Natural hazard fatalities in Switzerland from 1946 to 2015

Alexandre Badoux[1], Norina Andres[1], Frank Techel[2], Christoph Hegg[1]

[1]Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland
[2]WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos, Switzerland

Correspondence to: Alexandre Badoux (badoux@wsl.ch)

Abstract. A database of fatalities caused by natural hazard processes in Switzerland was compiled for the period between 1946 and 2015. Using information from the Swiss flood and landslide database and the Swiss destructive avalanche database, the data set was extended back in time and more hazard processes were added by conducting an in-depth search of newspaper reports. The new database now covers all natural hazards common in Switzerland categorized into seven process types: flood, landslide, rockfall, lightning, windstorm, avalanche, and other processes (e.g. ice avalanches, earthquakes). Included were all fatal accidents associated with natural hazard processes where victims did not expose themselves to an important danger on purpose or wilfully. The database contains information on 635 natural hazard events causing 1023 fatalities, which corresponds to a mean of 14.6 victims per year. The most common causes of death were snow avalanche (37%), followed by lightning (16%), flood (12%), windstorm (10%), rockfall (8%), landslide (7%) and other processes (9%). About 50% of all victims died in one of the 507 single-fatality events; the other half of victims were killed in the 128 multi-fatality events.

The number of natural hazard fatalities that occurred annually during our 70-year study period ranged from two to 112 and exhibited a distinct decrease over time. While the number of victims during the first three decades (until 1975) ranged from 191 to 269 per decade, it ranged from 47 to 109 in the four following decades. This overall decrease was mainly driven by a considerable decline in the number of avalanche and lightning fatalities. About 75% of victims were males in all natural hazard events considered together, and this ratio was roughly maintained in all individual process categories except landslides (lower) and other processes (higher). The ratio of male to female victims was most likely to be balanced when deaths occurred at home (in or near a building), a situation that mainly occurred in association with landslides and avalanches. The average age of victims of natural hazards was 35.9 years, and accordingly, the age groups with the largest number of victims were the 20-29 and 30-39 year-old groups, which in combination represented 34% of all fatalities. It appears that the overall natural hazard mortality rate in Switzerland during the past 70 years has been relatively low in comparison to rates in other countries or rates of other types of fatal accidents in Switzerland. However, a large variability in mortality rates was observed within the country with considerably higher rates in Alpine environments.

38   **1. Introduction**

39   Every year, world-wide natural hazard events not only generate tremendous financial damage costs but also

40   cause a large number of human fatalities (MunichRe, 2016). According to the NatCatSERVICE database of

41   MunichRe, the average annual global loss of life due to natural catastrophes was 68,000 during the last ten

42   years and 54,000 during the last thirty years (23,000 in 2015; Ins. Inf. Inst., www.iii.org/fact-

43   statistic/catastrophes-global).

44

45   In scientific literature, information and data sets on loss of human lives due to specific natural hazard

46   processes cover various time periods and exist at different aggregation levels: at the global scale (e.g.

47   Jonkman, 2005; Petley, 2012; Auker et al., 2013; Dowling and Santi, 2014), the continental scale (e.g. Di

48   Baldassarre et al., 2010; Sepúlveda and Petley, 2015) and most commonly the regional/national scale (e.g.

49   Guzzetti, 2000; Ashley and Ashley, 2008; Höller, 2009; Vranes and Pielke, 2009; Singh and Singh, 2015,

50   Techel et al., 2016). Moreover, there are studies that describe the circumstances during specific catastrophic

51   natural hazard events and/or assess the patterns and reasons behind the associated massive loss of life (e.g.

52   Chowdhury et al., 1993; Tsai et al., 2001; Doocy et al., 2007; Jonkman et al., 2009; Ando et al., 2013).

53

54   While some authors have analysed natural hazard mortality data that include many hazard types (e.g. Shah,

55   1983; Noji, 1991; Borden and Cutter, 2008), the bulk of studies have focussed on a distinct hazard process.

56   Jonkman (2005) studied statistics about loss of human life caused by various freshwater flood types (river

57   floods, flash floods and drainage problems) on a global scale and for the period from 1975 to June 2002

58   based on the EM-DAT International Disaster Database. This investigation showed that while flash flood

59   events have the highest average mortality rate (deaths divided by number of affected persons), Asian river

60   floods are most devastating in terms of the number of persons killed or affected. In addition, very high

61   death tolls have been reported for coastal flood events (e.g. Chowdhury et al., 1993; Gerritsen, 2005;

62   Jonkman et al., 2009; Kure et al., 2016) and tsunamis (e.g. Doocy et al., 2007; Inoue et al., 2007; Ando et

63   al., 2013). However, these events were not included in Jonkman (2005) due to the rather limited availability

64   of information. On a national scale, flood fatalities have been assessed by many authors for countries all

65   around the world, such as the USA (Ashley and Ashley, 2008), India (Singh and Kumar, 2013), Pakistan

66   (Paulikas and Rahman, 2015) and Australia (Coates, 1999; FitzGerald et al., 2010).

67

68   Petley (2012) assembled a global data set of fatalities from non-seismically triggered landslides that took

69   place from 2004 to 2010 based on the Durham Fatal Landslide Database (DFLD). The total number of

70   landslides and fatalities during the 7-year period turned out to be an order of magnitude larger than

71   numbers suggested by other sources, and the study indicated that most fatalities occur in Asia. In a study

72   focusing on fatalities caused by debris flows (often included in landslides studies), Dowling and Santi

73   (2014) considered 213 events that occurred between 1950 and 2011 and during which a total of 77,779

74   people were killed. Results of this global analysis provided evidence that more debris-flow fatalities tend to

75   occur in developing countries. This is reflected in the median number of fatalities per recorded deadly

76   debris flow which is 23 in developing countries, and only 6 fatalities per flow in advanced countries (11

77   when considering all data; Dowling and Santi; 2014). The value is very high when compared to data for the

78   European Alps, where for example torrential processes cause an annual number of fatalities of

79   approximately 1.5 in Austria (Fuchs and Zischg, 2014). On a national scale, landslide events with fatal

80   consequences were compiled by Guzzetti (2000) for events that occurred in contemporary Italy from 1279

81   to 1999. Fast mass movements, such as rockfall events, rockslides, rock avalanches and debris flows were

82   included in this study and were found to have caused the largest number of fatalities.

83

84   Loss of life due to snow avalanches has been analysed by numerous authors, most often at a national level,

85   e.g. for Austria (e.g. Höller, 2009), France (e.g. Jarry, 2011), Norway (e.g. Kristensen, 1998) or

86   Switzerland (e.g. Schneebeli et al., 1998), but also at a regional level, e.g. for the European Alps (Techel et

87   al., 2016).

88

89   Loss of life related to meteorological hazard events, such as lightning and all the different types of wind

90   storms, has also been the subject of many national and regional studies. In the USA, medium- to long-term

91   data sets of wind related deaths have been investigated, for example for tornados (Ashley, 2007) and

92   hurricanes (Rappaport, 2000; Czajkowski et al., 2011), as well as for (nontornadic) convective (Black and

93   Ashley, 2010) and nonconvective (Ashley and Black, 2008) high-wind events. While convective and

94   nonconvective high-winds can cause serious problems in Switzerland (e.g. WSL and BUWAL, 2001),

95   tornadoes are much more rare but have caused fatalities e.g. in the 1920ies and 30ies (Bader, 2001).

96   Various publications have presented national lightning data sets, for example from the UK (Elsom, 2001),

97   India (Singh and Singh, 2015), Australia (Coates et al., 1993), Colombia (Navarrete-Aldana et al., 2014),

98   USA (Holle, 2016; López and Holle, 1996; Curran et al., 2000), and Swaziland (Dlamini, 2009).

99   Additionally, Holle (2016) summarized and synthesized lightning fatality data from 23 recent national-

100   scale investigations from both developed and developing countries.

101

102   Geophysical events such as tsunamis and volcanic activity might not be very relevant for Switzerland, but

103   are of considerable importance when assessing consequences of natural hazards at a global level (e.g.

104   Auker et al., 2013). Earthquakes, in contrast, have occurred in Switzerland with dramatic effects, but events

105   causing fatalities or large amounts of damage are rare. The Basel earthquake of 18 October 1356 is

106   arguably one of the three most devastating natural hazard incidents of the last 1000 years in Switzerland

107   (the other two being Biasca rockslide/water surge in 1513/1515 and the Goldau rock avalanche in 1806)

108   and is regarded as the strongest historically documented earthquake event in central Europe (Giardini et al.,

109   2004). While the 1356 event destroyed large parts of Basel, the overall number of victims remains

110   uncertain and estimates range from 300 to 2000 fatalities (Fäh et al., 2009). The highest estimates,

111   however, were evaluated to be highly improbable by Fäh et al. (2009). For countries more frequently struck

112   by seismic activity, various fatality databases exist (e.g. Vranes and Pielke, 2009).

113

114   In Switzerland, fatalities caused by floods, debris flows, and landslides have been systematically collected

115   since 1972. They are recorded in the Swiss flood and landslide damage database (Hilker et al., 2009) and

116   were briefly analysed by Schmid et al. (2004). Deaths due to rockfall incidents have been included in the

117   database since 2002. For disastrous events causing loss of life that occurred before 1972, only partial and

118   scattered information is available (e.g. Röthlisberger, 1991). In parallel, information on loss of life caused

119   by snow avalanches in Switzerland has been collected since the hydrological year 1936/1937 by the WSL

120   Institute for Snow and Avalanche Research SLF. To our knowledge, no systematic data acquisition of

121   fatalities and damage induced by convective and non-convective high winds and lightning has been carried

122   out at national scale in Switzerland.

123

124   In the study presented here, we compiled the available data on natural hazard fatalities mentioned above,

125   extended the period covered by the database, and expanded it to include all process types relevant for the

126   study area. We present this new, detailed 70-year (1946-2015) data set of loss of life in Switzerland caused

127   by (i) floods, (ii) debris flows, (iii) landslides and hillslope debris-flows, (iv) rockfall events and rockslides,

128   (v) windstorms, (vi) lightning strikes, (vii) earthquakes and (viii) avalanches. Temporal and spatial patterns

129   in the results are discussed and the numbers of fatalities as well as the characteristics of the underlying

130   incidents for different process types are assessed. Finally, we compare our data with similar data from other

131   countries and regions and attempt to explain differences qualitatively.

132

133   According to the Federal Constitution of the Swiss Confederation, the cantons and municipalities are

134   responsible to ensure the protection of the population against natural hazards. The aim of this study is to

135   support authorities to better understand the occurrence of fatal incidents, to identify potential improvements

136   in hazard prevention and to further reduce the number of victims of natural hazards.

137   **2. Study area**

138   Switzerland is located in central Europe between latitudes 45° and 48° N, and between longitudes 5° and

139   11° E, with a total area of 41,285 km^2 and an altitudinal range of 193 to 4634 m a.s.l. The Swiss

140   Confederation consists of 20 cantons and 6 half cantons, and its territory can be roughly divided into four

141   regions based on its geomorphology (see Figure 1): the Alps (a high-altitude mountain range running across

142   the central-south of the country), the Swiss Plateau (a relatively flat area between Lake Geneva and Lake

143   Constance), the Prealps (the transitional area between the Alps and the Swiss Plateau) and the Jura (a hilly

144   mountain range in the north-west). The population grew from 4.5 to 8.3 million people between 1946 and

145 2015 and is clustered mostly on the Swiss Plateau (over 60% of the total population is located on less than a
146 third of the total area of the country). The Swiss climate is temperate but can vary regionally. In large parts
147 of the Alps the mean annual rainfall is around 2000 mm/year or more, and along the Swiss Plateau this
148 value amounts to 1000-1500 mm/year. Most precipitation falls during the summer months.

149 **3. Data and methods**

150 The data for this study were extracted from the Swiss flood and landslide damage database (section 3.1)
151 and the Swiss destructive avalanche database (section 3.2). The data set (except for avalanches) was then
152 extended (i) in time to include an additional period of 26 years back to the year 1946 and (ii) in breadth to
153 include additional relevant natural hazard processes, such as lightning, windstorm, and earthquake, by
154 carrying out an extensive newspaper search (sections 3.3 and 3.4).

155 **3.1 Swiss flood and landslide damage database**

156 Since 1972, fatalities and estimates of financial damage costs caused by naturally triggered floods, debris
157 flows, landslides and (since 2002) rockfall events have been collected by the Swiss Federal Research
158 Institute WSL in the Swiss flood and landslide damage database (Hilker et al., 2009; Badoux et al., 2014).
159 Fatality and damage information is primarily provided by approximately 3000 Swiss newspapers and
160 magazines, which are scanned daily by a media-monitoring company. Additional information is often
161 compiled from insurance companies and the websites of public authorities such as police and fire brigades.
162 An in-depth description of the structure of the Swiss flood and landslide damage database was presented by
163 Hilker et al. (2009). For this study, the database provided information on a total of 129 deaths due to floods,
164 debris flows, landslides, hillslope debris-flows or rockfall from 1972 to 2015.

165 **3.2 The Swiss destructive avalanche database**

166 Data on avalanche casualties since the winter 1936/37 are stored in the destructive avalanche database from
167 the WSL Institute for Snow and Avalanche Research SLF (Techel et al., 2015). In the 79 years from
168 1936/37 to 2014/15, 1255 avalanches killed 1961 people in Switzerland. We retrieved data for our study
169 period from this database and considered cases that occurred (i) in settlement areas, (ii) on high-alpine
170 building sites, (iii) on transportation corridors (including roads and railway lines, ski runs and winter hiking
171 trails, if any of these were officially open or if they were closed but the casualty was work related), and (iv)
172 on hiking trails during summer if the trail was open and snow-free.

173

174 We explicitly excluded all cases that occurred outside of transportation corridors and settlements (except
175 hiking trails in summer, see (iv) above). Thus, cases associated with ski or snowshoe touring, and skiing or
176 snowboarding away from open ski trails were not included in our data set. Also, we did not incorporate
177 avalanche fatalities related to vehicles illegally driving on officially closed roads. The destructive avalanche

178   database is considered complete for fatality data, and data quality is generally very high. Thus, no

179   systematic search of avalanche related events in a newspaper was necessary.

3.3 Further extension of the record of natural hazard fatalities in Switzerland

181   With the aim of extending the data series to 70 years and combining it with other natural hazard processes

182   like windstorm, lightning, earthquake and ice avalanche, we made a search in a newspaper. We selected the

183   „Neue Zürcher Zeitung" (NZZ) because it is a national newspaper and a digital archive exists back until

184   1780. The NZZ is written in German, which is the most spoken language in Switzerland (see also section

185   5.1). We accessed the digital archive via an internet platform, where a keyword search was possible. In a

186   first step, we derived adequate keywords (in German) for the search. We selected the years 1986-1995, for

187   which we already had some data from the Swiss flood and landslide database, as validation period. We

188   generated a list with possible keywords and checked how often these words were used in the newspaper for

189   the description of casualties that occurred in Switzerland and abroad. The casualties from abroad were

190   included to get more search hits. We then shortened the list to the most relevant keywords. Where possible,

191   we combined the keywords for the different processes. For example, we searched for casualties caused by

192   "flood OR inundation OR landslide OR landslip OR mudslide OR mudflow" combined with "dead OR

193   casualty OR death OR human life OR drown OR killed OR dead body OR buried". An overview of the

194   keywords and the combinations used is given in the supplementary material (Table S1). With these

195   keyword combinations, we found most cases (roughly 90%) already stored in the Swiss flood and landslide

196   database for the selected validation period 1986-1995.

197

198   In a next step, we used the selected keywords to scan the newspaper for the remaining years (1946-1977,

199   1988-2015). For the years where we already had data from the Swiss flood and landslide database for the

200   processes flood, landslide, debris flow and rockfall, we restricted the search to the processes not already

201   covered. The search for fatalities produced up to 300 hits per year. We initially viewed all hits, but many

202   were not relevant for our research (e.g. fatalities abroad). Further, the digital scan of the newspaper was

203   sometimes of bad quality, which resulted in the misspelling of words and thus influenced our search

204   because not all of our keywords were found. In addition, some gaps exist in the digital archive of the NZZ

205   (e.g. 04. – 15.08.1978).

206

207   For each casualty found, a database entry was made. The following information describing the fatal

208   accident and the victim was stored: name of municipality, canton, date, time, coordinates, description of the

209   event, age, gender, locality (i.e. in or around a building, on a transportation route, in open terrain, in a

210   stream channel, on a lake), mode of transport (on foot, by bicycle, in vehicle, by public transport, by boat,

211   by ski), activity (work, leisure time), and data source. For most of the above-mentioned categories, the

212   quality of the information was also assessed. In doing so, we distinguished between two types of

213   information quality: (i) a concise statement describing a certain characteristic of the event (certain); and (ii)

214   an indication of a characteristic that we deduced based on the available information (probable). In contrast,

215   if no information was available to describe certain aspects of a fatal incident, those characteristics were

216   considered unknown.

217   **3.4 Natural hazard processes considered in the new database**

218   In the present study, we assigned the fatalities found in our search (or adopted from the flood and landslide

219   damage database or the destructive avalanche database) to the following seven process categories:

220

221   • Flood: includes people drowned in flooded or inundated areas or carried away in streams under high-
222   water conditions.

223   • Landslide: includes people killed by landslides, hillslope debris flows and channelized debris flows.
224   Because debris flows were often not identified as such in the press media (especially in the first half of
225   our study period), we decided to add debris flow fatalities to the category of landslide processes. This
226   approach has been applied previously, for example by Guzzetti (2000).

227   • Rockfall: includes people killed by rockfall.

228   • Lightning: includes people who died after being struck by lightning.

229   • Windstorm: includes people killed by falling objects or trees during very strong wind conditions and
230   people who drowned in lakes because their boat capsized during such conditions.

231   • Avalanche: includes people killed in snow avalanches (except roof avalanches, see below).

232   • Other: includes people killed by hazard processes that are not frequent in Switzerland (e.g. ice
233   avalanches, earthquakes, lacustrine tsunamis, roof avalanches). Most of the fatalities assigned to this
234   process type were caused by the 1965 Mattmark ice avalanche.

235

236   Fatalities due to forest fires did not occur during our study period, and people who died during

237   meteorological heat waves were not included. Overall, we considered only casualties where people did not

238   expose themselves to a considerable danger on purpose or wilfully. For example, we excluded loss of life

239   due to high-risk sports (e.g. canoeing and river surfing during floods) and other outdoor activities in

240   potentially dangerous environments, such as canyoning, mountaineering and rock climbing. We also

241   excluded popular snow sports experienced outside of ski resorts, such as freeriding and alpine touring, that

242   have been described elsewhere (e.g. Techel and Zweifel, 2013; Schweizer and Lütschg, 2001). Further, we

243   only included cases where the process directly induced a casualty or an action that led to death. For

244   example, we did not consider cases where a forest ranger was killed during forest clearing operations after a

245   windstorm or where a firefighter was killed in a flooded basement due to an electric shock.

246   **4. Results**

247   **4.1 Types of natural hazard processes associated with fatalities**

248   Our newly compiled database includes reports on 1023 fatalities associated with natural hazard processes in
249   Switzerland during the period from 1946 to 2015 (Table 1). This result corresponds to an average of 14.6
250   fatalities per year. More than one third of all fatalities (378 deaths) were caused by snow avalanches during
251   winter and spring. The second most frequent cause of loss of life was lightning (16.0%), followed by flood
252   (12.1%) and windstorm (10.3%). Landslides and rockfall events each represented less than 10% of the total
253   number of fatalities in Switzerland. Processes that caused sporadic deaths included an earthquake (3
254   deaths), a lacustrine tsunami (1) and a roof avalanche (1). The worst incident, in terms of the number of
255   fatalities involved, that occurred during our 70-year study period was the catastrophic 30 August 1965 ice
256   avalanche, which broke off at the terminus of the Allalin Glacier in the canton of Valais, destroyed the
257   Mattmark Dam construction site and killed 88 people. This incident was the only deadly ice avalanche
258   event we considered in the database (and is included in the category *other* processes, Table 1).

259   **4.2 Temporal distribution of natural hazard fatalities in Switzerland**

260   **4.2.1 Annual distribution of fatalities**

261   The annual number of natural hazard fatalities in Switzerland during our 70-year study period ranged from
262   two (in five years and most recently in 2010) to 112 (in 1951; Figure 2). The resulting median over the
263   entire period was 9.0 deaths per year, which is below the mean value of 14.6 and highlights the large
264   influence of severe multi-fatality events (see also section 5.2). While two years had an annual number of
265   deaths greater than 100, a total of five years exceeded the value of 33.2 (mean plus one standard deviation).
266   The annual number of events ranged from one (in 1995) to 45 (in 1951), with a median over the study
267   period of 7.0 and a mean value of 9.1 (Figure 2).

268

269   The number of people killed by natural hazards in the last 70 years showed a clear decrease over time
270   (Figure 2). The downward trend in the total number of annual fatalities is statistically significant (Mann-
271   Kendall trend test: 2-sided P-value = $<10^{-3}$; Theil-Sen slope estimate: -0.207 deaths per year; R-packages
272   *Kendall* (McLeod, 2011) and *zyp* (Bronaugh and Werner, 2009)). This pattern is confirmed when the total
273   number of deaths during the first 35 years of the study period (747) is compared with the value for the
274   second 35 years (276). Thus, nearly three times as many people were killed by natural hazard processes
275   from 1946 to 1980 than from 1981 to 2015 (Figure 2). Further, only three years after 1981 exhibited a
276   number of fatalities larger than the mean value for the full 70-year period: 1985, 1999 and 2000. The
277   decrease in natural hazard fatalities over the 70-year period is also apparent in the number of fatalities per
278   decade. On average, nearly three times as many people died in accidents during each of the first three
279   decades of the study period as during each of the last four decades.

280

281   The temporal distributions of victims of specific hazard types showed a distinct decrease for lightning and
282   avalanches only (Figures 3 and 4). The trend is statistically significant for avalanches (Mann-Kendall trend
283   test: 2-sided p-value = $<10^{-3}$; Theil-Sen slope estimate: -0.042 deaths per year) and lightning (Mann-
284   Kendall test: 2-sided p-value = $<10^{-3}$; Theil-Sen slope estimate: -0.063 deaths per year). For both process
285   types, around four times more fatalities were recorded in the first half of the study period than in the second
286   half (Figure 4). Interestingly, during the last 15 years, the database revealed only seven avalanche fatalities,
287   resulting in an average for this most recent period that is ten times smaller than the overall mean value. In a
288   qualitative sense, only deaths due to landslide processes seem to have increased slightly over the 70-year
289   period. However, this impression was strongly influenced by the large number of fatalities (16) that
290   occurred during the severe October 2000 event in the canton of Valais, when 13 people died in the Gondo
291   landslide.
292
293   There were several years in the data set of each natural hazard type when no fatal incidents were reported
294   (Figure 3). The three hazard types for which at least one fatality was reported in most years during the
295   study period are lightning (49 years), avalanches (48 years) and floods (48 years). While at least one
296   fatality associated with windstorm and rockfall events occurred in 40 and 37 years, respectively, fatal
297   accidents related to landslide processes occurred only in one third of the investigated years. Even though
298   only one deadly ice avalanche happened between 1946 and 2015 (category *other* processes), this event was
299   responsible for more fatalities than all rockfall or all landslide incidents (Figure 4).
300
301   Normalization of fatality data by population resulted in a clearly declining annual crude mortality rate. We
302   found an annual average rate of 3.9 deaths per million persons for the first 35 years of the study period and
303   a rate of 1.1 for the second 35 years. The yearly mean for the whole period is 2.5 victims per million
304   persons. A very distinct decrease in the mortality rate from the first to the second half of the study period
305   appears for the processes lightning (0.7 to 0.14) as well as avalanche (1.63 to 0.29), and to a slightly lesser
306   extent for the processes flood (0.41 to 0.18), rockfall (0.31 to 0.10) and windstorm (0.30 to 0.19).

307   **4.2.2 Monthly distribution of fatalities**

308   The monthly distribution of natural hazard fatalities from 1946 to 2015 showed two distinct peaks, one in
309   summer and one in winter (Figure 5). The first peak was due to the seasonal distribution of classic "summer
310   processes" such as lightning, floods and, to a lesser extent, also landslides and rockfall incidents, which
311   occur most frequently in June, July and August. Additionally, the catastrophic ice avalanche event in 1965
312   contributed considerably to the establishment of August as the month with most loss of life (207 fatalities).
313   The winter peak was largely caused by avalanches, the most fatal process type in Switzerland, which
314   accounted for 242 of the overall 280 deaths in the months of January (135 avalanche related deaths out of
315   145 total deaths) and February (107 avalanche deaths/135 total deaths). The months of March, April and
316   May in spring and September through December in autumn and early winter exhibited relatively low

317   fatality numbers, i.e. below 60. The month with the fewest deaths related to natural hazard processes was

318   November, when a total of 22 deaths occurred during the last 70 years. This corresponds to a fatality

319   number roughly one order of magnitude smaller than the value in August.

320

321   These seasonal patterns resulted in a high percentages of fatalities in summer (June, July and Aug.; 41.7%)

322   and winter (Dec., Jan. and Feb.; 32.2%). In contrast, spring (Mar., Apr. and May; 16.0%) and autumn

323   (Sept., Oct. and Nov.; 10.1%) displayed low percentages. While 85.4% of lightning deaths and 67.7% of

324   flood deaths occurred in summer, 70.6% of avalanche victims were killed in winter and 24.9% in spring. In

325   autumn, only fatalities by landslides show an relatively high percentage (39.2%). The temporal distribution

326   of seasonal fatality data (all process types combined) is displayed in Figure 6. The plots show a distinct,

327   statistically significant decrease over time for fatalities that occurred in winter (Mann-Kendall trend test: 2-

328   sided p-value = $<10^{-3}$; Theil-Sen slope estimate: y = -0.047), spring (Mann-Kendall trend test: 2-sided p-

329   value = 0.002; Theil-Sen slope estimate: y = -0.024) and summer (Mann-Kendall trend test: 2-sided p-value

330   = $<10^{-3}$; Theil-Sen slope estimate: y = -0.074). In contrast, the number of autumn victims has not

331   significantly changed over the study period.

332   **4.2.3 Natural hazard fatalities classified by time of day**

333   Based on information on the fatality event time, we assigned the cases to four different time periods:

334   morning (06:00-11:59 local standard time), afternoon (12:00-17:59), evening (18:00-23:59) and night

335   (00:00-05:59). Most of the fatalities occurred in the afternoon (39%), followed by the evening (23%), the

336   morning (17%) and the night (11%). For ten percent of the fatalities, no exact event time could be

337   determined (Figure 7). Fatalities due to lightning strikes, floods or windstorms occurred mostly in the

338   afternoon and in the evening, whereas no characteristic time period could be distinguished for the

339   occurrence of fatalities due to avalanches, rockfall events and landslides. However, avalanches and

340   landslide processes showed a considerably higher percentage of deaths during the night (roughly 20%)

341   compared to the other processes (less than 10%).

342   **4.3 Spatial distribution of natural hazard fatalities in Switzerland**

343   Fatalities caused by natural hazard processes were relatively homogenously distributed over the entire

344   territory of Switzerland (Figure 8). There are a few, mostly small, areas where very few or even no deaths

345   were found in our data set. This is also visible in Figure 9 that shows the number of fatalities and events

346   using a 10x10 km raster grid. Multi-fatality events were much more frequent in the mountainous parts of

347   the country (Alps) compared to the Swiss Plateau and the hilly Jura (Figure 8).

348

349   As can be expected, fatalities resulting from avalanches occurred mainly in the high-alpine parts of

350   Switzerland (Figures 8 and S1). A few accidents were reported from the western and central Prealps

351   (transitional areas to the high-alpine part of Switzerland). In contrast, no fatal incidents relating to

352 avalanches occurred in the hilly Jura and in the Swiss Plateau region. Clusters are present, e.g. in the area

353 around Andermatt in the southern part of the canton Uri (UR) and around Davos in the canton Grisons

354 (GR). Also, a notably large number of multi-fatality avalanche events is visible in Figure 8 (see also section

355 5.2). Interestingly, some mountainous but populated regions showed very few or no deaths by avalanches at

356 all. Such areas are located in several parts of Grisons and Valais (VS), as well as in parts of northern

357 Ticino (TI).

358

359 Most of the fatalities caused by landslide processes were recorded in the Alps and Prealps, and a few were

360 documented in the Swiss Plateau (Figure 8 and S1). The largest number of landslide deaths occurred in the

361 canton Valais , and the worst landslide event in the database (with 13 fatalities) occurred in Gondo (VS) in

362 October 2000. Similar to landslide accidents, fatal rockfall accidents predominantly took place in the

363 central Alps and Prealps, e.g. in the cantons of Valais, Grisons, Vaud (VD) and Uri. A limited number of

364 these fatalities occurred in the Jura and the Swiss Plateau.

365

366 Flood fatalities were rather homogenously distributed over Switzerland and occurred in almost all

367 regions/cantons during the last 70 years (Figure 8 and S1). Still, there were considerably more cases (some

368 of them multi-fatality incidents) in the Swiss Plateau than in any other Swiss region. The fewest deaths by

369 floods occurred in the region Jura and the canton Valais. Some areas, such as the canton of Neuchâtel (NE),

370 the eastern part of canton Grisons and south-eastern Valais exhibited no flood fatalities at all.

371

372 Lightning fatalities occurred all over Switzerland, and by far most of them took place on the Swiss Plateau

373 (Figure 8 and S1). However, some high-mountain areas in several different parts of Switzerland exhibited

374 very few lightning related deaths (e.g. in cantons Grisons, Valais, Uri and Ticino). Windstorm related

375 fatalities were also mainly registered along the Swiss Plateau. This region exhibited more than half of all

376 windstorm related fatalities. Some cases occurred in the Jura, the Prealps and on the border to the Alps. In

377 contrast, very few wind related fatalities occurred in the large alpine cantons Grisons, Valais and Ticino.

378 Areas around lakes (Lake Zurich, Lake Neuchatel, Lake Geneva, Lake Constance) had clusters of

379 windstorm fatalities due to a considerable number of capsizing accidents.

380

381 The spatial distribution of natural hazard fatalities for the different process types was confirmed by the

382 altitude data for each event. For roughly three quarters of the fatalities, we were able to define the exact

383 altitude at which the victim died (for slightly less than 25% of the fatalities the accident altitude was

384 estimated). While median altitude was highest for avalanche and rockfall victims (1467 and 1082 m a.s.l.,

385 respectively), landslide and lightning victims were killed at intermediate altitudes (820 and 692 m a.s.l.,

386 respectively). In contrast, flood and windstorm fatalities were mainly registered at low altitudes

387 representative for the Swiss Plateau (median values of 559 and 431 m a.s.l., respectively).

388

389   By combining the gridded natural hazard fatality data (Figure 9) with population data (Figure 10, above), a

390   spatially distributed mortality rate with a 10 km grid resolution was assessed for all of Switzerland

391   (fatalities per year and per one million persons; Figure 10, below). Obviously, the weakly populated, high-

392   alpine areas with avalanche, landslide and rockfall incidents show the grid cells with the highest mortality

393   rates on Swiss territory. A cluster of cells with very high rates is discernible in the central part of the Alps.

394   While in the Prealps high rates are still widespread, the more densely populated Swiss Plateau displays a

395   majority of grid cells with mostly low and some medium mortality rates. The hilly Jura shows a few cells

396   with medium or slightly elevated rates. Grid cells where fatal natural hazard did occur, but that are not

397   populated due to their position in high-alpine terrain (in most cases in the immediate vicinity of the

398   country's borders), are indicated in red (Figure 10, below; section 5.6).

399   **4.4 Natural hazard fatalities classified by age and gender**

400   The age of victims was provided for more than 93% of the natural hazard fatalities reported in our database

401   (954 out of 1023). Overall, the age groups with the highest death toll were the 20-29 year-old (172

402   fatalities) and 30-39 year-old (177 fatalities) groups, followed by the 40-49 year-old group with 151

403   fatalities (Figure 11, Table S2 in supplementary material). These values correspond to a combined 500

404   victims (or 48.9%) between 20 and 49 years of age. While children and teenagers (0-19) accounted for

405   20.9% of natural hazard deaths, people above 60 years of age made up only 12.6%.

406

407   When focusing on age related patterns for the individual process types, several discrepancies from the

408   overall numbers attract attention. For example, about one fifth of all flood victims were younger than ten

409   years of age, compared to 7.5% for all hazard processes (Figure 11). Most of these very young victims

410   drowned in the first half of the study period. In addition, the percentage of victims over 60 years of age was

411   more than twice as high for flood fatalities (25.8%) as for all fatalities. Lightning rarely killed young

412   children (2.4% in the 0-9 year-old age group) but seems to particularly affect teenagers. The 10-19 year-old

413   age group constituted 23.2% of all lightning victims, which is much higher than the value for all processes

414   (13.4%). The large majority of these teenagers were killed in the first part of our investigation period.

415   Finally, windstorm victims below 20 years of age were underrepresented (10.5%) compared to the full data

416   set (20.9%).

417

418   Gender was provided for practically all (99.5%) natural hazard fatalities in our database. Summarized for

419   all process types, more than three quarters of all natural hazard victims were males, indicating that males

420   were approximately three times as likely to become fatality victims as females (Table 1). Male fatalities

421   greatly outnumbered female deaths for every process category (percentage of male fatalities between 74.2

422   and 79.3%), with the exception of landslides and processes in the *other* category (including ice avalanches)

423   (Figure 11). While the proportions of male and female victims of landslides were quite similar (55.4 and

424   44.6%, respectively; Table 1), the victims killed by the ice avalanche of 1965, which destroyed a dam

425   construction site, were practically all males (96.6%). Expressed differently, female landslide deaths

426   represented 13.6% of all female natural hazard fatalities, whereas the same value for males was only 5.3%.

427   Correspondingly, processes classified as *other* were the cause of death in 11.0% of male victims in our

428   records, while this value was negligible for female victims (2.9%).

429

430   Regarding the ages of victims, the number of male victims in natural hazard fatalities was considerably

431   larger than the number of female fatalities within every age group (Figure 11). This pattern is accentuated

432   for young adults between 20 and 39 years of age, where the percentage of male victims was more than

433   80%, whereas for young children from 0 to 9 years of age the percentage of female victims was highest at

434   34%. Accordingly, the age distribution of male and female victims of natural hazard processes exhibits a

435   few differences. Whereas 26.4% of female fatalities were younger than 20 years of age, this applied to only

436   19.4% of male victims (Table S2). In contrast, the percentage of young-adult victims between 20 and 39

437   years of age was much higher for males (37.2% of all deaths) than for females (25.2%).

438   **4.5 Natural hazard fatalities in different accident circumstances**

439   Accident circumstances, such as *activity* (work or leisure time), *locality* (on transportation routes, in open

440   terrain, in or around buildings, on a lake, in the immediate vicinity of a stream channel) and *mode of*

441   *transportation* (on foot, in a vehicle, on a boat, on skis, on a bicycle, in public transport) were analysed for

442   the 1023 entries in our database (Figure 12, Table 2). Regarding the victims' activity, we found that 52% of

443   all fatalities occurred during leisure time, 35% occurred during work, and the activity could not be assigned

444   in 13% of the cases. The assessment of incident locality revealed that most of the fatalities occurred on

445   transportation routes (33%), in open terrain (14%) or in or around buildings (home 20%, other buildings

446   6%, around buildings 3%). For all fatalities except those in buildings, the mode of transport was

447   determined: 62% of victims were killed whilst on foot, 18% in a vehicle, 7% on a boat, 6% on skis and 1%

448   or less in public transport or on a bicycle.

449

450   Avalanches killed more than twice as many people during leisure time (245) as during work (110). People

451   killed by avalanches during work were mostly located on transportation routes (72), mainly travelling by

452   foot (35) or in vehicles (16). People who died in avalanches during leisure time were usually at home (159)

453   or were travelling on transportation routes (83). Similarly, for floods, windstorms, landslides and rockfall

454   events, fatalities that occurred during leisure time were at least twice as frequent as those that occurred

455   during work. The single hazard event with the largest number of people killed during work was the ice

456   avalanche in Mattmark with 88 deaths (category *other*). People fatally struck by lightning were working in

457   43% of the cases (Table 2).

458

459   Most victims of floods were killed in the stream channel sector (63) and were usually carried along by the

460   high water. Flood related fatalities on transportation routes were also relatively common (31), with 11

461 victims travelling in vehicles, 16 by foot, two by bicycle, one in public transport and one case unclear.

462 Regarding windstorm related incidents, most of the fatalities occurred on lakes with victims located in

463 boats (44). Thirty-four windstorm related fatalities occurred on transportation routes, where 20 victims

464 were killed in vehicles, 13 on foot and one on a bicycle. Loss of life caused by landslide processes occurred

465 mostly in and around buildings (40). Twenty people were killed by landslides whilst on transportation

466 routes, and 11 of these victims were in vehicles, eight on foot and one in public transport. Most people

467 killed by rockfall were on transportation routes (58), of which 30 people were travelling by foot and 27 in a

468 vehicle (one unclear), whereas 14 people were killed by rockfall on open terrain. Most of the lightning

469 fatalities occurred on open terrain (95 victims, of which 90 were moving by foot), in or around buildings

470 (33) or on transportation routes (28 victims, of which 13 were travelling by foot, 10 in or on a vehicle and 5

471 by bicycle; Table 2).

472 **5. Discussion**

473 **5.1 Data quality**

474 **5.1.1 Completeness of the data set**

475 Several factors influenced the integrity of our data set: (i) Fatal accidents caused by natural hazard

476 processes during the 70-year study period could simply not have been reported in the Neue Zürcher Zeitung

477 (NZZ) or in the additional data sources used. (ii) The NZZ is a German written newspaper. The coverage of

478 the news includes all parts of Switzerland (e.g. regarding severe natural hazard events), but there might be a

479 bias towards an underreporting in the other language regions (French, Italian, Rhaeto-Romanic), which

480 represent roughly one third of the population. (iii) For practical reasons, we had to apply a limited number

481 of keywords in our search. Thus, we could have missed reports on natural hazard fatalities in the data

482 sources because our keywords were not used in the respective news coverage. (iv) There were a few small

483 data gaps in our main data source. Some issues of the NZZ were not present in the data portal applied;

484 hence, we possibly missed fatalities that occurred during such periods. (v) The NZZ archive was

485 established by scanning all newspaper issues and applying a character recognition program (with the

486 exception of all new editions available digitally since 1994). This procedure is susceptible to errors

487 whenever the character recognition fails due to insufficient scan quality. We encountered this problem

488 when searching for keywords in the first few decades of the study period, mainly for long keywords. (vi)

489 Finally, media articles sometimes mix up technical terms and thus hazard processes (a problem already

490 discussed in Badoux et al., 2014). For example, we suspect that several fatal debris flows were not exactly

491 identified as such in the media during the first few decades of the study period because this process was not

492 yet commonly understood.

493

494 All in all, we acknowledge that our database for the time period between 1946 and 2015 is not fully

495 complete and that we might have missed a certain number of natural hazard deaths, mainly in the first

decades of our study period. Taking into account our success rate for the validation period (see section 3.3), we are confident that we passed over considerably less than 10% of the fatalities that occurred. There are two main reasons for this. First, approximately 37% of all fatalities in the data set presented here were caused by snow avalanches. Because the destructive avalanche database is considered complete for fatality data, less than two thirds of our data is subject to underestimation. Second, grave events with several deaths are normally described in numerous articles that span over a couple of days or even a few weeks (some incidents are even mentioned in subsequent years for commemoration or retrospection). It is thus very unlikely that we did not register at least one article on a multi-fatality event. Hence, we believe that our database is valuable in its present state.

5.1.2 Quality of the data

The quality of our natural hazard fatality data was assessed by considering the levels of uncertainty associated with the incident characteristics and circumstances. In general, uncertainty was low (Table 3). This finding applies primarily to the date of events, the victims' gender and age, and the locality of the incident (data was labelled as *certain* in 88% or more of the cases). Exact reporting of the time an incident occurred was often lacking, and we had to estimate the event time for more than one third of the fatalities. Data was unavailable in more than 10% of the cases only for the variables event time and victims' activity. Finally, data quality increased in the course of our study period, in that all variables except one (victims' activity) show lower uncertainty for the sub-period between 1981 and 2015.

5.2 The impact of multi-fatality events

A total of 635 natural hazard events with fatal consequences occurred in Switzerland during the study period (Table 4). The most common situation observed in the last 70 years was for one victim to be killed in a natural hazard incident. Roughly 50% of the total number of victims lost their life in one of the 507 single-fatality events recorded in the database. While incidents with two or three fatalities occurred 73 and 25 times, respectively, 25 incidents registered four to ten fatalities. Only five events caused more than ten deaths each, resulting in a combined 15.7% of the total number of victims in the entire study period (Table 4).

The largest of those five events was the Mattmark ice avalanche of 1965 that killed 88 people. The second and third worst multi-fatality events were both avalanches. The first of these avalanches occurred in February 1970 in Reckingen (canton of Valais) and represents one of the largest avalanche disasters in the Alps of the 20th century (30 deaths). Amongst other damage, the avalanche destroyed a Swiss army barrack and residential buildings, killing 19 officers and 11 civilians. The latter incident with 19 deaths occurred in January 1951 in Vals (canton of Grisons) during the worst avalanche winter in Swiss history (Figures 3 and 4).

531 Regarding the relative importance of single-fatality events, we detected two distinct categories of natural

532 hazard process types. Flood, rockfall, windstorm and lightning incidents with one victim were responsible

533 for more than 70% of the total fatalities associated with each of these process types. This value was much

534 smaller for avalanches (26.2%) and landslides (31.1%) (Table 4). This distinction is probably related to the

535 fact that fatal victims of both avalanche and landslide process types are more often killed in buildings

536 (around 50% of all cases) than victims of other hazard processes. Affected buildings are likely to be

537 occupied or inhabited by more than one person, and thus, multi-fatality events are more frequent for

538 avalanches and landslides. Lightning was associated with the highest percentage of deaths in single-fatality

539 events in Switzerland (87.8%). This value is only slightly lower than percentages reported for the USA

540 (90.9%, Curran et al., 2000) and Australia (92%, Coates et al., 1993).

541 **5.3 Evolution of fatality numbers during the last 70 years**

542 General attempts to explain the decrease in natural hazard fatalities observed in other countries and globally

543 have been made previously. For example, Goklany (2007) indicated that societies' collective adaptive

544 capacities lead to reduced mortality rates due to extreme weather. For the USA, Curran et al. (2000)

545 attributed a decline in lightning related deaths over time to improved medical care, emergency

546 communication and transportation, as well as better awareness of the serious threat posed by lightning.

547 Improved forecasting, process detection and warning systems may have also contributed to the decrease in

548 fatalities (Curran et al., 2000; López and Holle, 1996). Furthermore, fewer people currently work in open

549 fields than in the past (Elsom, 2001). With the expansion of urban areas more people are spending a greater

550 proportion of their time inside lightning-safe structures compared with decades ago (e.g. Curran et al.,

551 2000; Holle, 2016). These points also apply to Switzerland, which is confirmed by significant decreases in

552 lightning fatalities in particular and total fatalities more generally.

553

554 A significant reduction in avalanche fatalities in settlements and on transportation corridors since the

555 1970's has been noted throughout the countries of the European Alps (e.g. Techel et al., 2016), as well as in

556 other developed regions like in Scandinavia (Kristensen, 1998) and North America (e.g. Page et al., 1999;

557 Jamieson et al. 2010). Explanations for this decrease, also detected in our data set for Switzerland, include

558 (i) large investments into permanent avalanche defence structures, which reduce the potential for

559 catastrophic avalanches (e.g. SLF, 2000); (ii) hazard mapping and risk assessment to evaluate appropriate

560 measures for the protection or closure of avalanche-threatened sections of roads during winter (e.g.

561 Wilhelm, 1997; Margreth et al., 2003); (iii) the preventive artificial release of avalanches (e.g. Stoffel,

562 2001); (iv) the improved avalanche education of local authorities responsible for avalanche safety (e.g.

563 Bründl et al., 2004); and (v) an improved and more widely distributed avalanche forecast (Etter et al.,

564 2008).

565

566   Many fatalities related to floods and inundations occur because people act imprudently and put themselves

567   in dangerous situations. We assume that a substantial proportion of all flood deaths in our data set can be

568   ascribed to such inappropriate behaviour. For example, outdoors, when victims are carried away by

569   floodwaters because they were standing too close to a channel or inside a building, when victims intend to

570   save belongings from flooded basements or try to drive vehicles out of inundated underground car parks

571   (see also section 5.5). Similar observations were made abroad, e.g. in association with the use of motor

572   vehicles, when people decided to cross floodwaters, often underestimating the depth and force of flowing

573   water and thus taking significant risks (e.g. FitzGerald et al., 2010; Diakakis and Deligiannakis, 2013).

574   Hence, although Swiss flood protection has been developed and refined considerably in the last decades

575   (e.g. BWG, 2001), implying large financial investments, fatal events can only be prevented by such

576   measures to a limited extent. This could partly explain the relatively moderate decrease in flood fatality

577   over our study period. However, it has to be taken into consideration that deaths caused by floods were

578   dramatically reduced since the middle of the 19th century in Switzerland, as showed e.g. in Petrascheck

579   (1989). Still, it will be very important in the future to better inform and train people who regularly stay in or

580   close to flood prone areas. A similar recommendation could be made for windstorms, as fatalities related to

581   these events also often occurred due to negligent behaviour in dangerous situations.

582   **5.4 Demography of fatality data**

583   Our study revealed that male natural hazard fatalities have been much more frequent than female fatalities

584   (75.9% male vs. 23.7% female). This pattern has also been observed in other countries, for example for

585   fatal flood (Ashley and Ashley, 2008; Coates, 1999) and lightning (Singh and Singh, 2015; Navarrete-

586   Aldana et al., 2014; Elsom, 2001; Curran et al., 2000) victims. To explain this striking gender difference,

587   we first need to focus on work related deaths, which represent slightly more than one third of all recorded

588   fatalities (Figure 12, Table 2). A remarkable 93.5% of all natural hazard victims killed at work were men,

589   and this percentage was at least 95% in the four first decades of the study period. This finding is probably

590   mainly due to the fact that (i) during the study period, the ratio of men working full time was considerably

591   higher than the ratio of women working full time, especially in the first half of the period; and (ii) many

592   accidents were associated with occupations that are physically demanding and thus were, and to some

593   extent still are, almost exclusively carried out by men, such as farm labour, forestry work, construction

594   work, road maintenance (e.g. snow clearing) and rescue services. Thus, men have been more involved than

595   women in employment (often involving outdoor work) that puts them at risk of dying in a natural hazard

596   event.

597

598   More than half of all fatalities in our data set occurred during leisure time (Figure 12). Of these 536

599   victims, approximately two thirds were men and one third were women. Obviously, the predominance of

600   male fatalities was not as strong as that observed in work related accidents, but it was still considerable. We

601   assume that the gender difference observed for fatalities during leisure time activities was due to the higher

602 risk perception of women compared to men (e.g. Bubeck et al., 2012; Lindell and Hwang, 2008; Tekely-
603 Yesil et al., 2011). This effect probably leads to a more cautious and less adventurous behaviour of women,
604 which could explain the difference between the number of male and female fatalities. What applies for
605 recreational activities might also be valid for work and it seems that men have an overall greater disposition
606 towards risk-taking than women. This is e.g. confirmed by Jensenius (2014) for lightning deaths in the
607 USA. However, a growing recognition of the equality of the genders has led to a greater proportion of
608 women being at risk relative to men (Coates, 1999). This trend is somewhat supported by our data, in that
609 55.6% of all leisure-time fatalities in the last decade of the study period involved women.

5.5 Effects of location, mode of transport, activity and inappropriate behaviour

611 The percentage of people who drowned in vehicles was much smaller in Switzerland (17% of all flood
612 victims) compared to values reported in studies of other countries. For example, 77% of flood fatalities
613 were vehicle related in a study about the US state of Texas (Sharif et al., 2015), and 63% were vehicle
614 related in a study of the USA as a whole (Ashley and Ashley, 2008). It was suggested that this large
615 number of fatalities occurs because people incautiously try to cross rivers in their vehicles (Sharif et al.,
616 2015). Most of the people in our study were killed while travelling on foot (62%). This percentage includes
617 people who accidentally fell, were swept into the floodwaters, or tried to walk through the floodwaters. We
618 assume that most of these fatalities occurred because of inappropriate behaviour and underestimation of
619 risk and thus could have been prevented. The same could be said for all the lightning deaths in our study. In
620 most cases, the danger was underrated (e.g. people were struck during work on open fields) or people used
621 inadequate shelter (e.g. under trees). For fatalities due to lightning, a clear trend over time away from
622 outdoor worker casualties towards recreational accidents was apparent in our data set and has also been
623 observed elsewhere (López et al., 1995; Coates et al., 1993). Inappropriate behaviour also led to many of
624 the deaths related to windstorm events. Here, most fatalities occurred on lakes due to capsized boats, when
625 the victim(s) underestimated the heavy winds. Further, many victims were struck by falling tree (parts) or
626 other material that was swirling through the air. Regarding avalanche incidents, most of the fatalities in our
627 database occurred in buildings (185, 49%) because we excluded deaths due to sports like ski touring and
628 free skiing. We assume victims killed in buildings thought they were safe, as the specific damage threshold
629 of buildings is comparably high. However, once this threshold is exceeded during an event, statistics show
630 a high mortality rate for people located in a building (Wilhelm, 1997). Similarly, in the landslide process
631 category, most of the fatalities occurred in buildings (54%), suggesting that the inhabitants were not
632 expecting an event and unable to escape from the threat.

5.6 Comparison of Swiss natural hazard fatality data with data from abroad

634 The EM-DAT International Disaster Database is a free and searchable source of information on world-wide
635 victims of natural disasters (EM-DAT, www.emdat.be). In that database, we found 21 database entries for
636 Switzerland in our study period, and 329 fatalities associated with natural hazard processes that were

considered in our study. Avalanche events led to most of the fatalities recorded in EM-DAT (275), followed by storms (24), landslides (20) and riverine floods (10). A considerable difference from our overall results exists because EM-DAT focuses only on large catastrophic events with at least ten fatalities, 100 affected people, a call for international assistance, or the declaration of a state of emergency. This leads to an underestimation of total fatalities, a problem also stated by Petley (2012). Furthermore, this issue causes an underappreciation of natural hazard processes with a high percentage of single-fatality events (Table 4).

Worldwide, EM-DAT registered a total of 5 million fatalities, including those due to earthquake (1.51 million, 30.1%), mass movement (0.06 million, 1.2%; including landslide, avalanche, rockfall and subsidence), flood (2.48 million, 49.2%) and storm (0.98 million, 19.5%) for the period of 1946 to 2015. Normalized by population (UN, Department of Economic and Social Affairs, Population Division, World Population Prospects, the 2015 Revision, http://esa.un.org), this results in a mean yearly mortality rate of 19 victims per million people (earthquake 4.6, flood 11.4, mass movement 0.2, storm 3.2). This rate is much higher compared to the average annual mortality rate determined in our study for Switzerland (overall 2.5 fatalities per million population and year; flood 0.29, landslide 0.16, rockfall 0.20, storm 0.24, lightning 0.42, avalanche 0.96, other 0.23; Table 1).

With the different data collection methods in mind, explanations for these differences could be that most events that occurred in Switzerland during our study period did not cause more than ten fatalities (all but five events, Table 4). Due to the geographical location of the study area, some very deadly hazard processes, such as tropical storms, did not occur. Further, even though severe earthquakes are possible in Switzerland and have been observed historically, only three such fatalities (all in 1946) were registered. Furthermore, Switzerland exhibits a considerable network of protection measures and a well-developed risk management system (see section 5.3). These tactics probably additionally help to keep natural hazard mortality rates low in comparison to other regions of the world, particularly less privileged ones (e.g. Bründl et al., 2004; Lateltin et al., 2005).

Higher flood mortality rates compared to Switzerland have been reported for Texas (1.08 fatalities per million population per year) as well as several other US states (Sharif et al., 2015) and also for India (1.5; Singh and Kumar, 2013). Coates (1999) found a large decrease in the flood mortality rate in Australia, from 239.8 in the 1800's to 0.4 in the 1990's. Also, a decreasing frequency of fatalities due to landslides was found in Italy, with 1.8 fatalities per million population per year in 1950 and 1.4 in 1999 (Guzetti, 2000). The average annual rate of fatalities due to lightning we found for Switzerland was similar to that reported for the USA (0.42; Curran et al., 2000) and considerably lower than that reported for India (approximately 2.5-3.0; Illiyas et al., 2014). However, reports from India differ substantially with other authors recently suggesting much lower mortality rates based on essentially different data sources (0.25; Singh and Singh,

674 2015). The decrease in lightning related fatalities we found over the last 70 years has also been observed in
675 the USA (López and Holle, 1996) and in England and Wales (Elsom, 2001). In a comparative global
676 summary of published lightning fatality estimates, Singh and Singh (2015) listed a value for 19th century
677 Switzerland of 6.0 deaths per million population per year, which is more than ten times the value estimated
678 in our study. Even though this figure was based on only two years of data (1876-1877), it illustrates the
679 various improvements (e.g. better medical care, increased awareness) and the socio-economic changes that
680 have occurred in Switzerland over the past 150 years.

681

682 The numbers reported in this section are rough estimates of mortality rates because they are based on the
683 entire population of a political entity. This may lead to a considerable underestimation of the actual
684 mortality rate at a given location. In an alternative approach to better reflect local or regional mortality
685 rates, we applied a 10x10 km raster grid that related fatalities to the actual resident population in a given
686 grid cell (Figure 9). This method reveals areas in Switzerland, mostly located in high-alpine environments
687 that have mortality rates that are much larger than the average value of 2.5 fatalities per million people and
688 year. A total of 60 cells (out of 485) display values larger than 30 fatalities per million people and year, and
689 22 cells have rates larger than 150 fatalities per million people and year. This method has considerable
690 shortcomings. The main difficulty is that dependent on the process, other parts of the grid cell are at risk.
691 For example, in grid cells located in the Alps, only a small fraction of the people assigned to this cell really
692 live in or enter a given hazard process zone (e.g. an avalanche zone). Moreover, only approximately half of
693 all fatalities occurred close to or in the victim's place of residence or the victim's municipality. In many
694 cases the natural hazard victims were killed at a large distance from their home, or the victims were from
695 another Swiss region or a foreign country. This confirms that it is very difficult to assess an accurate natural
696 hazard mortality rate. Finally, because gridded population data has only become available recently, it has to
697 be kept in mind that by using current data, the resulting gridded mortality rates (Figure 9) represent a
698 considerable underestimation (Swiss population has been increasing considerably since the middle of the
699 last century). This also supports our statement that mortality data has to be regarded as a proxy and should
700 be treated with caution.

701 **5.7 Comparison of natural hazard fatality data with data from other accidental deaths**

702 In his recent contribution, Goklany (2007) assessed death and death rates due to extreme weather events,
703 such as extreme heat, extreme cold, floods, lightning, tornados and hurricanes. This analysis indicated that
704 globally, as well as for the USA, the aggregate contribution of extreme weather events to overall mortality
705 is relatively small, ranging from 0.03% (globally) to 0.06% (USA).More specifically, the global
706 contribution of fatalities due to extreme weather events to all accidental deaths is also quite small (0.4%).
707 For example, based on EM-DAT data for 2000-2006 and World Health Organization data for 2002,
708 Goklany (2007) showed that, while roughly 20,000 people per year die during extreme weather events,
709 many more are killed in road traffic accidents (approx. 1.2 million people in 2002).

710

711 The natural hazard processes considered in the study mentioned above are not exactly the same as in the
712 present study (e.g. heat waves were not considered here and mass movements probably were not included
713 in Goklany, 2007) and the two study periods differ. Nevertheless, Goklany's point also applies to our Swiss
714 analysis: fatalities and mortality rates from the different hazard processes studied in the present paper are
715 relatively low. A comparison of our data with Swiss road and railroad accident fatality data (Swiss
716 Statistics, www.bfs.admin.ch) confirms the ratio suggested above at the global level. For the same 70-year
717 time frame from 1946 to 2015, a total of 64,561 people died on Swiss roads during traffic accidents. This
718 corresponds to an average value of 922 fatalities per year, with a maximum of 1773 deaths in 1971 and a
719 minimum of 243 deaths in 2014. Thus, on average for our study period, more than sixty times as many
720 people were killed in traffic accidents than by natural hazards. Swiss railroad fatalities also clearly
721 outnumbered natural hazard related fatalities, although to a lesser extent than traffic fatalities (4871 victims
722 from 1946 to 2014, corresponding to roughly five times the number of natural hazard related deaths). Note
723 that both road and railroad fatality numbers show a distinct decrease in Switzerland since the 1970s, similar
724 to the natural hazard fatality data presented here (Figs. 3 and 5).

725

726 Comparing the presented fatality numbers with those of recreational accidents in mountainous terrain,
727 which were not considered in our study, shows similar patterns (see section 3.4). For instance, data from
728 the Swiss Alpine Club (SAC, www.sac-cas.ch) show that mountaineering accidents (e.g. mountaineering,
729 hiking, climbing, canyoning) caused by lightning and rockfall led to 62 fatalities from 2000 to 2013,
730 compared to 21 fatalities in our database for the same two processes (with six fatalities appearing in both
731 data sources). Comparable patterns exist for avalanche fatalities: during the last twenty years (1995/96-
732 2014/15), 15 times more people lost their life during recreational activities in unsecured backcountry terrain
733 than in settlements or on transportation corridors in Switzerland (Techel et al., 2015). On a larger spatial
734 scale covering the entire European Alps, this proportion is even more pronounced (a factor of
735 approximately 30 for the 15 years from 2000/01 to 2014/15; Techel et al., 2016). In the vast majority of
736 cases, victims in unsecured terrain triggered the avalanche themselves (e.g. Schweizer and Lütschg, 2001),
737 as opposed to fatalities caused by avalanches in settlements and on transportation routes, where most
738 avalanches released naturally (85% of the avalanche victims reported in the present study were killed by
739 naturally triggered events).

740 **6. Conclusions**

741 In this study, we compiled data from the Swiss flood and landslide database, the destructive avalanche
742 database, and information collected in an in-depth newspaper search to establish a new database of fatalities
743 caused by natural hazard processes in Switzerland. For a 70-year period from 1946 to 2015, we were able
744 to assemble detailed data on 635 events during which 1023 people were killed by processes we summarized
745 into seven hazard types (flood, landslide, rockfall, lightning, windstorm, avalanche, and *other* processes).

746 Fatalities that occurred in connection with high-risk sports or certain popular summer and winter outdoor

747 sport activities were not considered. Snow avalanches claimed 378 victims and clearly represent the

748 deadliest natural hazard process in Switzerland. With 164 deaths, less than half as many fatalities were

749 caused by lightning. Floods, windstorms, rockfall events and landslides killed 124, 105, 85 and 74 people,

750 respectively.

751

752 Natural hazard fatalities were considerably variable over time. The number of people who died in one

753 single year varied by one to two orders of magnitude. In 1951 and 1965, fatal events resulted in 112 and

754 108 deaths, respectively, whereas five years had only two fatalities each. For the 70-year study period, the

755 average and median number of people who died due to natural hazards amounted to 14.6 and 9.0,

756 respectively. Annual loss of life data showed a decrease over time, which was primarily induced by a

757 marked decrease in deaths due to avalanches and lightning strikes. The reduction in avalanche fatalities in

758 settlements and on transportation routes is a trend that has also been observed in other European countries

759 and elsewhere. The decrease is due to improvements in both technical (defence structures, preventive

760 artificial release) and organizational (e.g. hazard mapping, emergency planning) measures and to

761 significant progress in avalanche education and forecasting. A reduction in lightning victims during the last

762 century also occurred in many other countries around the world. In Switzerland, the main reasons for this

763 distinct decrease might be that today fewer people work outdoors and there is a much improved awareness

764 of the threat posed by lightning.

765

766 Most people were killed by natural hazard events in summer (JJA, 41.7% of fatalities) and winter (DJF,

767 32.2%). Accordingly, the four months with the largest number of victims were August (20.2%), January

768 (14.2%), February (13.2%) and July (12.9%). While the summer peak mainly occurred due to flood and

769 lightning events (together with one catastrophic ice avalanche in August 1965), the winter peak was caused

770 by snow avalanche incidents. Furthermore, almost two thirds of the fatalities took place in the afternoon

771 and evening.

772

773 Natural hazard fatalities were quite homogenously distributed over Switzerland. However, mountainous

774 parts of the country (Prealps, Alps) were somewhat more prone to fatal events compared to the Swiss

775 Plateau and the Jura. The reason for this is that avalanche fatalities, and to a slightly lesser extent rockfall

776 and landslide fatalities, occur mainly in the alpine parts of Switzerland. In contrast, deadly events

777 associated with floods and lightning were observed in practically all regions of Switzerland, with a definite

778 maximum occurring along the Swiss Plateau. Finally, windstorm related fatalities were mostly observed on

779 the Swiss Plateau, especially on lakes.

780

781 The age groups with the largest number of natural hazard victims were the 20-29 and 30-39 year-old groups

782 (172 and 177, respectively), and almost 50% of all victims were between 20 and 49 years of age. Young

783 children (0-9 years of age) were the age group that was most underrepresented in the fatality data compared
784 to the Swiss age distribution. Three quarters of all fatalities were men, and men outnumbered women in all
785 process types except landslides. We assume that this large gender difference was strongly influenced by
786 two factors: first and probably more importantly, virtually all work related fatality incidents involved
787 physically difficult occupations that put workers at risk and where the majority of workers are men; second,
788 we speculate that women have a considerably higher risk perception compared to men and that,
789 accordingly, men have a greater disposition towards risk taking than women. Both of these points are
790 (probably) especially relevant for the first half of the study period.

791

792 Large catastrophic events with several hundreds of fatalities have occurred in Switzerland in the last 1000
793 years (e.g. Basel earthquake of 1356, Goldau rock avalanche of 1806), but not during the period studied
794 here. Apart from the tragic Mattmark ice avalanche of 1965 that killed 88 people, only one landslide and
795 three avalanche events caused more than ten victims in the period from 1946 to 2015. Together, these five
796 incidents led to 161 deaths, which correspond to 15.7% of all fatalities in the data set. Hence, single-fatality
797 events (that account for approximately half of the total natural hazard deaths) and events with up to a few
798 victims strongly influence the natural hazard fatality statistics in the recent past. For some process types,
799 such as lightning and rockfall, this influence is particularly strong. When compared with natural hazard
800 mortality rates in other countries or with accidental deaths from other causes in Switzerland, the fatality
801 numbers presented here are quite low. For example, traffic accidents kill an average of approximately 60
802 times more people than natural hazard events. Nevertheless, we think that current annual natural hazard
803 fatality numbers can still be further reduced by investing in and further developing both structural and
804 organizational (e.g. alarm systems, emergency planning, hazard awareness creation) protection measures.
805 The data set (and analysis) presented here can be used by decision makers at different political levels
806 (municipal, cantonal and federal authorities) to plan and implement such measures.

807

818   **References**

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1012   Table 1: Natural hazard fatalities in Switzerland (1946-2015) classified by gender.

1013

Process type	Total fatalities		Normalized fatalities	Female fatalities		Male fatalities		Gender unclear	Percent female deaths	Percent male deaths	Altitude (A)
	[deaths]	[%]	[deaths 10^{-6} a^{-1}]	[deaths]	[%]	[deaths]	[%]	[deaths]	[%]	[%]	[m a.s.l.]
Flood	124	12.1	0.29	31	12.8	92	11.9	1	25.0	74.2	559
Landslide	74	7.2	0.16	33	13.6	41	5.3	0	44.6	55.4	820
Rockfall	85	8.3	0.20	21	8.7	64	8.2	0	24.7	75.3	1082
Windstorm	105	10.3	0.24	25	10.3	79	10.2	1	23.8	75.2	431
Lightning	164	16.0	0.42	33	13.6	130	16.8	1	20.1	79.3	692
Avalanche	378	37.0	0.96	92	38.0	285	36.7	1	24.3	75.4	1467
Other	93	9.1	0.23	7	2.9	85	11.0	1	7.5	91.4	2081
All processes	1023	100	2.50	242	100	776	100	5	23.7	75.9	1179

1014

1015   (A) Note that for snow avalanches only, the altitude of the lowest deposition point was used for technical reasons, which might lead to a slight

1016   underestimation in comparison with the other processes.

1017

1018   Table 2: Natural hazard fatalities in Switzerland (1946-2015) classified by victims' activity, accident locality and victims' mode of transport.

1019

		Flood	Landslide	Rockfall	Windstorm	Avalanche	Lightning	Other	All processes	All processes [%]
Activity	work	35	13	15	24	110	70	88	**355**	**34.7**
	leisure time	73	40	40	52	245	82	4	**536**	**52.4**
	other/unclear	16	21	30	29	23	12	1	**132**	**12.9**
	total	**124**	**74**	**85**	**105**	**378**	**164**	**93**	1023	100
Locality	in or around a building	14	40	8	4	192	33	2	**293**	**28.6**
	on transportation routes	31	20	58	34	164	28	1	**336**	**32.8**
	in open terrain	4	11	14	9	4	95	1	**138**	**13.5**
	on a lake			1	44		1		**46**	**4.5**
	in a stream channel	63	2						**65**	**6.4**
	other/unclear	12	1	4	14	18	7	89	**145**	**14.2**
	total	**124**	**74**	**85**	**105**	**378**	**164**	**93**	1023	100
Mode of transport	on foot	77	22	51	36	78	112	90	**466**	**61.6**
	in vehicle	20	11	27	20	46	14		**138**	**18.2**
	by boat	5			44		1		**50**	**6.6**
	by ski					49			**49**	**6.5**
	by bicycle	3			1		6		**10**	**1.3**
	by public transport	1	1			4			**6**	**0.8**
	other/unclear	9	0	2	4	16	5	2	**38**	**5.0**
	total [A]	**115**	**34**	**80**	**105**	**193**	**138**	**92**	757	100

1020

1021   [A] Note that 266 fatalities that occurred in buildings are not considered in this section (mode of transportation)

1022

1023   Table 3: Quality of the data describing the circumstances of fatal natural hazard events and the victims (certain = information regarding this variable is fully

1024   reliable; probable = information regarding this variable was deduced but is very probable; unknown = no information available).

1025

	Certain		Probable		Unknown		Total
	[no. of deaths]	[%]	[no. of deaths]	[%]	[no. of deaths]	[%]	[no. of deaths]
Date of event	965	94.3	58	5.7	0	0.0	1023
Time of event	558	54.5	360	35.2	105	10.3	1023
Gender	1015	99.2	3	0.3	5	0.5	1023
Age	938	91.7	16	1.6	69	6.7	1023
Activity	788	77.0	107	10.5	128	12.5	1023
Locality	898	87.8	101	9.9	24	2.3	1023
Mode of transportation [(A)]	541	71.5	181	23.9	35	4.6	757

1026

1027   [(A)] Note that 266 fatalities that occurred in buildings are not considered in this row (mode of transportation)

1028

1029

1030 Table 4: Fatal natural hazard events in Switzerland (1946-2015) classified by number of victims. The last two columns indicate the percentage of people that died
1031 in single fatality events (second to last column) and in events with more than ten deaths (last column); note that in the bottom row 100% corresponds to 1023
1032 deaths for all process types.

1033

	Number of events with *n* deaths					All fatal events	Percent of people killed in events where *n*=1	Percent of people killed in events where *n*>10
	n=1	*n*=2	*n*=3	4≤*n*≤10	*n*>10			
							[%]	[%]
Flood	97	9	3	–	–	109	78.2	0.0
Landslide	23	13	2	1	1	40	31.1	17.6
Rockfall	68	4	–	2	–	74	80.0	0.0
Windstorm	74	10	1	2	–	87	70.5	0.0
Lightning	144	10	–	–	–	154	87.8	0.0
Avalanche	99	27	18	20	3	167	26.2	15.9
Other	2	–	1	–	1	4	2.2	94.6
All processes	**507**	**73**	**25**	**25**	**5**	**635**	**49.6**	**15.7**

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1038 **Figure 1: Study area showing the Swiss stream network, the Swiss cantons (red polygons with abbreviations, see**
1039 **www.bfs.admin.ch/bfs/portal/en/index/dienstleistungen/premiere_visite/03/03_02.html), the geomorphologic-climatic regions Jura, Swiss Plateau, Prealps and Alps**
1040 **(areas with different background colours), and several key cities (DHM source: dhm25 © 2016 swisstopo (5704 000 000)).**
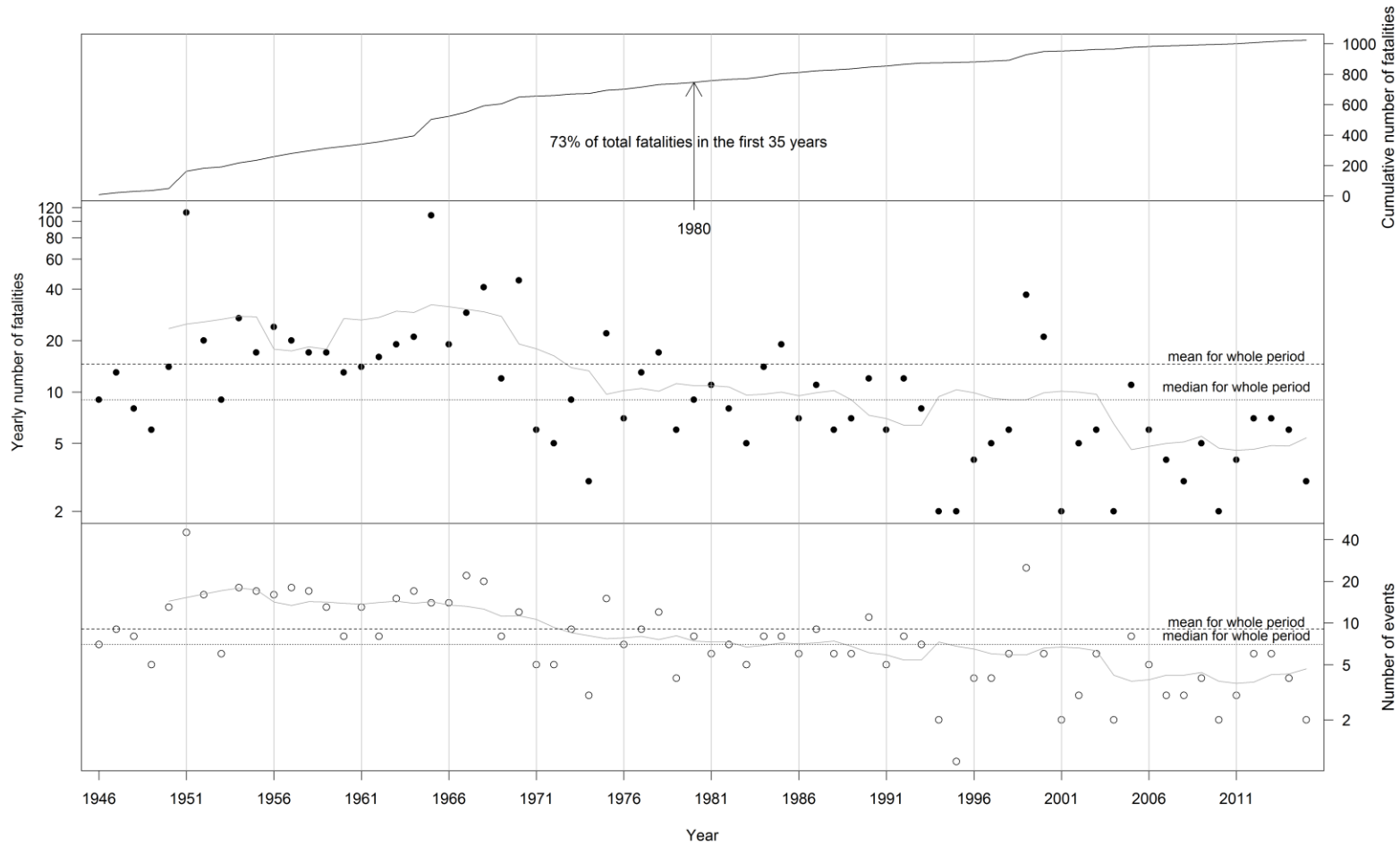
Figure 2: Total number of natural hazard deaths in Switzerland from 1946 to 2015: Cumulative number of fatalities (top) and annual frequency of fatalities (middle). At the bottom of the figure, the number of fatal natural hazard events is displayed. The dashed and dotted horizontal lines in the middle and bottom panels indicate the mean and median annual fatality frequencies and mean and median annual event frequencies, respectively. The thin grey lines in the middle and bottom panels show a 10-year running mean.
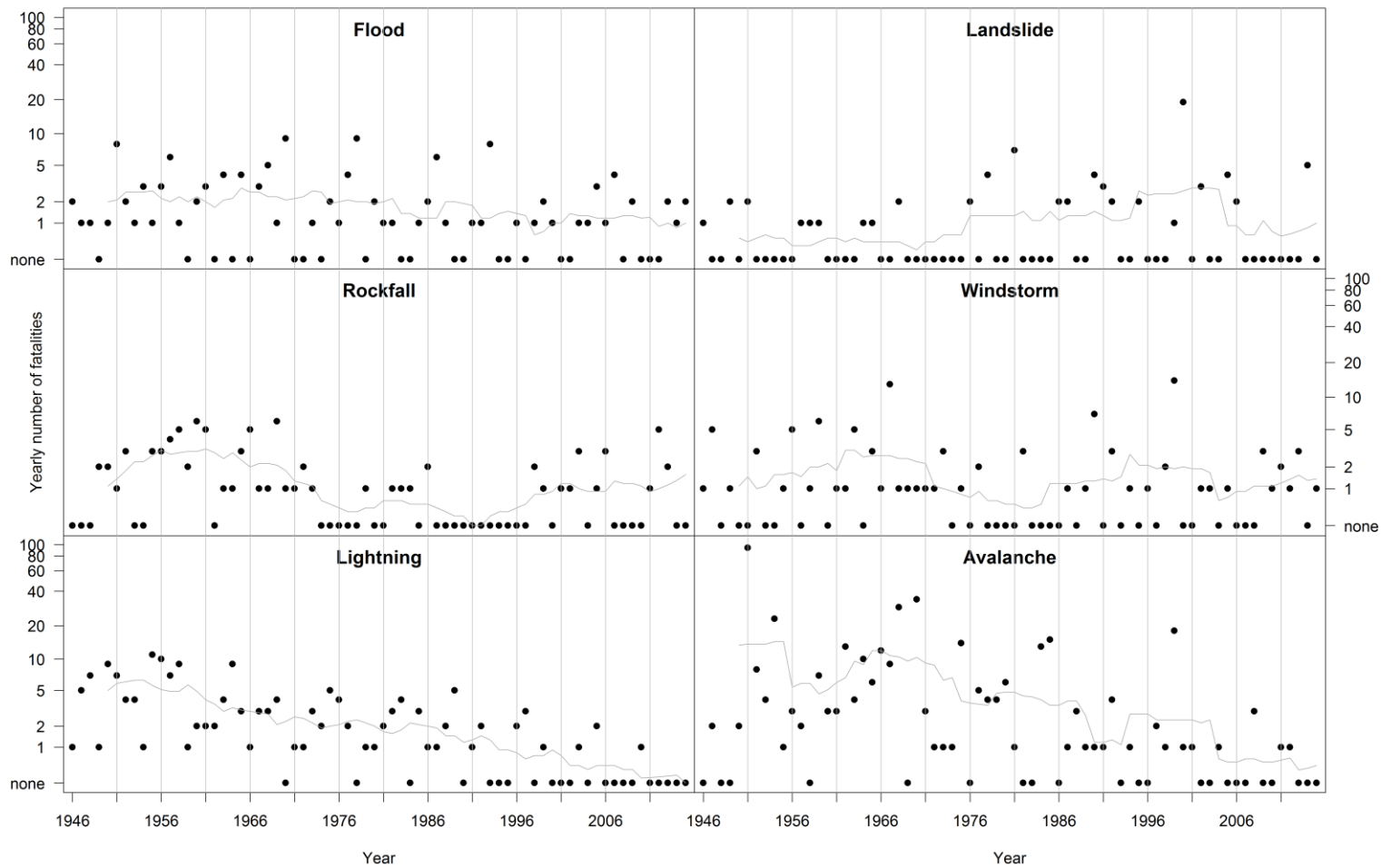
1046

Figure 3: Annual frequency of fatalities in Switzerland for the different natural hazard categories considered in this study (except the category other). The thin grey
lines in all panels the show a 10-year running mean. Note that years with no fatalities were assigned an arbitrary value of 0.5 for plotting purposes and are labelled
"none" on the y-axis.
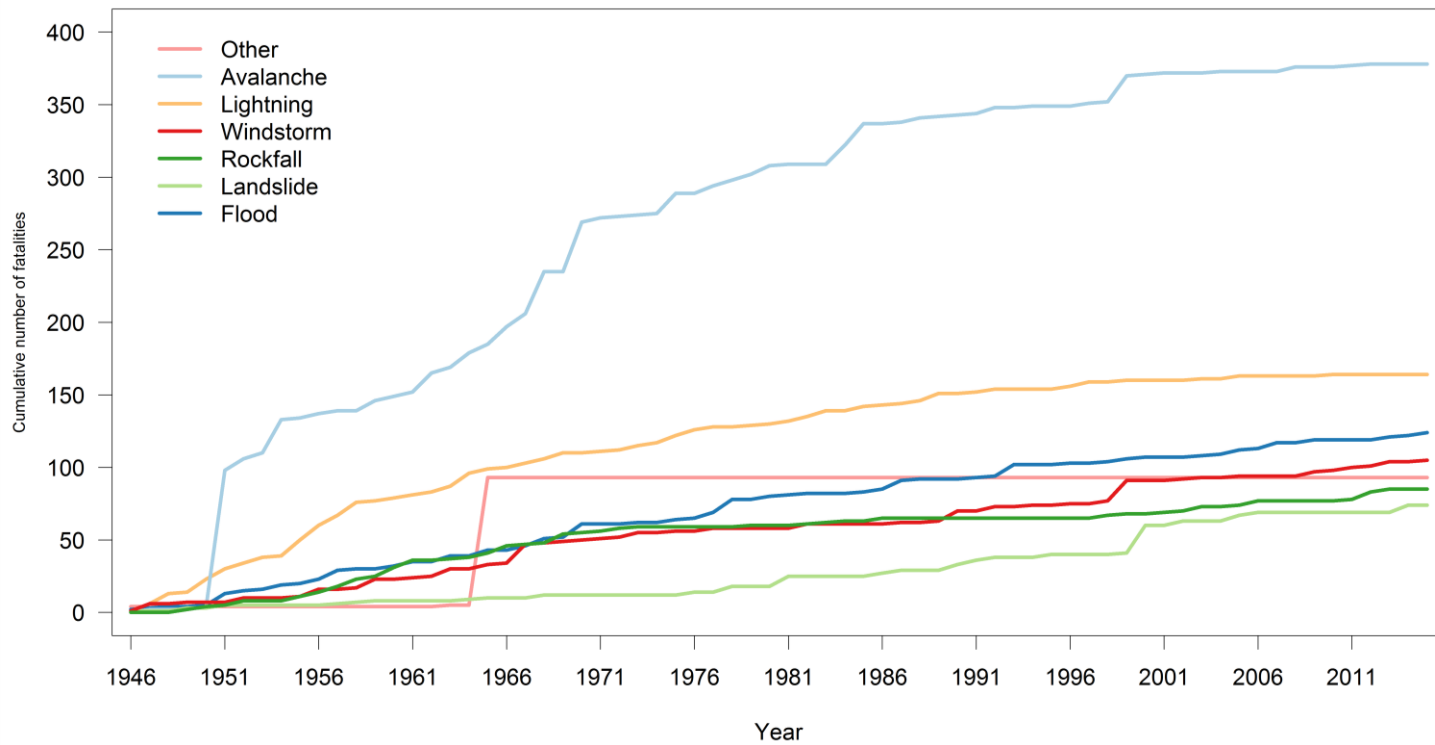
1050
1051   **Figure 4: Cumulative plot of the number of natural hazard deaths in Switzerland from 1946 to 2015 for the different natural hazard categories considered in this study.**

1052

1053
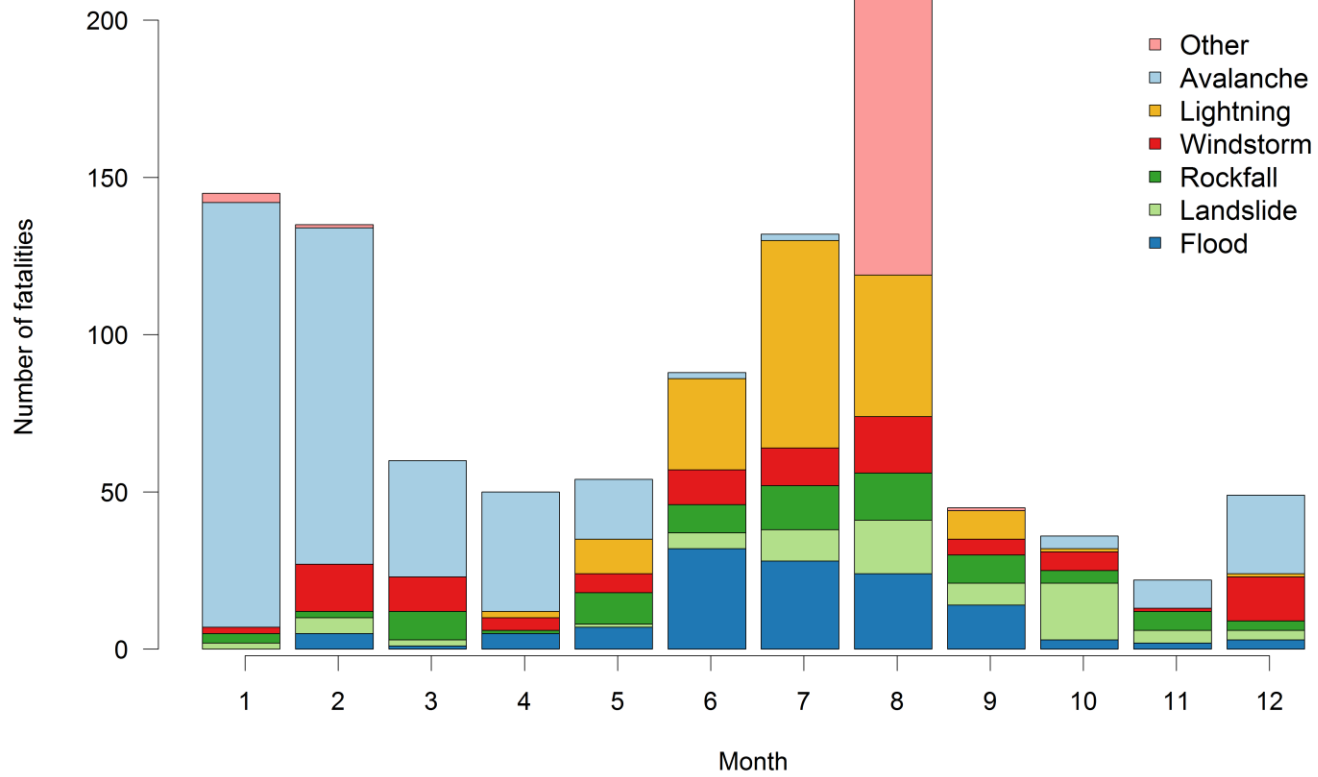
1054

1055 **Figure 5: Monthly distribution of natural hazard fatalities in Switzerland from 1946 to 2015 (sum over study period). The different colours indicate the seven process**
1056 **categories defined for this study.**
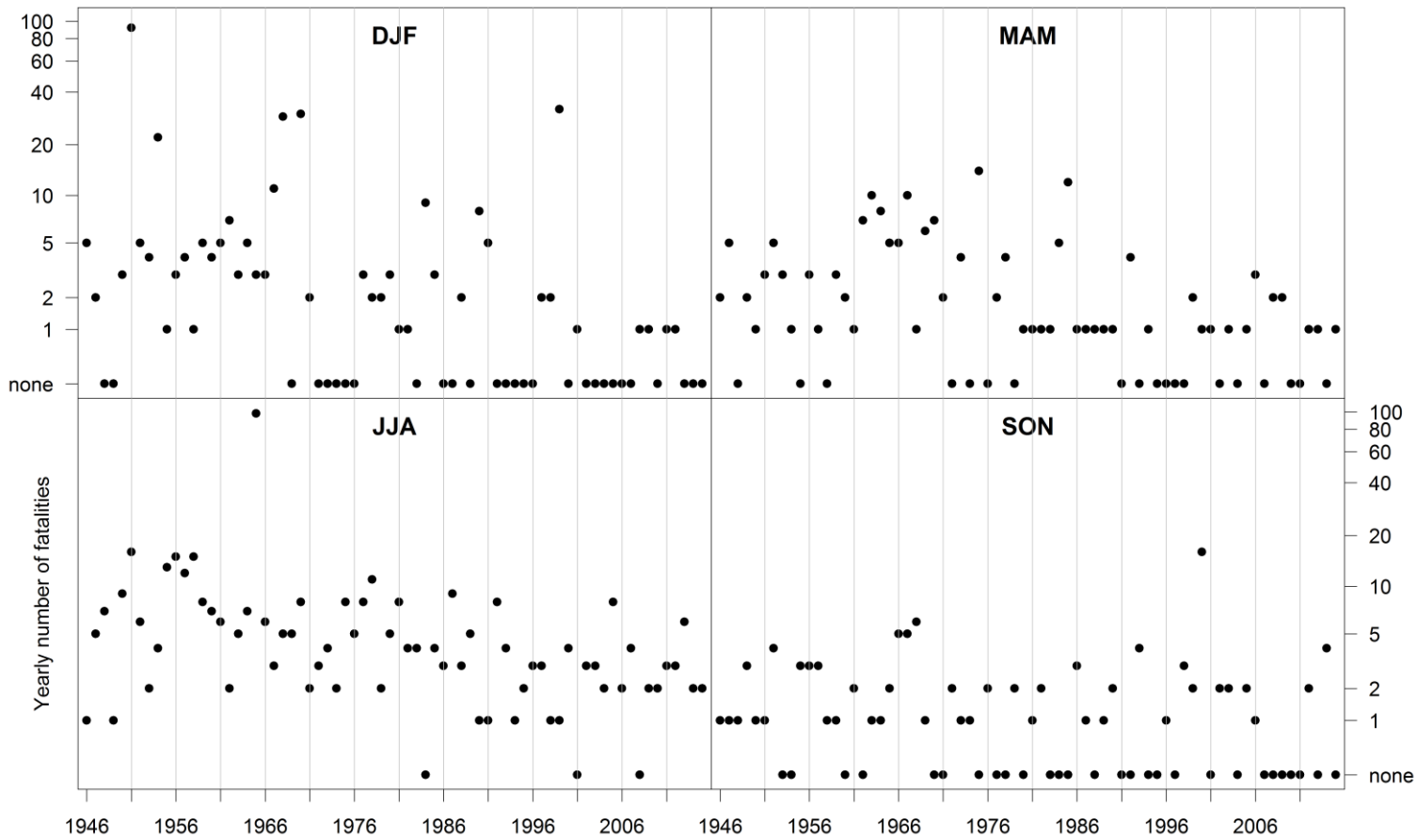
1057

Figure 6: Annual frequency of total natural hazard fatalities in Switzerland from 1946 to 2015 for the four northern hemisphere seasons winter (DJF, top left), spring (MAM, top right), summer (JJA, bottom left) and autumn (SON, bottom right). Note that years with no fatalities in a certain season were assigned an arbitrary value of 0.5 for plotting purposes and are labelled "none" on the y-axis.
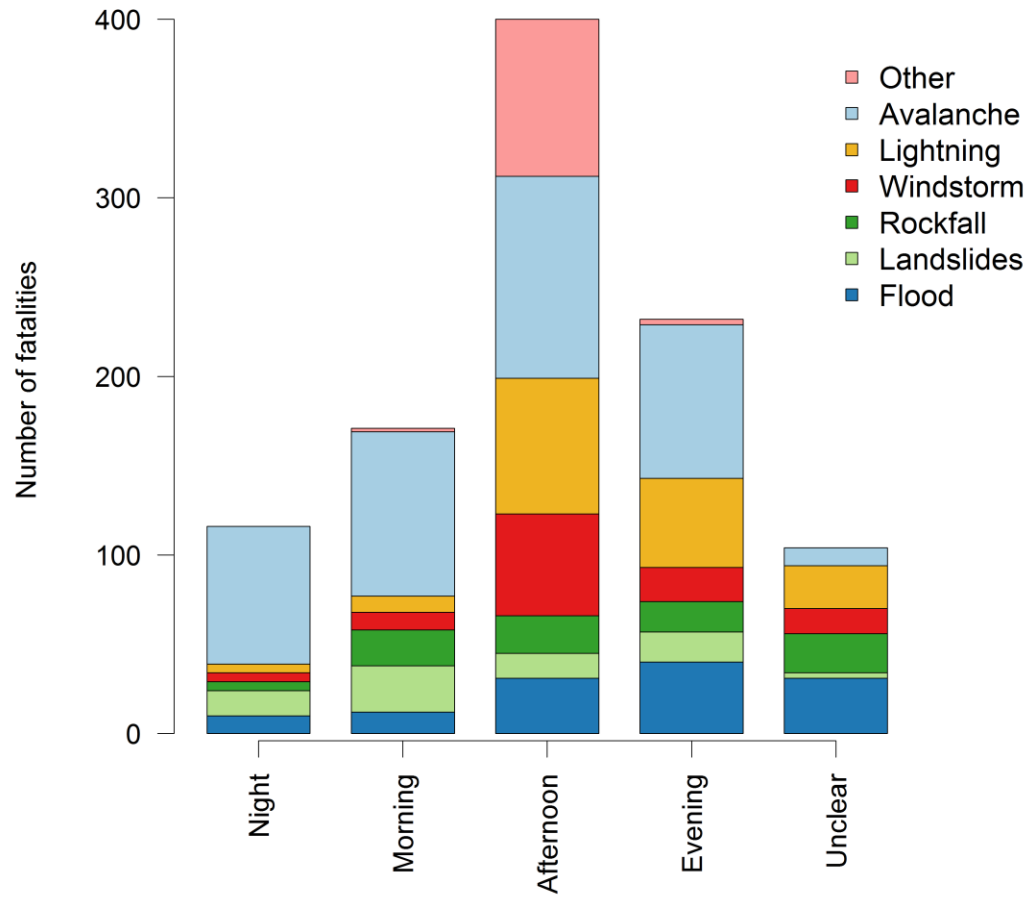
Figure 7: Distribution of natural hazard fatalities in Switzerland from 1946 to 2015 by time of day (sum over study period); morning (06:00-11:59 local standard time), afternoon (12:00-17:59), evening (18:00-23:59) and night (00:00-05:59). The different colours indicate the seven process categories defined for this study.

Hazard process
- Other
- Avalanche
- Lightning
- Windstorm
- Rockfall
- Landslide
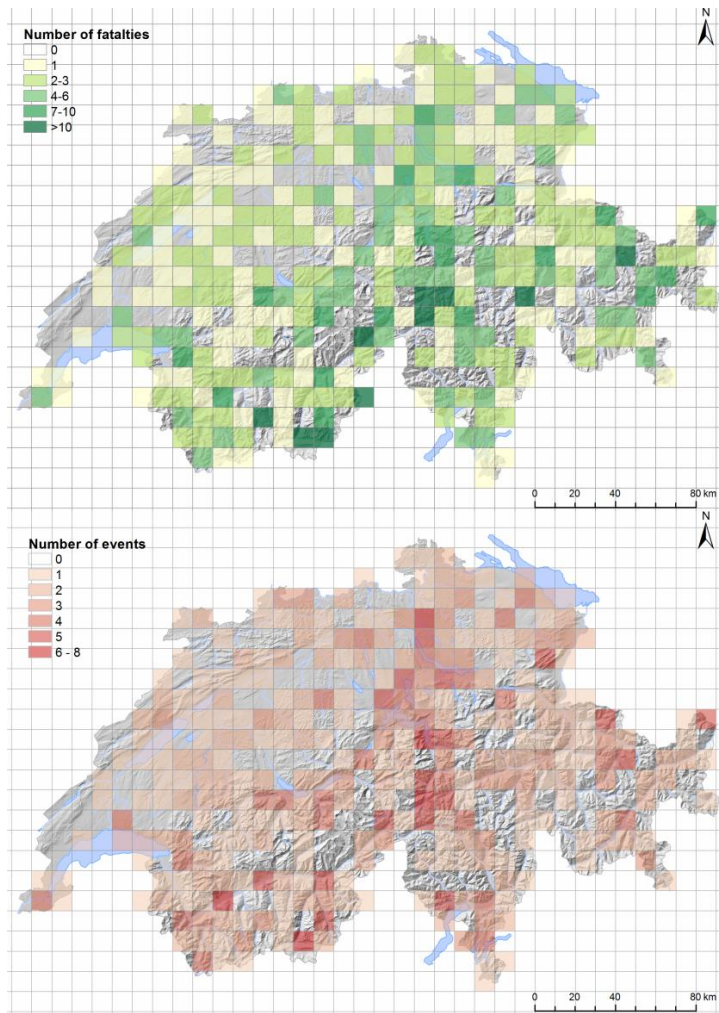- Flood

Number of fatalities
- 1
- 2-5
- 6-15
- 16-30
- >30

0   25   50   100km
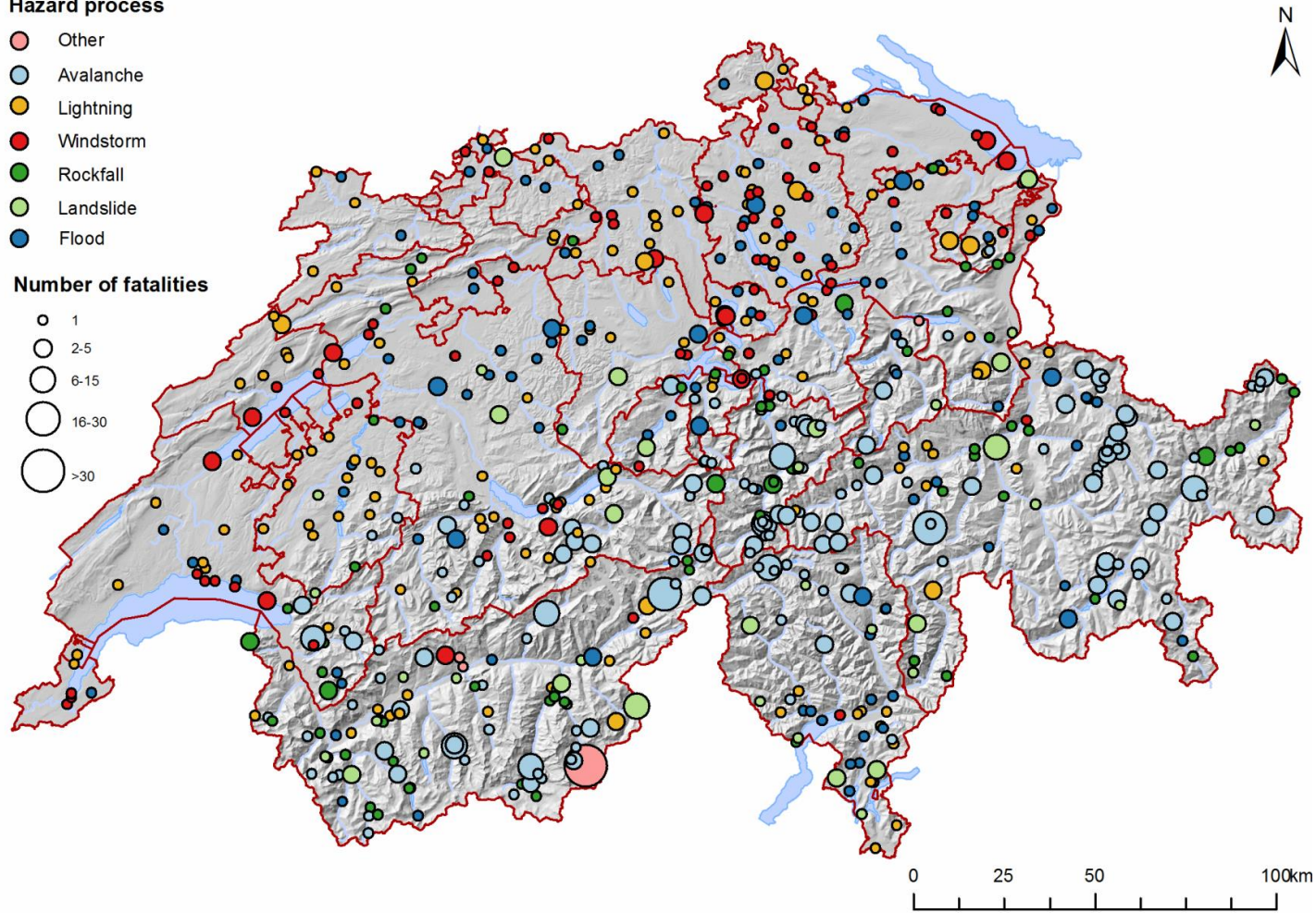
1065

1066 **Figure 8: Spatial distribution of fatalities caused during natural hazard events in Switzerland from 1946 to 2015. The colour of each data point indicates the process**
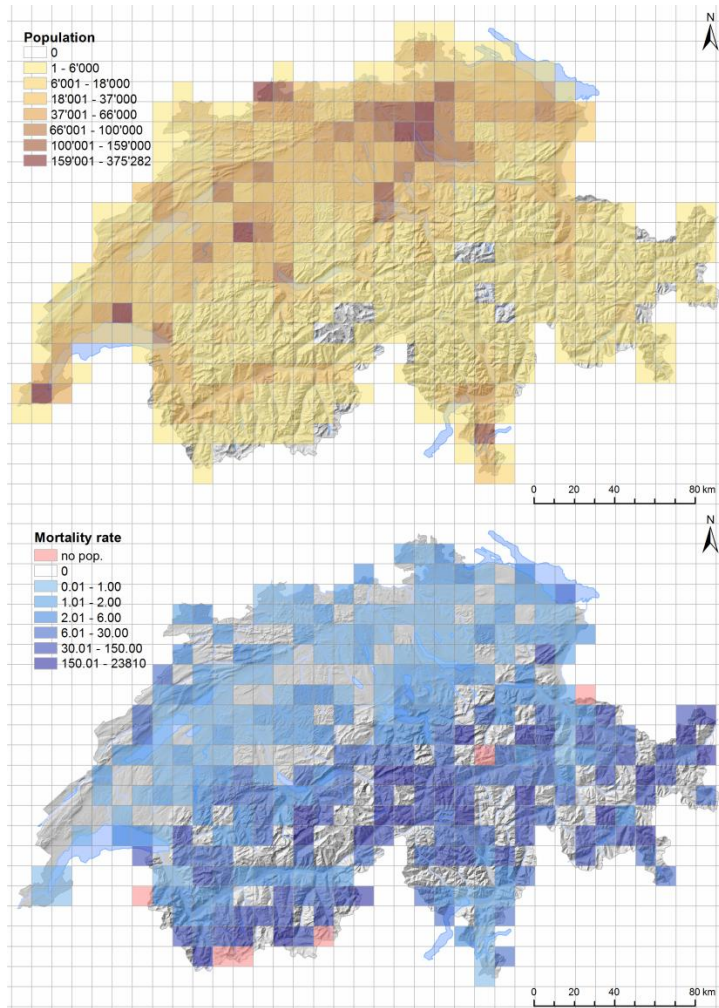1067 **type, and the size of the symbol shows the number of deaths per fatal accident (DHM source: dhm25 © 2016 swisstopo (5704 000 000)).**

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1069

Figure 9: Spatial distribution of natural hazard fatalities (above) and fatal natural hazard events (below) in Switzerland over the 70-year study period using a 10x10 km raster grid (DHM source: dhm25 © 2016 swisstopo (5704 000 000)).

Figure 10: Spatial distribution of population as of 2015 (above) and normalized natural hazard fatalities per year and million population (below) in Switzerland over the 70-year study period using a 10x10 km raster grid (DHM source: dhm25 © 2016 swisstopo (5704 000 000)). Note that the gridded mortality rate (below) represents a rough estimate because the population data of 2015 was used for its calculation (prior data not available in this format). Also, note that no mortality rate was calculated for the red grid cells because they are not populated (even though fatalities occurred there).
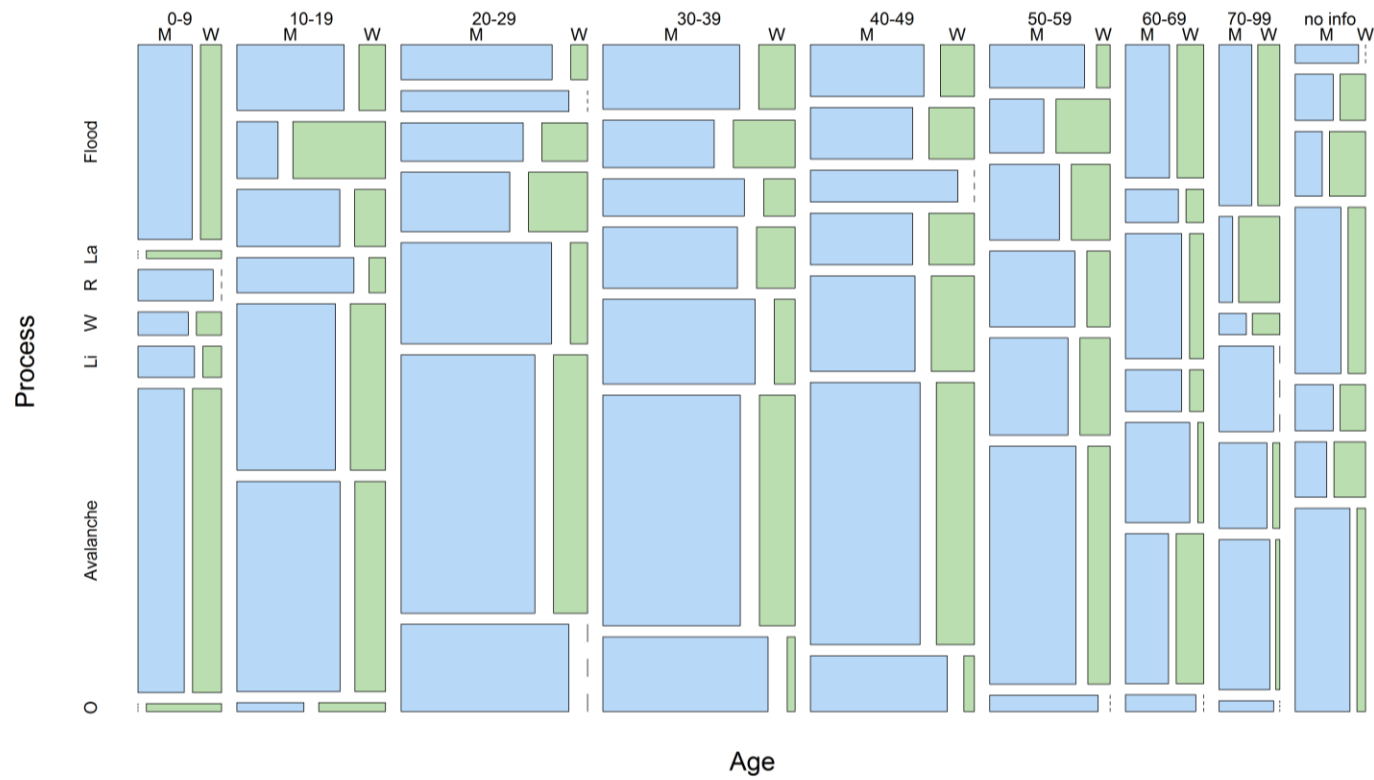
1077
1078 **Figure 11: Mosaic plot showing age groups and gender for natural hazard fatalities in Switzerland (1946-2015). Fatalities are subdivided according to the hazard type**
1079 **(flood, La=landslide, R=rockfall, W=windstorm, Li=lightning, avalanche, and O=other). Also see Table S2 in the supplementary material.**

1080
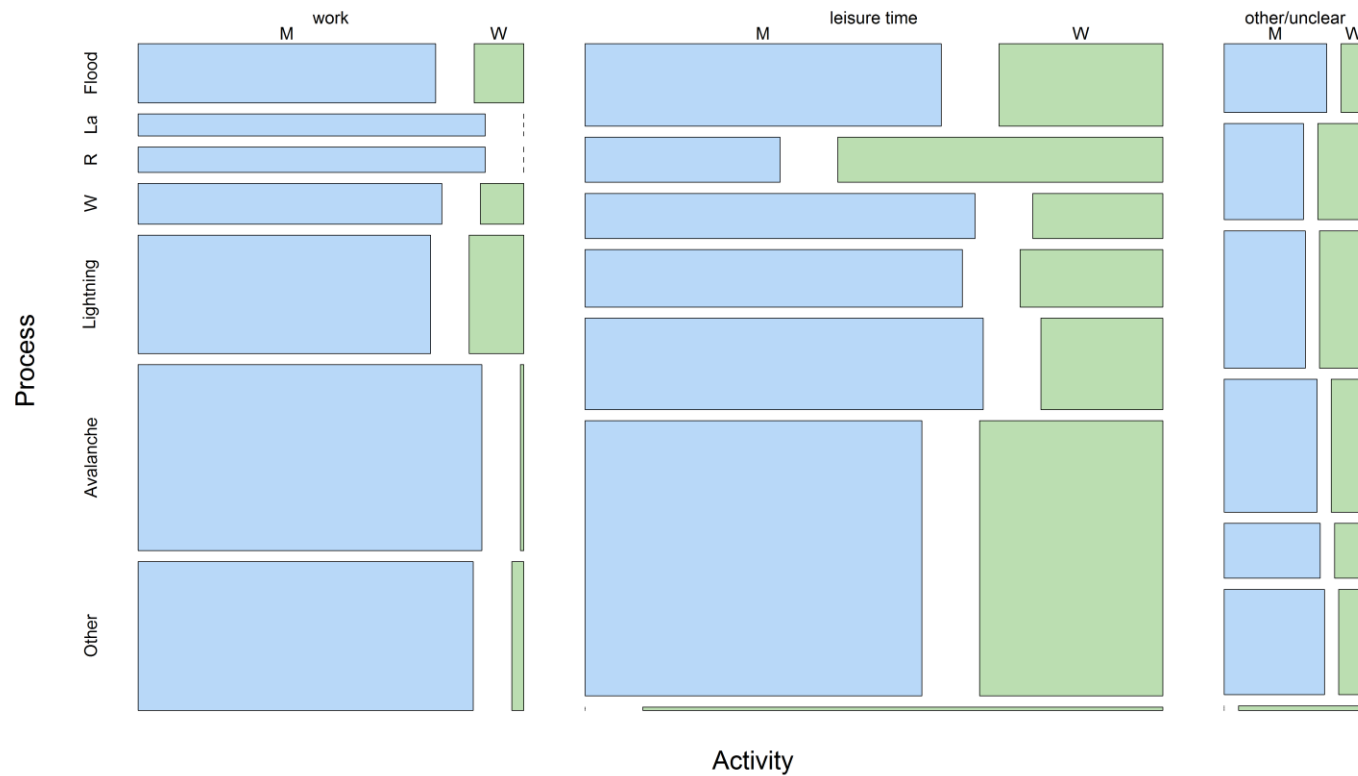
Figure 12: Mosaic plot showing victim's activity and gender for natural hazard fatalities in Switzerland (1946-2015). Fatalities are subdivided according to the hazard type (flood, La=landslide, R=rockfall, W=windstorm, lightning, avalanche, and other). Also see Table 2.