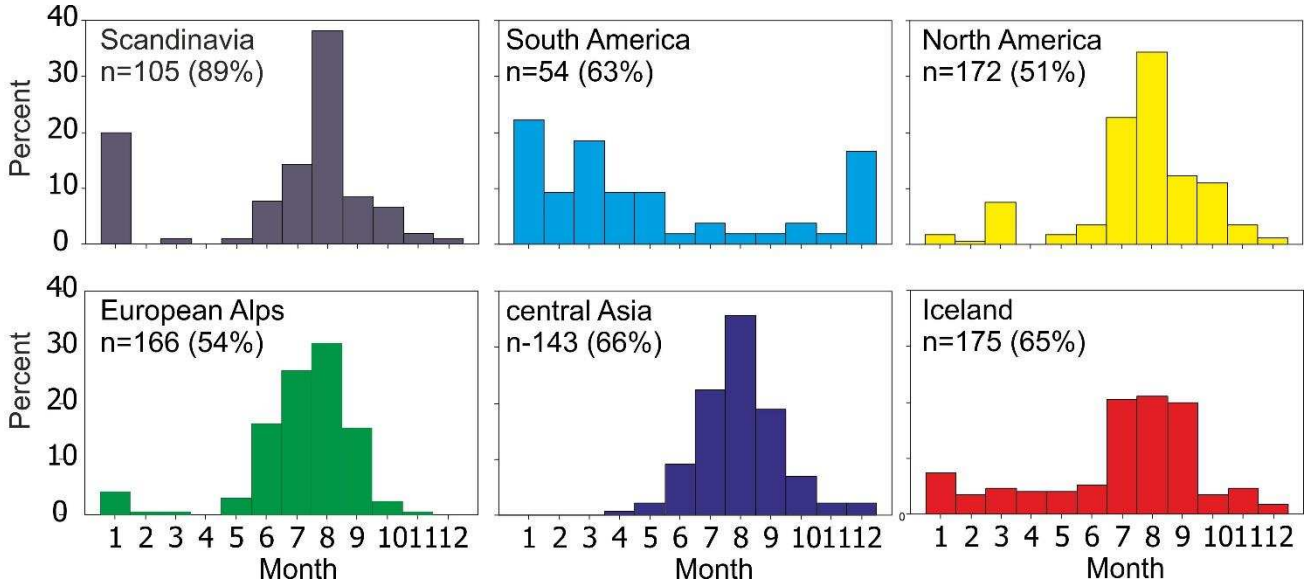
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1249 **Figure 3.** Number of glacier outburst floods per 25 years by major region (A) and as a global
1250 cumulative total (B). Note that for clarity the x-axis is limited to displaying records from the last 500
1251 years.
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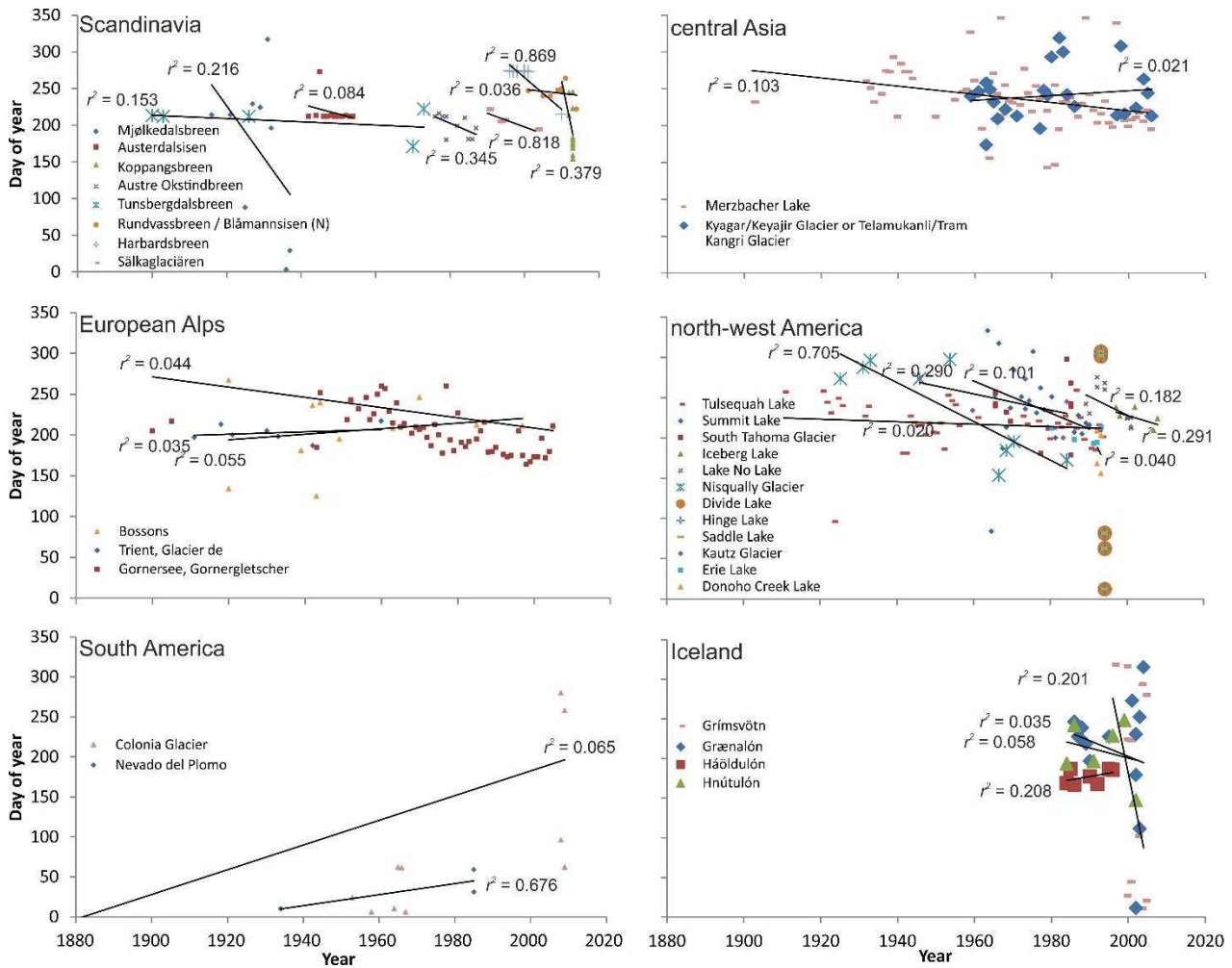
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Figure 4. Percentage of glacier outburst floods occurring per month by major region. Note ‘n’ is number of records for which month is known and % in brackets is proportion of all records of glacier floods in that major world region.

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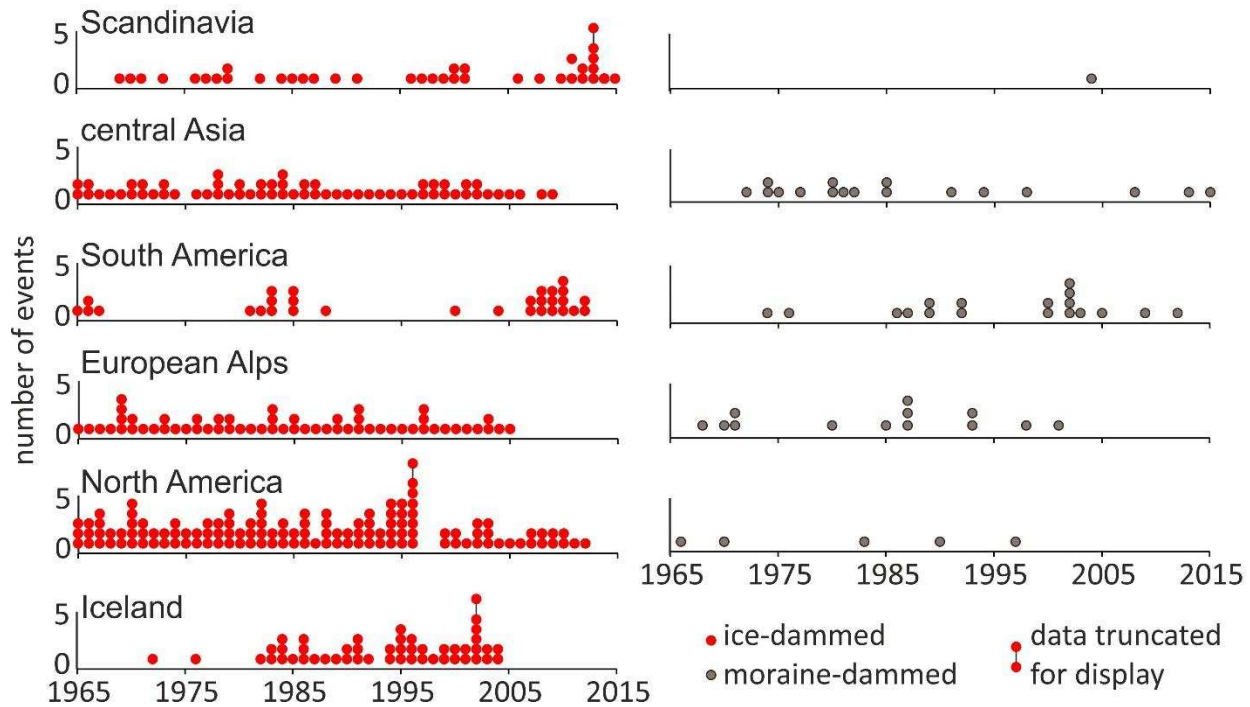
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Figure 5. Comparison by major region of the day of year on which glacier lakes have drained, for glacier lakes for which the day of the year is known. Black lines are linear regression best fits. Note that we only have record of three glacier outburst floods from Nevado del Plomo but is included here because there are few multiple glacier lake drainages recorded in South America. Note only lakes that have drained more than 5 times are depicted for clarity.



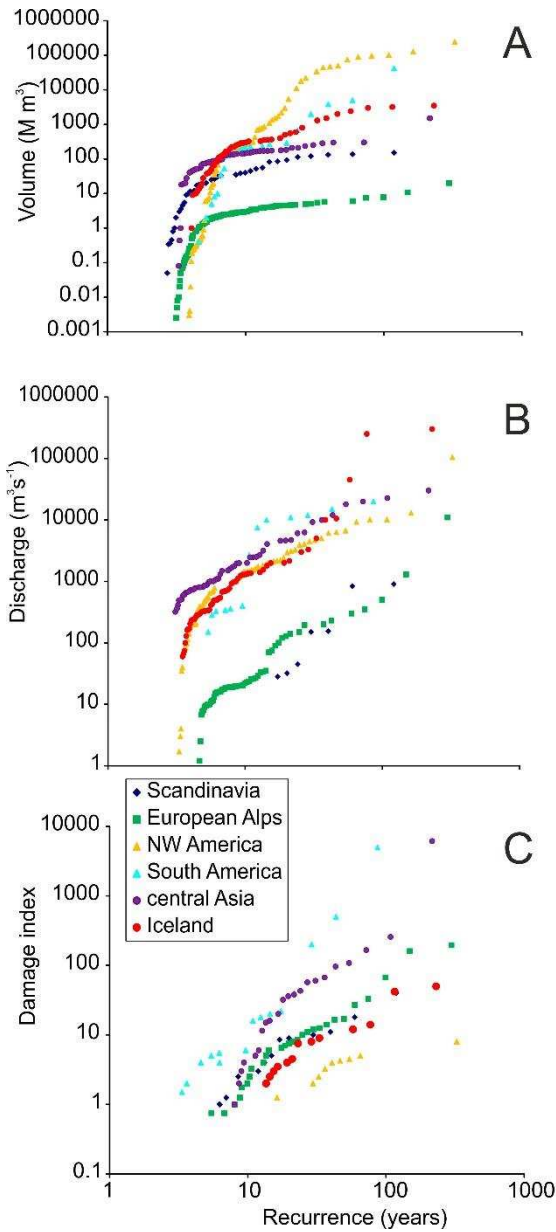
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Figure 6. Number of recorded glacier outburst floods per year, discriminated by dam type. The excessively high number of events in 2013 in Scandinavia, in 1996 in North America and in 2003 in Iceland were events in the Lyngen Alps (Jackson and Ragulina, 2014), at Brady Glacier (Capps and Clague, 2014) and at multiple lakes around Vatnajökull (Veðurstofa Íslands, 2016), respectively. Glacier floods from volcanism, ice-dammed lake – volcano interactions, bedrock-dams and from englacial water pockets are not shown for brevity and clarity.

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1344 **Figure 7.** Global glacier outburst flood recurrence intervals calculated by magnitude as defined by
 1345 volume (A), discharge (B) and an index of damage (C). Note both x and y scales are logarithmic. Note
 1346 the lack of error margins because we cannot define the magnitude of likely inaccuracies in volume or
 1347 peak discharge, nor the effect of likely unreported impact. For this reason it is the shape of these
 1348 lines and the relative placing of the lines pertaining to each major region that is most important rather
 1349 than the absolute values. These estimates of recurrence intervals are fits to past events and not
 1350 predictions of future ones.

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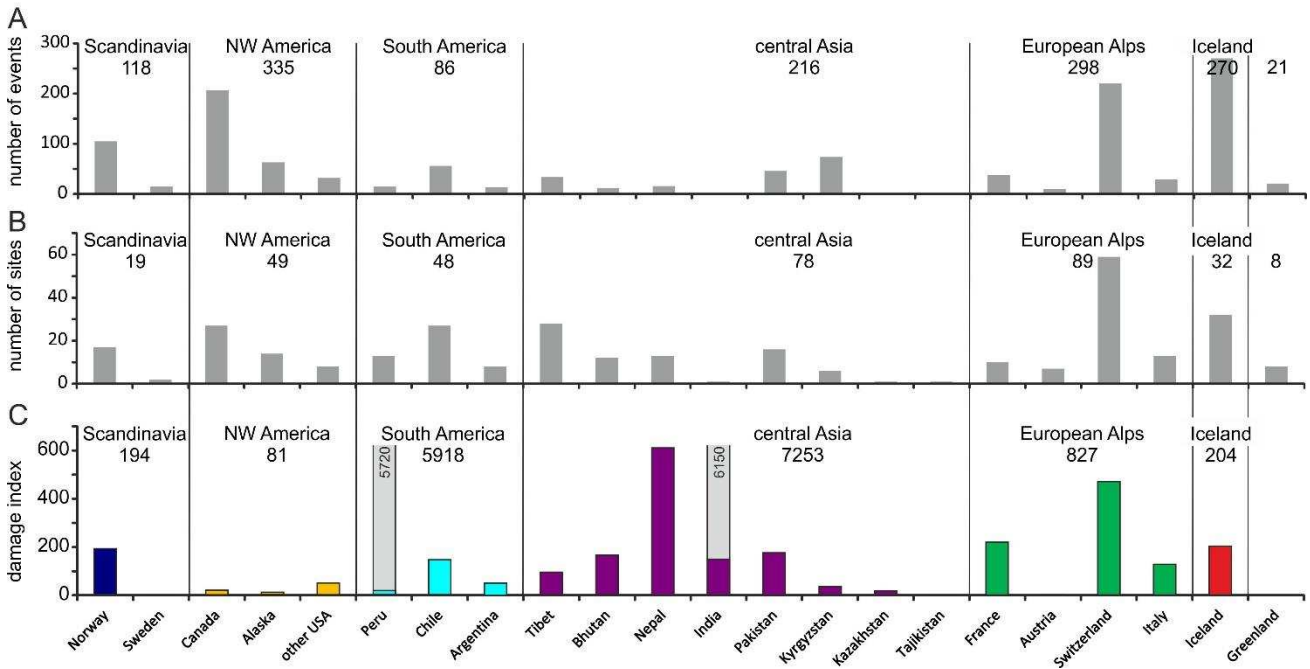
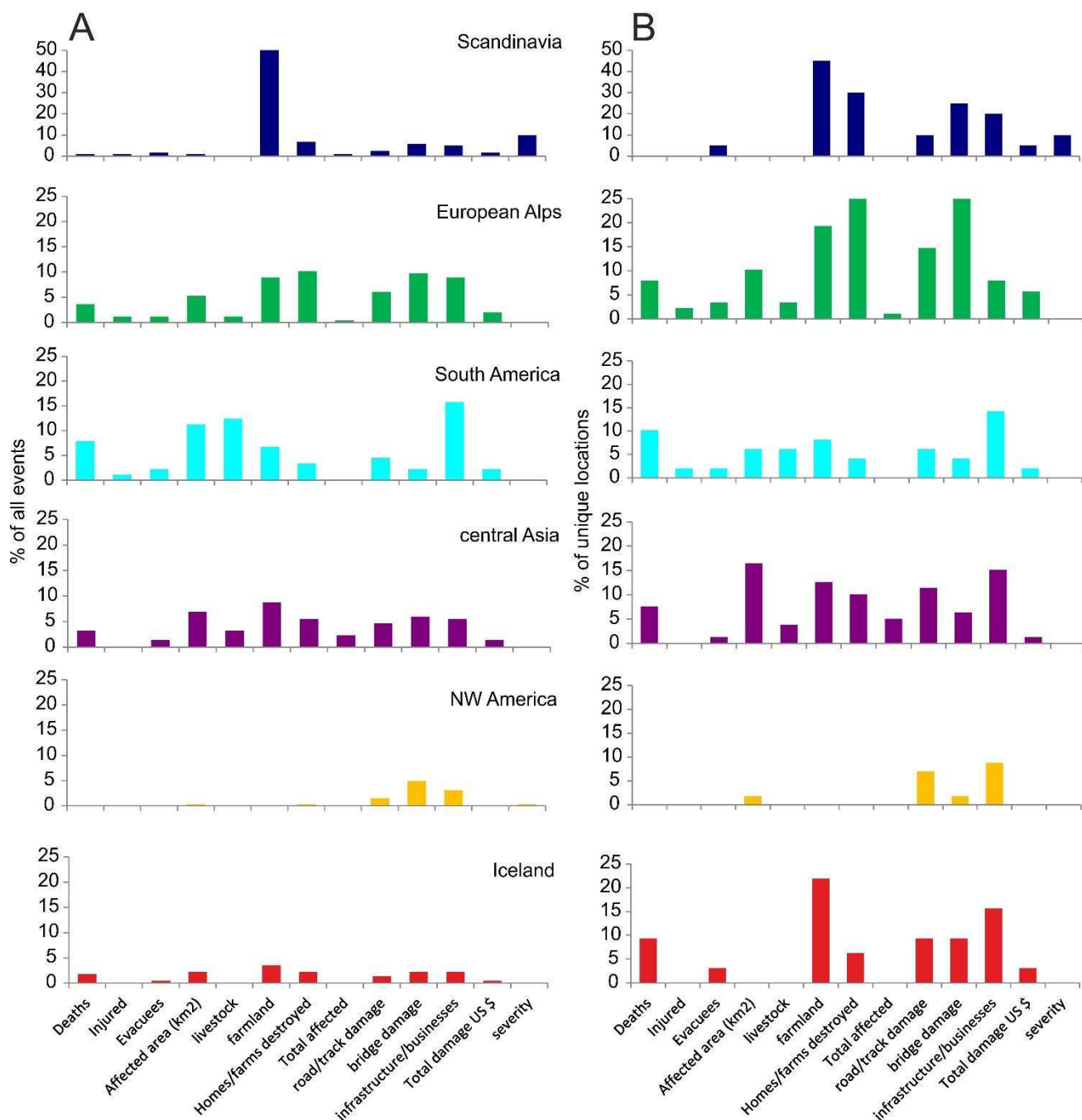


Figure 8. Total number of recorded glacier floods (A), sites with recorded glacier floods (B), and damage index (C) per country and per major world region. The absolute value of the damage index is somewhat arbitrary, but permits comparison between countries and between regions.

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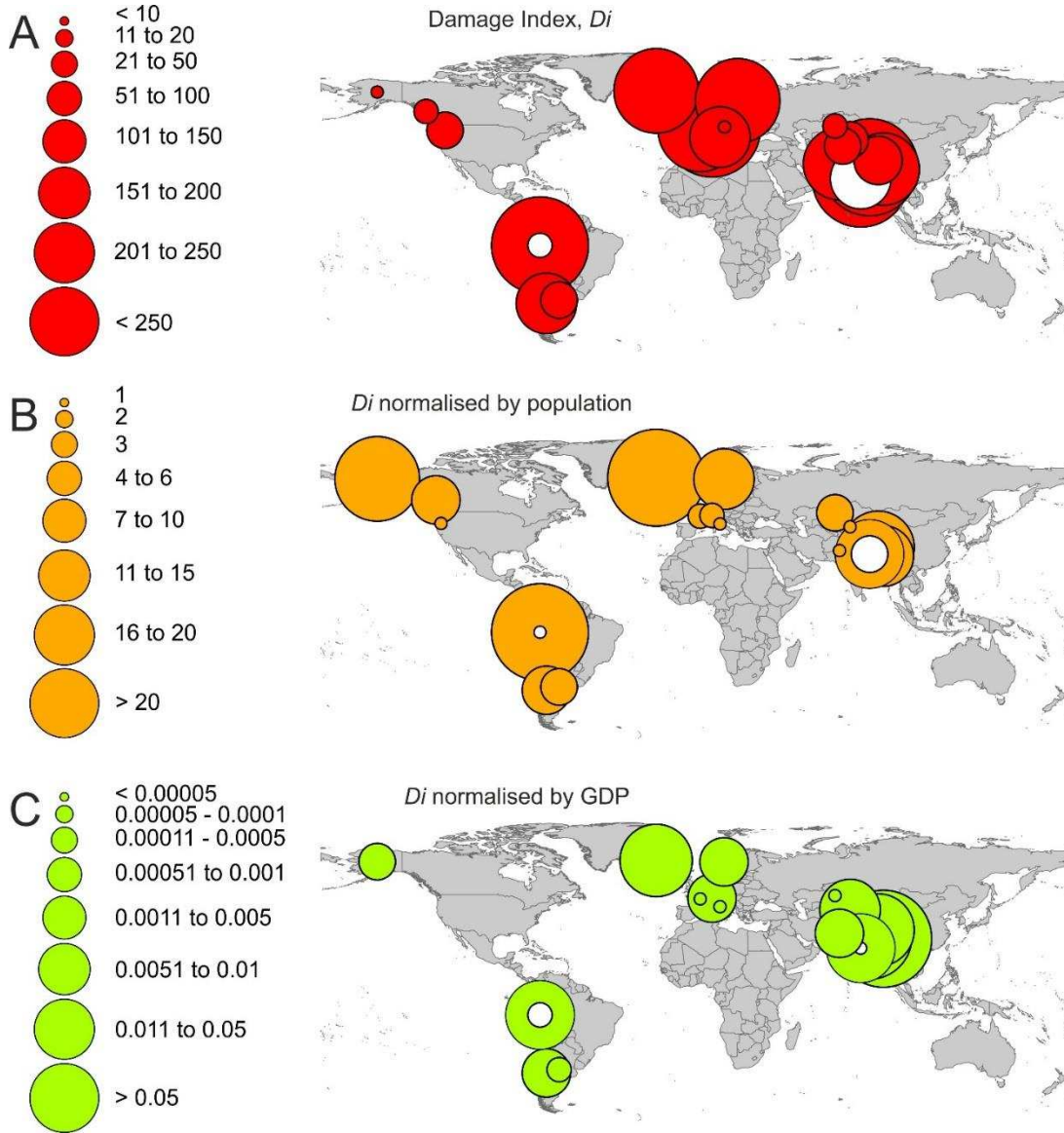
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Figure 9. Proportion of all glacier outburst floods (A) and proportion of all glacier outburst flood sites (B) that have some attributes of societal impact recorded. Note different y-scale for Scandinavia.

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Figure 10. Global societal impact of glacier outburst floods as defined by a relative damage index (A), and this index normalised by population density (B) and by country GDP (C). White circles denote country value without exceptionally high numbers of deaths included. Note that it is the spatial pattern rather than the absolute values that are of interest.