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Submission of revised manuscript nhess-2016-232

Dear Dr. S. Fuchs

Dear Sven

please consider the revised version of our manuscript "Natural hazard fatalities in Switzerland from 1946 to 2015" for publication in Natural Hazards and Earth System Sciences.

We have addressed all the comments of the two referees and provide detailed responses and information on the changes made in the manuscript. If requested, we can gladly provide a version of the revised manuscript with highlighted track changes to assist in identifying all changes.

Thank you for considering our article for publication in NHESS.

Yours sincerely,

Alexandre Badoux
and co-authors

Reply to referee #1

We thank referee #1 for her/his detailed and insightful comments on our manuscript nhess-2016-232. Below we give detailed replies to the annotations and briefly outline the changes made in the manuscript.

2. Major point of criticism

1) The use of the whole population to calculate mortality rates is (technically and methodologically) misleading and may lead to a strong underestimation of the mortality rate. Although it is used by many authors working on that topic I think using a better suited definition of the population would greatly enhance the value of the study. To put it in a different manner: imagine a building with three floors. In the third floor, which is hermetical separated from the other two floors, a laboratory is situated in which new and highly deadly poison is tested. If there is an accident the poison would only spread in the third floor. Calculating now the mortality rate based on the all the people in the building would underestimate the real risk because only those working on the third floor are at risk.

We acknowledge this point. Certainly, the difficulty is that dependent on the process, other parts of the population are at risk. Here, maybe a regular grid raster as proposed in comment # 2 could be a solution. In this approach only a part of the population (according to the grid cell) will be used to calculate the mortality rates.

However, when using a grid raster, we see the following general shortcoming: A rough estimation of our data shows that approximately 55% of all fatalities occurred close to or in the victim's place of residence or the victim's municipality (unpublished data, since the acquisition was difficult). In 30-35% of the cases the victims were killed in large distance from their home or the victims were from a foreign country (for 10-15 % of the fatalities their origin was unknown or unclear). This shows that it is very difficult to come up with an adequate mortality rate, especially when choosing a high resolution grid (let's say with a resolution of a mean extent of a municipality).

We chose an approach using a regular grid raster. This choice is commented directly below in our response to the second major point of criticism of the referee and e.g. in our response to point 3.5 of this review.

2. The artificial political borders to agglomerate the data are a point that is directly related to this criticism, in geostatistics also well-known as MAUP. To analyze the spatial distribution of fatalities and the mortality rate, the authors should find a better solution (such as e.g. a regular grid raster).

We agree with the criticism of referee # 1. We considered the solution of using a regular grid to display the mortality rate. However, suitable population data for applying this approach is available only since the 1990ies (Swiss Statistics BFS). Older gridded population data is not available. Hence, we used the current data as a proxy for raster population 1946-2015. This is associated with a few problems such as (i) non-linear population growth; (ii) differences in population growth of different cantons; (iii) grid resolution (only roughly 55% of all fatalities occurred close to the place of residence, also see our response to the first major point of criticism of referee 1 above).

We produced a grid raster to show the mortality rate in Switzerland and used population data of the year 2015 (see new Figures 9 and 10). We deleted the original bottom paragraph of section 4.3 (in the Results chapter) of the manuscript that described the old Figure 8b. We replaced the text and now present a new paragraph that briefly describes the new Figure 10 (see also our response to point 3.5 of this review). Moreover, we added a detailed paragraph at the end of section 5.6 (in the Discussion chapter) to address the difficulties associated with the assessment of an adequate mortality rate.

3. Detailed review

3.1 Introduction

Here it would be of added value if the authors could also include results from other Alpine countries, since a comparison with mortality rates of e.g. the US or some least-developed countries does not seem to be very targeted. For Switzerland, also the works of Schneebeli et al. (1997), Laternser and Schneebeli (2002) or Wilhelm (1997, see Table page 76 based on Laternser et al. 1995) should be acknowledged. For Austria, examples include those of Oberndorfer et al. (2007) or Luzian and Eller (2007), Luzian (2002) or Fuchs (2009).

We agree with the referee and added references to studies carried out in Alpine countries at three locations: (i) in the second paragraph of the Introduction (studies at the regional/national scale); (ii) in a new short paragraph of the Introduction summarising previous work on avalanche fatalities; and (iii) in sections 5.3 and 5.5 of the Discussion.

3.1.1 Flood

Coastal floods where excluded from the analysis by Jonkman (2005) but the authors gave a reference to Chowdhury et al. how described a tidal surge caused by a cyclon which killed 67,000 people. Here I do not think that this reference is enough to give the statement enough confidence – there many other scientific reports about deaths caused by storm surges around that should be mentioned.

We see the referee's point. We added references to coastal floods or storm surges (e.g. Jonkman et al., 2009; Gerritsen, 2005; Kure et al., 2016) and to floods caused by tsunamis (e.g. Doocy et al., 2007; Inoue et al., 2007; Ando et al., 2013) to the introduction text.

3.1.2 Landslides

[…] the authors summarize an article from Dowling and Santo from the year 2014 which is explicitly focusing on debris flows. With 213 debris flows causing 77,779 fatalities the authors yielding an average of 365 fatalities per fatal debris flow. This extraordinary high number is caused by two massive events which make up nearly 50 percent of all fatalities recorded by the two authors. The median number may therefore better reflect the number of fatalities with 11 per fatal debris flow but also this number may still be very high, compared to the European Alps. To give an example, in Fuchs and Zischg (2013) an average of around 1.5 fatalities due to torrential processes is recorded annually for the Austrian Alps.

We added the comparison suggested by the referee between fatalities in torrential environments of developing and advanced (such as e.g. Austria, cf. Fuchs and Zischg, 2014) countries. The difference in median values is considerable.

The reference to the study about landslides in South America (Sepuleva and Petley 2005) may be deleted or more information on reported findings should be given. It would also be more convenient to refer to this study before Guzetti (2000) because of its spatial scale […]

We followed the advice of referee #1 and deleted the reference to the study by Sepúlveda and Petley (2005) here. This also helps to keep the introduction section reasonably short and concise.

3.1.1 Meteorological

Focusing on meteorological hazards, the authors are reporting studies about tornados and hurricanes on a *national level. Tornados are not very common in the study region of the authors. Referring to a report of the meteorological survey of Switzerland the frequency is one to five tornados per 10 years (0.1 to 0.5 per year) which is large enough to cause serious damage. In this report four tornados are described in more detail (1890, 1934, 1926, 1971) where three of them caused fatalities.*

We thank the referee for this interesting information. The MeteoSwiss report states that of the four especially serious events two caused fatalities in Switzerland (one death in 1926 and three in 1934) and one event killed several people in France (1890). The one event that lies within our study period (1971) did only cause light injuries. We added a sentence to the text stating that tornadoes have occurred in Switzerland in the past causing several fatalities.

3.1.4 Other

Because of the unimportance of hazards such as volcanic eruptions, earthquakes and tsunamis in Switzerland the author are not further considering geophysical hazards but mention an earthquake as an example of an extreme high death toll later in the discussion.

In connection with comment 3.8 of referee #1 (discussion on the historical events in Switzerland), we decided to delete section 5.6 of the Discussion (Comparison of recent Swiss natural hazard fatality data with historic data) and to integrate it in the sixth paragraph of the Introduction in a very condensed form.

3.2 Data

[…] Later in the discussion the authors were also talking about the drawbacks of the data collection. I would like to jump to that section (section 5.1 in the article) and express some of my concerns.
1. fatality not reported; 2. spatial bias because of the language of the newspaper; 3. wrong selection of keywords; 4. time spans with no newspaper available; 5. technical problems because of bad scans; 6. wrong hazard type
The authors then conclude, based on their validation strategy, that only a small fraction of 10% of all fatal hazard events were missed. At least three of the main reasons that impair the quality of the data are subject to the first 35 years of the time span analyzed. The validation was carried out for the years 1986 to 1995. If all newspaper of that period where already digitally available problem 5 could not occur. If there were no gaps also problem 4 would be underestimated. Finally problem 6 could also be of lesser importance than in the period before 1986. So maybe expanding the validation period could damp these concerns.

We agree that we could have chosen a different validation period (e.g. starting from 1972, which is the start of the Swiss Flood and Landslide damage database) or we could have opted for a longer validation period. Thereby trying to improve the quality of the search. However, we selected ten years of validation mainly to speed up the process and concentrate our efforts on the actual search. Also, we selected the years 1986-1995 because during this period more fatalities were recorded in the Swiss Flood and Landslide damage database than between 1972 and 1981 (27 vs. 20 victims). We stated in the manuscript that the overall data quality improved over time and is clearly better for the second 35 years of the study period (e.g. lines 466/7). This statement is based on two essential facts. (a) The main improvement that influences our data quality came in 1994 with the digital availability of all NZZ newspaper articles. (b) To complete the NZZ digital archive, newspaper issues older than 1994 were scanned and scans were processed using character recognition (problem no. 5 in section 5.1 of our manuscript). This effort was probably carried out by the Swiss Media Database in the last 10 to 20 years. Of course, older articles were more weathered at the time of scanning which resulted in qualitatively inferior scans. This, in turn, negatively affected character recognition.

Note that problem/point no. 6 in section 5.1 of the article should not affect the total number of fatalities detected in our search. For example, if a fatal channelized debris flow in the 1950ies was not identified as such, it was called something else by the newspaper (often e.g. “Schlammlawine” = mudflow or mud avalanche). However, it was still considered in our search, because we used all kinds of designations as keywords. Also note that we have not detected an increase in the occurrence of data gaps in our source of information (problem/point no. 4 in section 5.1).
In summary, we agree with referee #1 that the result of the methodological validation carried out for later years of the overall study period is probably not a good proxy for estimating the completeness of our database (or in other words the percentage of missed natural hazard deaths). By extending the validation period, this shortcoming could have been somewhat mitigated. However, we cannot expand the validation period at this point anymore. This would merely result in faintly different keywords combinations that would have to be run for all the newspaper issues again (months of work).
There are two main reasons why we think that the percentage of missed natural hazard fatalities in our overall study is not larger than 10 %. These are: (1) Approximately 37% of all fatalities in the data set presented here were caused by snow avalanches. Now, the destructive avalanche database is considered complete for fatality data and no additional search was carried out. This means that only less than two thirds of our data is subject to underestimation. (2) Grave events that cause several deaths are normally not just mentioned once in a newspaper. Often such events are described in numerous articles that span over a couple of days or even a few weeks. Some events are also mentioned in subsequent years for commemoration or retrospection. It is thus very unlikely that by reason of a data gap in the digital library, we did not register a single article on a multi-fatality event (note that about 36% of all victims died in a multi-fatality event with at least three deaths, and50% of all victims in an event with at least two deaths). We included parts of this reasoning in section 5.1 of the manuscript to strengthen our statement concerning the completeness of the data set.

3.3 Results temporal analysis (section 4.2 in the article)

First general statistics about the data are given. These mostly basic statistics are then used to describe the importance of multi-fatality events. The short sentences about the number of events per year may be enforced by adding the number of events to figure 2 (see also comments on figure 2 in section 4.2 of this review).

This is a good point. And as outlined below in section 4 (“Comments on figures”), we added the number of events per year in Figure 2 (at the bottom) to strengthen our statement made in the first paragraph of section 4.2.1.

The determination of a trend in the data is done in two ways: with the nonparametric Mann-Kendall test and by checking the significance of the slope of a linear regression. The choice of the non-parametric test is a good one but the linear regression performed on the normal scale of the data is not appropriate for count data and I suggest to use a Poisson regression or a regression on the natural log scale if the authors still want to use the slope as an indicator of the trend.

We agree with the referee and will drop the linear regression performed on the normal scale of the data. Additionally to the Mann-Kendall test, we applied the non-parametric Theil-Sen slope test as slope estimator According changes were made to the text in sections 4.2.1 and 4.2.2.

The fatality rate is used wrongly in line 283 (and in other places) since according to my understanding the authors are referring to a mortality rate. Because it is not age-adjusted the term crude death rate would be in better accordance with epidemiological terms.

We replaced the term *fatality rate* with the term *mortality rate* (or *crude mortality rate*) throughout the text (according to the remark of referee #1).

3.4 Results monthly distribution (section 4.2.2 in the article)

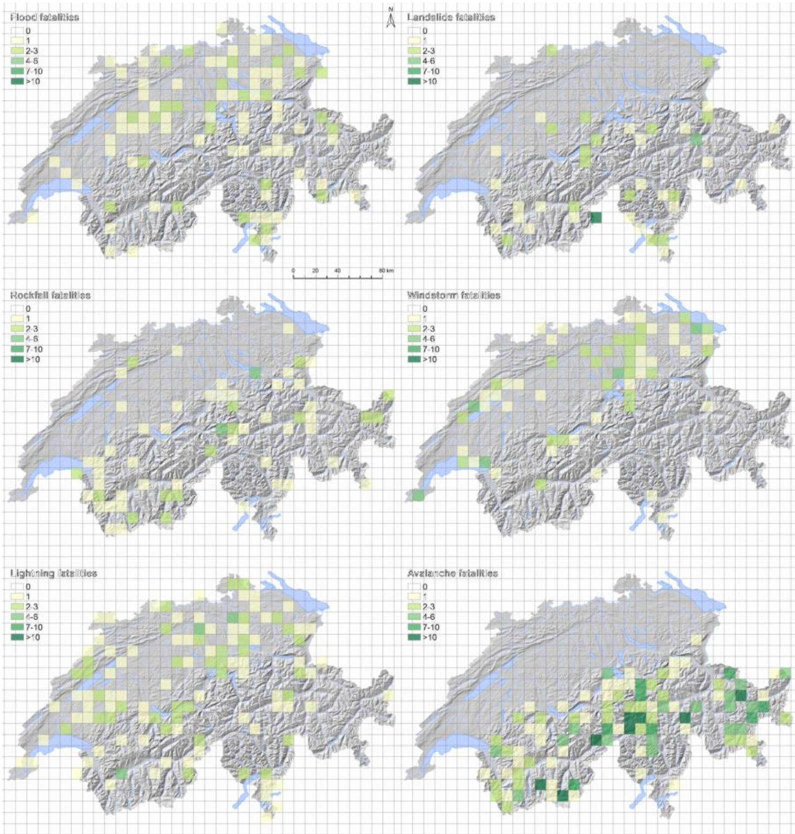
The key findings are the two peaked distribution of fatal natural hazards in Switzerland. The winter season dominated by avalanches and the summer season by lightning. The authors mentioned earlier that they see declining and rising trends in the annual temporal distribution and it may contribute to the monthly results if the authors would check for trends in seasonality also displaying figure 6 as a - maybe paneled – seasonal plot or adding some words to the text.

Natural hazards fatality numbers in winter (DJF) as well as in the months of March and April are dominated by avalanches (>62% for each of these months). The summer peak is definitely strongly influenced by lightning fatalities, a proportion of 50% is, however, only reached for the month of July.
We liked the suggestion of the referee to check for trends in seasonal fatality numbers over the study period. We hence established a 2 by 2 panel graph showing the annual frequency of natural hazard fatalities in Switzerland (1946-2015) for the four seasons DJF, MAM, JJA, and SON (new Fig. 6). Because the hazard process types snow avalanches and lightning are the ones that show a clear decrease in the temporal distribution of fatalities, we expected that winter (DJF) and summer (JJA) fatalities would have a significant decreasing trend over the study period. The statistical tests carried out for the seasonal data series confirmed this. Additionally, the number of victims that occurred in spring (MAM) also displays a statistically significant decreasing trend with time. It is weaker, however, compared to the trend detected for winter and summer fatalities. We added a few sentences to the second paragraph of section 4.2.2 to introduce and comment the new figure as well as the test results.

3.5 Results spatial distribution (section 4.3 in the article)

The authors explained in a clear manner the spatial distribution of the fatalities caused by the different hazard types. They also refer to the geomorphological region which makes their introduction at the former chapter plausible. A suggestion would be to use different maps for every hazard type and to count the number of fatalities divided by the number of events in a predefined raster or other geometrical grid. The authors may ask why my criticism is again aiming at the graphical representation this is because of the explorative nature of the topic. Paneling the hazard types would go perfectly with the excellent structured text of that chapter.

With all the new graphs in the manuscript (see also replies to the comments in section 4 of this review), we would actually like to refrain from adding another large and panelled figure to the main manuscript. However, we still created a new figure with six panels (maps) for the different hazard types. In these maps, we show the fatality data in a raster, as proposed by the referee (see below). The figure uses the same colours and practically the same legend as the upper map in the new Figure 9 and it nicely complements Figure 8 (original Figure 8a). This is why we decided to add it to the supplementary material in form of Figure S1.
We added references to this new Figure S1 in the second through fifth paragraphs of section 4.3.



Spatial distribution of natural hazard fatalities according to the hazard types flood, landslide, rockfall, windstorm, lightning and avalanche using a 10x10 km raster grid. The applied grid cell colours are in accordance with the colours in the new Figure 9 (above).

The next paragraph is dealing with the distribution of mortality rates per political region. My main concern about this result is the use of the political borders as an artificial subdivision of the space with no further connection to the underlying nature of the hazards. As an example the Canton of Bern has more than the half of its population in the five largest cities (Bern, Biel, Brugdorf, Interlaken, and Thun). Dividing the fatalities by the population incorporates a lot of people not even at risk to individual hazard types, and may therefore bias the shown results.

We deleted this paragraph in its original form together with Figure 8b. We formulated a new text paragraph describing our new Figures 9 and 10 (see response above in section 2 of this review, "Major point of criticism"). The distribution of mortality rates is now explored by means of the new raster maps and not using political borders.

3.6 Results regarding different social factors (section 4.4 in the article)

[…] This section boils down to the presentation of different n × n tables which are then described by words. Using tables in transporting information is mostly not a good choice (transporting data it is one of the best). To be sure that my critic is not just the normal table-bashing I got the data of table 2 and made a circos plot which I printed out and had it a the side while reading the text. In this fashion the text transports more information and is better understood than with the table.
So I strongly recommend to find prober graphical ways (mosaic, circos tec.) to present the categorical data from table 2 and 3 (see attached figure 3 to this review).

We thank the referee for suggesting this interesting way to display data. We considered different solutions to present the information in the manuscript (i.e. the data in the original Tables 2 and 3), amongst others

mosaic and circos plots. We finally opted for mosaic plots and added two graphs to the article (new Figures 11 and 12). However, we decided to keep Table 3 in the article and Table 2 in the supplementary material of the manuscript for readers that are interested in the exact numbers.
The newly created Figure 11 presents age groups and gender for natural hazard fatalities in Switzerland subdivided according to the natural hazard type and replaces Table 2. The newly created Figure 12, instead, shows the victim's activity and gender subdivided according to the natural hazard category and complements Table 3.
We renounced to represent the victim's locality and mode of transport (also handled in the original Table 3) with additional mosaic plots because we do not want to unnecessarily extend the text. When discussing these two topics in section 4.5, we will rather reference the original Table 3 (which corresponds to the new Table 2).

3.7 Discussion fatality numbers (section 5.3 in the article)

At line 529 the authors state that they assume that about half of all flood deaths can be ascribed to inappropriate behavior, for example when victims are carried away by floodwaters or surprised in their home by rapidly intruding surface water in contrast at line 585 being surprised is not considered inappropriate.
How could being surprised be an inappropriate behavior when the water is also rapidly intruding?

We understand why referee #1 raised this point and agree that the sentence at lines 529-531 should be rephrased. This misunderstanding is due to an inaccurate description of what we wanted to say.
Based on the descriptions given in the examined newspaper articles, we assume that a considerable number of fatalities caused during floods and inundations occur because of incautious behaviour. The first example (in the original text) pertains to people that are carried away by flood flows because they were standing too close to a channel. These victims approached swollen, dangerous rivers or streams because they wanted to cross them, to retrieve wood or other things, to save something or somebody, out of curiosity or for other unknown reasons. In many cases, circumspection would have saved their lives. The second example in our text (529-531) describes a situation that often occurs inside or around buildings. Like in the first example, regardless of a dangerous situation, victims take bad decisions and instead of taking refuge they expose themselves to a hazard. For example people try to save valuable belongings from the basement even though it is already inundated and the water level is rising quickly; or people try to drive their vehicles out of flooded underground car parks.
In contrast, the text at lines 585-586 applies to people killed by landslides. For both process types snow avalanches and landslide processes, about 50% of the fatalities occur in buildings. We assume that most of these people were aware of a critical situation (rainfall or avalanche hazard) and thought they were safe in a building. They had most probably not been asked by authorities to evacuate the building. Hence, we suppose they did not expect an event.
We rephrased our sentence at lines 529-531 in order to better describe our point and took care to avoid using the term *surprised*. We also slightly sharpened our statement at lines 585-586.

3.8 Discussion about the historical events in Switzerland

The events of the database are by far not the most devastating that occurred in Switzerland; three events are described in detail that caused 1500, 600 and 457 lives. Although this is an interesting information I do not see the direct connection to the article that is primarily concerned about trends and proportions in the fatality record. Maybe this section should be presented in a more condensed way in the introduction.

When preparing the article, the authors have discussed the importance of section 5.6 (Comparison of recent Swiss natural hazard fatality data with historic data) several times. Also, the original text was shortened before submission but not left out for the sake of completeness. We understand the referee's point of view and deleted section 5.6 from the discussion. Some of its content is now briefly presented in the Introduction (sixth paragraph describing the significance of geophysical events in Switzerland).

4. Comments on figures

I liked how the authors stayed coherent with the use of colors and I can literally feel their agony in choosing the right figures that capture all the information they want to transport. The presentation of count data is difficult as is the analysis of count data. There are few standard techniques of handling count data graphically: the bar, cumulative, scatter or line chart. The authors decided to go with the bar chart which is in my opinion not the perfect solution although this might be a question of taste.

We thank the reviewer for the constructive suggestions on how to better handle our data graphically. We changed several of our figures according to the referee's advice (see below) and kept only two bar chart graphs (Figs. 6 and 7 in the original manuscript, showing the monthly distribution and distribution of fatalities by time of day, respectively).

4.1 Figure 1 of the article

The authors use this figure to set the spatial frame of the study introducing important categories like the cantons and the geomorphological classes of Switzerland. The hillshade was a good choice because it gives a good impression of the topography, only the use of the blue for the Swiss Plateau may be problematic because of the low distance in color space to the rivers and lakes.

We adapted the colour used for indicating the Swiss Plateau (orange instead of blue) in order to better represent the streams and lakes on the map.

4.2 Figure 2 of the article

The authors want to introduce their database and the trends in the number of population and the number of fatalities. I like how they plotted the mean and median which enforces the understanding of their data and has a direct link to the text. Another important point about that plot is that the authors use it to show the declining trend in the number of fatalities as well that the first 35 years include 73% of all fatalities. To get this information clearly transported I would suggest the following: the use of a second axis to show the population growth does not contribute to the topic – to be honest I find it distracting. By erasing it, the figure would get clearer. The most prominent feature of the figure is given by the two extremes in the year 1951 and 1965 with the high number of deaths. These two years masking the trend the authors found and I would therefore use a transformation of the count. Typically the natural logarithm is chosen because of is direct connection to the link function of the Poisson regression model. Adding a running mean with the size of 10 years - to have a connection to Figure 3 - to the transformed data will enhance the trend apparent in the data.

Another point in the text is the fact that 73% of the total fatalities occurred in the first 35 year period of the database. This fact and the declining "fatality growth" will be better shown - in my opinion - using a cumulative chart of the fatalities. This chart also has the advantage that its behavior can be used to infer if a simple Poisson process is generating the fatalities – which would be a straight line. Maybe the number of *events per year as a third panel below the yearly number of fatalities would help to transport the severe multi fatality arguments of the authors.*

The suggestions of referee #1 for the improvement of Figure 2 are all very helpful. Accordingly, we completely redesigned Figure 2 which now includes:

→ A top panel with the cumulative number of fatalities in Switzerland over the study period (x-axis, logarithmic scale);

→ A second panel with the annual fatality data (logarithmic scale; including information on mean, median, as well as a 10-year running mean);

→ A third panel showing the number of events per year (logarithmic scale; also including a mean, and a median line, as well as a 10-year running mean).

We also added a reference to Figure 2 in each of the first two paragraphs of section 4.2.1 to point to the new features of the graph (cumulative data and event data).

4.3 Figure 3 of the article

The authors want to show the general decline in the number of fatalities over the years, especially the decline in the deaths caused by avalanches and lightning. I think that the information of that figure can be also transported with an enhanced version of figure 1 and a slightly changed version of figure 4.

With strongly adapted and enhanced versions of our original Figures 2 and 4 and in accordance with the view of referee #1, we decided that the original Figure 3 is not necessary anymore in the revised manuscript. Thus, we removed it from the article.

4.4 Figure 4 of the article

The authors want to describe how the number of fatalities is changing over time per hazard type or more general show the temporal behavior (also that there are no fatalities at all) and the differences between the hazard types. The x-axis is the same for all plots and therefore combining these without repeating the x-axis is recommended organizing the plot as a 3 by 3 panel. A problem may arise from the higher numbers of avalanche fatalities but this could be overcome by using a square root or logarithmic transformation of the x-axis and labeling the axis with the real number of fatalities. To better detect the temporal trend adding a running mean or other smoothing would help. Also it may be better suited to plot the cumulative number instead the number per year as a step function which would also indicate when there are no fatalities.

We like the idea of a 3 by 2 panel graph suggested by the referee. We used the count data with a logarithmic transformation of the y-axis and added a 10-year running mean. Because it is important to explicitly show years with no fatalities, we assigned data points.

Furthermore, we decided to add a figure to the manuscript displaying the cumulative fatality numbers for all different process types over the study period. This will help identifying the considerable decrease in avalanche and lightning fatalities in the second part of the study period.

4.5 Figure 5 of the article

The key massage is the decline in crude mortality rate over the years. The same critiques as for figure 2 are true for figure 5. Because of the high spread of the rate the figure gets clumped and the distinction between the processes is hard. This is especially a problem when the figure is compared to the text from lines 286 to

288, since I am not able to see the distinct decline in mortality rate. Maybe transforming and paneling the data would help also in this case.

We noticed that with a transformed y-axis, the graphs for mortality rate and fatality count (in Fig. 2) look very much alike. This is why we decided to remove the original Figure 5 from the study. Also, because (1) we show that the decreasing trend in the total number of fatalities over time is statistically significant and (2) because the Swiss population obviously increased in the last 70 years, it is not necessary to include a graph showing the decreasing crude mortality rate in the manuscript.

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nhess-2016-232
Reply to referee #2 (Ronald Holle)

We thank Ronald Holle for his constructive comments.
Below we give detailed replies and outline the changes made in manuscript nhess-2016-232.

General comments

One of the general results is that younger males tend to be the most frequent victims of all types of natural disasters. It is mentioned that work scenarios are the dominant issue, but it is also stated that young males tend to be more risk-takers (line 559). It is apparent from other lightning studies that risk taking is more likely to be the dominant issue in the United States, at least.

This is an interesting point. We added a sentence and a reference (Jenensius, 2014) to consider this point in section 5.4 of the manuscript .

Another comment is that many databases of natural hazards start the threshold at ten people affected per event. Instead, many phenomena, including lightning, impact one person at a time. The large number of such single-fatality incidents can exceed the total of ten-plus events. This causes an under-appreciation of several natural hazards in many reporting hazard systems. In fact, such limits affect policy as to what is being warned for the public. This is not an easy issue to resolve, but rightly is identified on line 635 in the paper.

Thank you for bringing this up. We added a sentence at the end of the first paragraph of section 5.7 (at line 637) stating that additionally to the underestimation of total fatalities, this problem also leads to under-appreciation of natural hazard processes with a high percentage of single-fatality events.

Specific comments

1. Confusing comments near end: Line 211 states that the lightning total "includes all people who died after being struck by lightning." Tables 1, 2, and 3 show 164 lightning fatalities. However, on page 21, the first paragraph of the Conclusions states that some lightning deaths were not included in the previous data summary. Am I reading this wrong, or has a group been excluded from the preceding results? Do the data presented earlier in the paper not include those in connection with high-risk sports and other situations (line 718)? If so, what is the real number of lightning fatalities Switzerland, or is this an extra comment that doesn't affect the earlier numbers?

As stated in section 3.4 (lines 220-228) we omitted natural hazard fatalities where people willingly exposed themselves to a considerable danger. For example, we omitted loss of life due to high-risk sports (e.g. canoeing and river surfing performed deliberately during floods) and other outdoor activities in potentially dangerous environments, such as canyoning, mountaineering and rock climbing (which take place off of official hiking trails). We also excluded popular snow sport fatalities outside of ski resorts, such as freeriding and alpine touring, that have been described elsewhere. In the case of the process type lightning, this means that we did not include mountaineers or rock climbers struck by lightning for several reasons, including the fact that it is typically very difficult to determine the cause of death in such cases. Based on recent information of the Swiss Alpine Club, approximately six climbers/mountaineers died from 2000 to 2013 after having been struck from lightning. Prior data is not available.

At line 211, we deleted the word “all”, because it might be misleading and because we did not use for the other process types (flood, landslide, rockfall, windstorm, and avalanche). We also delete the word “all” at line 215 to be consistent in all bullet points of section 3.4. We did not carry out additional changes in section 3.4 because we don’t think it is necessary. Our point made in the paragraph above is quite clearly stated in lines 220-228.

2. Add global summary of fatality rates: Several lightning fatality studies are referenced starting with line 84. The following summary of national lightning fatality rates was not in the current version of the manuscript since it is quite recent: Holle, R.L., 2016: A summary of recent national-scale lightning fatality studies. Weather, Climate, and Society, 8, 35-42.

We added a reference to this new publication (i) in the list of US studies on lightning fatalities at lines 86-87 and (ii) at the end of the same paragraph in a new sentence emphasizing on the global summary for 23 countries on six continents.

3. Add reference to India fatality study: The manuscript on lines 660 and 665 references a study by Singh and Singh, who found an average of only 159 fatalities per year within India. There has been an additional study by Illiyas et al. who found 1,755 fatalities per year. The latter seems more likely in this very populous country. The reference is: Illiyas, F.T. K. Mohan, S.K. Mani, and A.P. Pradeepkumar, 2014: Lightning risk in India: Challenges in disaster compensation. Economic & Political Weekly, XLIX, 23-27.

Thank you for providing this alternative reference regarding lightning fatalities in India. Interestingly, the study of Singh and Singh (2015) was published after the contribution of Illiyas et al. (2014). However, the latter publication is not cited in Singh and Singh (2015). Also, the two studies use two different data sources. While Singh and Singh (2015) extracted information from a database on disastrous weather events of the India Meteorological Department, Illiyas et al. (2014) apply three different data sources: the Bureau of Indian Standards data set, data from the Disaster Update Bulletins of the Nat. Inst. of Disaster Management, and data from the National Crime Records Bureau.
The difference in fatality data from the two studies is very large (approximately one order of magnitude) and leaves us a bit confused. The fact that the slightly newer study by Singh and Singh (2015) was published in an indexed Journal (Meteorol. Appl. Of the Royal Meteorological Society) somehow supports it. In contrast, Illiyas et al (2014) was published in an non-indexed periodical. But then again, Illiyas et al. (2014) clearly state that lightning-associated fatalities have received little attention in India, leading to under-reporting of incidents and lower media coverage.
For us it is very difficult to decide which of the two investigations better describes the occurrence of lightning fatalities in India. However, the remark of referee R. Holle makes sense to us and the higher indication of lightning deaths by Illiyas et al. (2014) seems more likely. Especially when the data is compared to data from other, similarly developed countries (cf. e.g. Table 3 in Singh and Singh). We thus added the reference of Illiyas et al. (2014) to our text and slightly adapted our statement in the fourth paragraph of section 5.7.

4. Effect of buildings: Page 15, line 515 states that the reduction in lightning fatalities is partially due to building and structures attracting lightning. Cloud-to-ground lightning interception by large structures is relatively rare. Instead, it is recommended that the reason is due to more people spending more time inside lightning-safe structures compared with decades ago.

This phrase originates from Derek Elsom (2001). He used this argument to explain the decrease in lightning fatalities. With the expansion of urban areas there are more lightning-safe buildings and other structures. The comment brought up by referee #2 is very valuable and we included this point in the first paragraph of section 5.3 by slightly changing the formulation in the text.

Technical corrections

Line 103: The word lightning has an extra e.
Corrected.

Line 283: Figure 5 referenced here would be easier to read if a log scale were used, since most entries have small numbers.
We agree with referee R. Holle. As a matter of fact, we now use a logarithmic scale in both Figures 2 and 4. Figure 5 was removed from the manuscript because it had only a limited informative value.

Line 729: The word lightning is missing the first n.
Corrected.

Natural hazard fatalities in Switzerland from 1946 to 2015

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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 ~~fatality~~ 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.

Keywords: natural hazard fatality, ~~fatality~~ mortality rate, flood, landslide, avalanche, loss of life, natural disaster

1. Introduction

Every year, world-wide natural hazard events not only generate tremendous financial damage costs but also cause a large number of human fatalities (MunichRe, 2016~~5~~). According to the NatCatSERVICE database of MunichRe, the average annual global loss of life due to natural catastrophes was 68,000 during the last ten years and 54,000 during the last thirty years (23,000 in 2015; Ins. Inf. Inst., www.iii.org/fact-statistic/catastrophes-global).

In scientific literature, information and data sets on loss of human lives due to specific natural hazard processes cover various time periods and exist at different aggregation levels: at the global scale (e.g. Jonkman, 2005; Petley, 2012; Auker et al., 2013; Dowling and Santi, 2014), the continental scale (e.g. Di Baldassarre et al., 2010; Sepúlveda and Petley, 2015) and most commonly the regional/national scale (e.g. Guzzetti, 2000; Ashley and Ashley, 2008; Höller, 2009; Vranes and Pielke, 2009; Singh and Singh, 2015, Techel et al., 2016). Moreover, there are studies that describe the circumstances during specific catastrophic natural hazard events and/or assess the patterns and reasons behind the associated massive loss of life (e.g. Chowdhury et al., 1993; Tsai et al., 2001; Doocy et al., 2007; Jonkman et al., 2009; Ando et al., 2013).

While some authors have analysed natural hazard mortality data that include many hazard types (e.g. Shah, 1983; Noji, 1991; Borden and Cutter, 2008), the bulk of studies have focussed on a distinct hazard process. Jonkman (2005) studied statistics about loss of human life caused by various freshwater flood types (river floods, flash floods and drainage problems) on a global scale and for the period from 1975 to June 2002 based on the EM-DAT International Disaster Database. This investigation showed that while flash flood events have the highest average ~~fatality~~ mortality rate (deaths divided by number of affected persons), Asian river floods are most devastating in terms of the number of persons killed or affected. In addition, very high death tolls have been reported for coastal flood events (e.g. Chowdhury et al., 1993; Gerritsen, 2005; Jonkman et al., 2009; Kure et al., 2016) and tsunamis (e.g. Doocy et al., 2007; Inoue et al., 2007; Ando et al., 2013). However, these events~~ that~~ were not included in Jonkman (2005) due to the rather limited availability of information. On a national scale, flood fatalities have been assessed by many authors for countries all around the world, such as the USA (Ashley and Ashley, 2008), India (Singh and Kumar, 2013), Pakistan (Paulikas and Rahman, 2015) and Australia (Coates, 1999; FitzGerald et al., 2010).

Petley (2012) assembled a global data set of fatalities from non-seismically triggered landslides that took place from 2004 to 2010 based on the Durham Fatal Landslide Database (DFLD). The total number of landslides and fatalities during the 7-year period turned out to be an order of magnitude larger than numbers suggested by other sources, and the study indicated that most fatalities occur in Asia. Most recently, Sepúlveda and Petley (2015) published a new data set of landslides that caused loss of life in Central and South America as well as in the Caribbean. This continental analysis used an enhanced version of the DFLD and applied key search terms in Spanish. In a study focusing on fatalities caused by debris flows (often included in landslides studies), Dowling and Santi (2014) considered 213 events that occurred between 1950 and 2011 and during which a total of 77,779 people were killed. Results of this global analysis provided evidence that more debris-flow fatalities tend to occur in developing countries. This is reflected in the median number of fatalities per recorded deadly debris flow which is 23 in developing countries, and only 6 fatalities per flow in advanced countries (11 when considering all data; Dowling and Santi; 2014). The value is very high when compared to data for the European Alps, where for example torrential processes cause an annual number of fatalities of approximately 1.5 in Austria (Fuchs and Zischg, 2014). On a national scale, landslide events with fatal consequences were compiled by Guzzetti (2000) for events that occurred in contemporary Italy from 1279 to 1999. Fast mass movements, such as rockfall events, rockslides, rock avalanches and debris flows were included in this study and were found to have caused the largest number of fatalities.

Loss of life due to snow avalanches has been analysed by numerous authors, most often at a national level, e.g. for Austria (e.g. Höller, 2009), France (e.g. Jarry, 2011), Norway (e.g. Kristensen, 1998) or Switzerland (e.g. Schneebeli et al., 1998), but also at a regional level, e.g. for the European Alps (Techel et al., 2016).

Loss of life related to meteorological hazard events, such as lightning and all the different types of wind storms, has also been the subject of many national and regional studies. In the USA, medium- to long-term data sets of wind related deaths have been investigated, for example for tornados (Ashley, 2007) and hurricanes (Rappaport, 2000; Czajkowski et al., 2011), as well as for (nontornadic) convective (Black and Ashley, 2010) and nonconvective (Ashley and Black, 2008) high-wind events. While convective and nonconvective high-winds can cause serious problems in Switzerland (e.g. WSL and BUWAL, 2001), tornadoes are much more rare but have caused fatalities e.g. in the 1920ies and 30ies (Bader, 2001). Recent Various publications have presented national lightning data sets, for example from the UK (Elsom, 2001), India (Singh and Singh, 2015), Australia (Coates et al., 1993), Colombia (Navarrete-Aldana et al., 2014), USA (Holle, 2016; López and Holle, 1996; Curran et al., 2000), and Swaziland (Dlamini, 2009). Additionally, Holle (2016) summarized and synthesized lightning fatality data from 23 recent national-scale investigations from both developed and developing countries.

Geophysical events such as tsunamis and volcanic activity might not be very relevant for a country like our study area Switzerland, but are of considerable importance when assessing consequences of natural hazards at a global level (e.g. Auker et al., 2013). Earthquakes, in contrast, have occurred in Switzerland with dramatic effects ~~(Fäh et al., 2009)~~, but events causing fatalities or large amounts of damage are rare. The Basel earthquake of 18 October 1356 is arguably one of the three most devastating natural hazard incidents of the last 1000 years in Switzerland (the other two being Biasca rockslide/water surge in 1513/1515 and the Goldau rock avalanche in 1806) and is regarded as the strongest historically documented earthquake event in central Europe (Giardini et al., 2004). While the 1356 event destroyed large parts of Basel, the overall number of victims remains uncertain and estimates range from 300 to 2000 fatalities (Fäh et al., 2009). The highest estimates, however, were evaluated to be highly improbable by Fäh et al. (2009). For countries more frequently struck by seismic activity, various fatality databases exist (e.g. Vranes and Pielke, 2009).

In Switzerland, fatalities caused by floods, debris flows, and landslides have been systematically collected since 1972. They are recorded in the Swiss flood and landslide damage database (Hilker et al., 2009) and were briefly analysed by Schmid et al. (2004). Deaths due to rockfall incidents have been included in the database since 2002. For disastrous events causing loss of life that occurred before 1972, only partial and scattered information is available (e.g. Röthlisberger, 1991). In parallel, information on loss of life caused by snow avalanches in Switzerland has been collected since the hydrological year 1936/1937 by the WSL Institute for Snow and Avalanche Research SLF. To our knowledge, no systematic data acquisition of fatalities and damage induced by convective and non-convective high winds and lightening has been carried out at national scale in Switzerland.

In the study presented here, we compiled the available data on natural hazard fatalities mentioned above, extended the period covered by the database, and expanded it to include all process types relevant for the study area. We present this new, detailed 70-year (1946-2015) data set of loss of life in Switzerland caused by (i) floods, (ii) debris flows, (iii) landslides and hillslope debris-flows, (iv) rockfall events and rockslides, (v) windstorms, (vi) lightning strikes, (vii) earthquakes and (viii) avalanches. Temporal and spatial patterns in the results are discussed and the numbers of fatalities as well as the characteristics of the underlying incidents for different process types are assessed. Finally, we compare our data with similar data from other countries and regions and attempt to explain differences qualitatively.

According to the Federal Constitution of the Swiss Confederation, the cantons and municipalities are responsible to ensure the protection of the population against natural hazards. The aim of this study is to support authorities to better understand the occurrence of fatal incidents, to identify potential improvements in hazard prevention and to further reduce the number of victims of natural hazards.

2. Study area

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

Confederation consists of 20 cantons and 6 half cantons, and its territory can be roughly divided into four regions based on its geomorphology (see Figure 1): the Alps (a high-altitude mountain range running across the central-south of the country), the Swiss Plateau (a relatively flat area between Lake Geneva and Lake Constance), the Prealps (the transitional area between the Alps and the Swiss Plateau) and the Jura (a hilly mountain range in the north-west). The population grew from 4.5 to 8.3 million people between 1946 and 2015 and is clustered mostly on the Swiss Plateau (over 60% of the total population is located on less than a third of the total area of the country). The Swiss climate is temperate but can vary regionally. In large parts of the Alps the mean annual rainfall is around 2000 mm/year or more, and along the Swiss Plateau this value amounts to 1000-1500 mm/year. Most precipitation falls during the summer months.

3. Data and methods

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

3.1 Swiss flood and landslide damage database

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

3.2 The Swiss destructive avalanche database

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

We explicitly excluded all cases that occurred outside of transportation corridors and settlements (except hiking trails in summer, see (iv) above). Thus, cases associated with ski or snowshoe touring, and skiing or snowboarding away from open ski trails were not included in our data set. Also, we did not incorporate avalanche fatalities related to vehicles illegally driving on officially closed roads. The destructive avalanche database is considered complete for fatality data, and data quality is generally very high. Thus, no systematic search of avalanche related events in a newspaper was necessary.

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

With the aim of extending the data series to 70 years and combining it with other natural hazard processes like windstorm, lightning, earthquake and ice avalanche, we made a search in a newspaper. We selected the „Neue Zürcher Zeitung“ (NZZ) because it is a national newspaper and a digital archive exists back until 1780. The NZZ is written in German, which is the most spoken language in Switzerland (see also section 5.1). We accessed the digital archive via an internet platform, where a keyword search was possible. In a first step, we derived adequate keywords (in German) for the search. We selected the years 1986-1995, for which we already had some data from the Swiss flood and landslide database, as validation period. We generated a list with possible keywords and checked how often these words were used in the newspaper for the description of casualties that occurred in Switzerland and abroad. The casualties from abroad were included to get more search hits. We then shortened the list to the most relevant keywords. Where possible, we combined the keywords for the different processes. For example, we searched for casualties caused by “flood OR inundation OR landslide OR landslip OR mudslide OR mudflow” combined with “dead OR casualty OR death OR human life OR drown OR killed OR dead body OR buried”. An overview of the keywords and the combinations used is given in the supplementary material (Table S1). With these keyword combinations, we found most cases (roughly 90%) already stored in the Swiss flood and landslide database for the selected validation period ~~1985~~1986-1995.

In a next step, we used the selected keywords to scan the newspaper for the remaining years (1946-1977, 1988-2015). For the years where we already had data from the Swiss flood and landslide database for the processes flood, landslide, debris flow and rockfall, we restricted the search to the processes not already covered. The search for fatalities produced up to 300 hits per year. We initially viewed all hits, but many were not relevant for our research (e.g. fatalities abroad). Further, the digital scan of the newspaper was sometimes of bad quality, which resulted in the misspelling of words and thus influenced our search because not all of our keywords were found. In addition, some gaps exist in the digital archive of the NZZ (e.g. 04. – 15.08.1978).

For each casualty found, a database entry was made. The following information describing the fatal accident and the victim was stored: name of municipality, canton, date, time, coordinates, description of the event, age, gender, locality (i.e. in or around a building, on a transportation route, in open terrain, in a stream channel, on a lake), mode of transport (on foot, by bicycle, in vehicle, by public transport, by boat, by ski), activity (work, leisure time), and data source. For most of the above-mentioned categories, the quality of the information was also assessed. In doing so, we distinguished between two types of information quality: (i) a concise statement describing a certain characteristic of the event (certain); and (ii) an indication of a characteristic that we deduced based on the available information (probable). In contrast, if no information was available to describe certain aspects of a fatal incident, those characteristics were considered unknown.

3.4 Natural hazard processes considered in the new database

In the present study, we assigned the fatalities found in our search (or adopted from the flood and landslide damage database or the destructive avalanche database) to the following seven process categories:

- Flood: includes people drowned in flooded or inundated areas or carried away in streams under high-water conditions.
- Landslide: includes people killed by landslides, hillslope debris flows and channelized debris flows. Because debris flows were often not identified as such in the press media (especially in the first half of our study period), we decided to add debris flow fatalities to the category of landslide processes. This approach has been applied previously, for example by Guzzetti (2000).
- Rockfall: includes people killed by rockfall.
- Lightning: includes ~~all~~ people who died after being struck by lightning.
- Windstorm: includes people killed by falling objects or trees during very strong wind conditions and people who drowned in lakes because their boat capsized during such conditions.
- Avalanche: includes people killed in snow avalanches (except roof avalanches, see below).
- Other: includes ~~all~~ people killed by hazard processes that are not frequent in Switzerland (e.g. ice avalanches, earthquakes, lacustrine tsunamis, roof avalanches). Most of the fatalities assigned to this process type were caused by the 1965 Mattmark ice avalanche.

Fatalities due to forest fires did not occur during our study period, and people who died during meteorological heat waves were not included. Overall, we considered only casualties where people did not expose themselves to a considerable danger on purpose or wilfully. For example, we excluded loss of life due to high-risk sports (e.g. canoeing and river surfing during floods) and other outdoor activities in potentially dangerous environments, such as canyoning, mountaineering and rock climbing. We also excluded popular snow sports experienced outside of ski resorts, such as freeriding and alpine touring, that have been described elsewhere (e.g. Techel and Zweifel, 2013; Schweizer and Lütschg, 2001). Further, we only included cases where the process directly induced a casualty or an action that led to death. For example, we did not consider cases where a forest ranger was killed during forest clearing operations after a windstorm or where a firefighter was killed in a flooded basement due to an electric shock.

4. Results

4.1 Types of natural hazard processes associated with fatalities

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

4.2 Temporal distribution of natural hazard fatalities in Switzerland

4.2.1 Annual distribution of fatalities

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

The number of people killed by natural hazards in the last 70 years showed a clear decrease over time (Figure 2). The downward trend in the total number of annual fatalities is statistically significant (Mann-Kendall trend test: ~~Tau = -0.42,~~ 2-sided P-value = $<10^{-3}$~~3.35e-7~~; Theil-Sen slope estimate: -0.207 deaths per year~~ Linear Regression Model: 2-sided P-value = 0.001~~; R-packages *Kendall* (McLeod, 2011) and *zyp* (Bronaugh and Werner, 2009)). This pattern is confirmed when the total number of deaths during the first 35 years of the study period (747) is compared with the value for the second 35 years (276). Thus, nearly three times as many people were killed by natural hazard processes from 1946 to 1980 than from 1981 to 2015 (Figure 2). Further, only three years after 1981 exhibited a number of fatalities larger than the mean value for the full 70-year period: 1985, 1999 and 2000. The decrease in natural hazard fatalities over the

70-year period is also apparent in the number of fatalities per decade~~ (Figure 3)~~. On average, nearly three times as many people died in accidents during each of the first three decades of the study period as during each of the last four decades.

The temporal distributions of victims of specific hazard types showed a distinct decrease for lightning and avalanches only (Figures 3 and 4). The trend is statistically significant for avalanches (Mann-Kendall trend test: ~~Tau = -0.30, ~~2-sided p-value = $<10^{-3}$~~0.005~~; Theil-Sen slope estimate: -0.042 deaths per year~~ Linear Regression Model: 2-sided p-value = 0.0~~) and lightning (Mann-Kendall test: ~~Tau = -0.28, ~~2-sided p-value = $<10^{-3}$~~0.008~~; Theil-Sen slope estimate: -0.063 deaths per year~~Linear Regression Model: 2-sided p-value = 0.014~~). For both process types, around four times more fatalities were recorded in the first half of the study period than in the second half (Figure 4). Interestingly, during the last 15 years, the database revealed only seven avalanche fatalities, resulting in an average for this most recent period that is ten times smaller than the overall mean value. In a qualitative sense, only deaths due to landslide processes seem to have increased slightly over the 70-year period. However, this impression~~ is~~ was strongly influenced by the large number of fatalities (16) that occurred during the severe October 2000 event in the canton of Valais, when 13 people died in the Gondo landslide.

There were several years in the data set of each natural hazard type when no fatal incidents were reported (Figure ~~3~~4). The three hazard types for which at least one fatality was reported in most years during the study period are lightning (49 years), avalanches (48 years) and floods (48 years). While at least one fatality associated with windstorm and rockfall events occurred in 40 and 37 years, respectively, fatal accidents related to landslide processes occurred only in one third of the investigated years. Even though only one deadly ice avalanche happened between 1946 and 2015 (category *other* processes), this event was responsible for more fatalities than all rockfall or all landslide incidents (Figure 4).

Normalization of fatality data by population resulted in a clearly declining annual ~~fatality ~~crude mortality rate~~ (Figure 5)~~. We found an annual average rate of 3.9 deaths per million persons for the first 35 years of the study period and a rate of 1.1 for the second 35 years. The yearly mean for the whole period is 2.5 victims per million persons. A very distinct decrease in the mortality~~fatality~~ rate from the first to the second half of the study period ~~can be seen~~appears for the processes lightning (0.7 to 0.14) as well as avalanche (1.63 to 0.29), and to a slightly lesser extent for the processes flood (0.41 to 0.18), rockfall (0.31 to 0.10) and windstorm (0.30 to 0.19).

4.2.2 Monthly distribution of fatalities

The monthly distribution of natural hazard fatalities from 1946 to 2015 showed two distinct peaks, one in summer and one in winter (Figure ~~6~~5). The first peak was due to the seasonal distribution of classic "summer processes" such as lightning, floods and, to a lesser extent, also landslides and rockfall incidents, which occur most frequently in June, July and August. Additionally, the catastrophic ice avalanche event in 1965 contributed considerably to the establishment of August as the month with most loss of life (207 fatalities). The winter peak was largely caused by avalanches, the most fatal process type in Switzerland, which accounted for 242 of the overall 280 deaths in the months of January (135 avalanche related deaths out of 145 total deaths) and February (107~~5~~ avalanche deaths/135 total deaths). The months of March, April and May in spring and September through December in autumn and early winter exhibited relatively low fatality numbers, i.e. below 60. The month with the fewest deaths related to natural hazard processes was November, when a total of 22 deaths occurred during the last 70 years. This corresponds to a fatality number~~rate~~ roughly one order of magnitude smaller than the value~~rate~~ in August.

These seasonal patterns resulted in a high percentages of fatalities in summer (June, July and Aug.; 41.7%) and winter (Dec., Jan. and Feb.; 32.2%). In contrast, spring (Mar., Apr. and May; 16.0%) and autumn (Sept., Oct. and Nov.; 10.1%) displayed low percentages. While 85.4% of lightning deaths and 67.7% of flood deaths occurred in summer, 70.6% of avalanche victims were killed in winter and 24.9% in spring. In autumn, only fatalities by landslides show an relatively high percentage (39.2%). The temporal distribution of seasonal fatality data (all process types combined) is displayed in Figure 6. The plots show a distinct, statistically significant decrease over time for fatalities that occurred in winter (Mann-Kendall trend test: 2-sided p-value = $<10^{-3}$; Theil-Sen slope estimate: y = -0.047), spring (Mann-Kendall trend test: 2-sided p-value = 0.002; Theil-Sen slope estimate: y = -0.024) and summer (Mann-Kendall trend test: 2-sided p-value = $<10^{-3}$; Theil-Sen slope estimate: y = -0.074). In contrast, the number of autumn victims ~~of natural hazards~~ have not significantly changed over the study period.

4.2.3 Natural hazard fatalities classified by time of day

Based on information on the fatality event time, we assigned the cases to four different time periods: morning (06:00-11:59 local standard time), afternoon (12:00-17:59), evening (18:00-23:59) and night (00:00-05:59). Most of the fatalities occurred in the afternoon (39%), followed by the evening (23%), the morning (17%) and the night (11%). For ten percent of the fatalities, no exact event time could be determined (Figure 7). Fatalities due to lightning strikes, floods or windstorms occurred mostly in the afternoon and in the evening, whereas no characteristic time period could be distinguished for the occurrence of fatalities due to avalanches, rockfall events and landslides. However, avalanches and landslide processes showed a considerably higher percentage of deaths during the night (roughly 20%) compared to the other processes (less than 10%).

4.3 Spatial distribution of natural hazard fatalities in Switzerland

Fatalities caused by natural hazard processes were relatively homogenously distributed over the entire territory of Switzerland (Figure 8~~a~~). There are a few, mostly small, areas where very few or even no deaths were found in our data set. This is also visible in Figure 9 that shows the number of fatalities and events using a 10x10 km raster grid. Multi-fatality events were much more frequent in the mountainous parts of the country (Alps) compared to the Swiss Plateau and the hilly Jura (Figure 8).

As can be expected, fatalities resulting from avalanches occurred mainly in the high-alpine parts of Switzerland (Figure 8 and S1). A few accidents were reported from the western and central Prealps (transitional areas to the high-alpine part of Switzerland). In contrast, no fatal incidents relating to avalanches occurred in the hilly Jura and in the Swiss Plateau region. Clusters are present, e.g. in the area around Andermatt in the southern part of the canton Uri (UR) and around Davos in the canton Grisons (GR). Also, a notably large number of multi-fatality avalanche events is visible in Figure 8~~a~~ (see also section 5.2). Interestingly, some mountainous but populated regions showed very few or no deaths by avalanches at all. Such areas are located in several parts of Grisons ~~(GR)~~ and Valais (VS), as well as in parts of north~~-east~~ern Ticino (TI).

Most of the fatalities caused by landslide processes were recorded in the Alps and Prealps, and a few were documented in the Swiss Plateau (Figure 8 and S1). The largest number of landslide deaths occurred in the canton Valais ~~(VS)~~, and the worst landslide event in the database (with 13 fatalities) occurred in Gondo (VS) in October 2000. Similar to landslide accidents, fatal rockfall accidents predominantly took place in the central Alps and Prealps, e.g. in the cantons of Valais, Grisons, Vaud (VD) and Uri. A limited number of these fatalities occurred in the Jura and the Swiss Plateau.

Flood fatalities were rather homogenously distributed over Switzerland and occurred in almost all regions/cantons during the last 70 years (Figure 8 and S1). Still, there were considerably more cases (some of them multi-fatality incidents) in the Swiss Plateau than in any other Swiss region. The fewest deaths by floods occurred in the region Jura and the canton Valais. Some areas, such as the canton of Neuchâtel (NE), the eastern part of canton Grisons and south-eastern Valais exhibited no flood fatalities at all.

Lightning fatalities occurred all over Switzerland, and by far most of them took place on the Swiss Plateau (Figure 8 and S1). However, some high-mountain areas in several different parts of Switzerland exhibited very few lightning related deaths (e.g. in cantons Grisons, Valais, Uri and Ticino). Windstorm related fatalities were also mainly registered along the Swiss Plateau. This region exhibited more than half of all windstorm related fatalities. Some cases occurred in the Jura, the Prealps and on the border to the Alps. In contrast, very few wind related fatalities occurred in the large alpine cantons Grisons, Valais and Ticino. Areas around lakes (Lake Zurich, Lake Neuchatel, Lake Geneva, Lake Constance) had clusters of windstorm fatalities due to a considerable number of capsizing accidents.

The spatial distribution of natural hazard fatalities for the different process types was confirmed by the altitude data for each event. For roughly three quarters of the fatalities, we were able to define the exact altitude at which the victim died (for slightly less than 25% of the fatalities the accident altitude was estimated). While median altitude was highest for avalanche and rockfall victims (1467 and 1082 m a.s.l., respectively), landslide and lightning victims were killed at intermediate altitudes (820 and 692 m a.s.l., respectively). In contrast, flood and windstorm fatalities were mainly registered at low altitudes representative for the Swiss Plateau (median values of 559 and 431 m a.s.l., respectively).

By combining the gridded natural hazard fatality data (Figure 9) with population data (Figure 10, above), a spatially distributed mortality rate with a 10 km grid resolution was assessed for all of Switzerland (fatalities per year and per one million persons; Figure 10, below). Obviously, the weakly populated, high-alpine areas with avalanche, landslide and rockfall incidents show the grid cells with the highest mortality rates on Swiss territory. A cluster of cells with very high rates is discernible in the central part of the Alps. While in the Prealps high rates are still widespread, the more densely populated Swiss Plateau displays a majority of grid cells with mostly low and some medium mortality rates. The hilly Jura shows a few cells with medium or slightly elevated rates. Grid cells, where fatal natural hazard did occur but that are not populated due to their position in high-alpine terrain (in most cases in the immediate vicinity of the country's borders), are indicated in red (Figure 10, below; section 5.6). ~~Figure 8b shows the overall number of fatalities per Swiss canton. Most deaths occurred in the canton of Valais (VS, 272), followed by Grisons (GR, 193), Bern (BE, 100), Ticino (TI, 71), Uri (UR, 60), Vaud (VD, 44) and St. Gallen (SG, 43). Normalizing the number of deaths to canton population (deaths per year and per one million persons) shows that cantons in the Alps with a medium to very low population density had especially higher fatality values. The relatively small and sparsely populated canton of Uri showed the highest normalized value (UR, 27.4), followed by Valais (VS, 19.1), Grisons (GR, 18.2), Appenzell Innerhoden (AI, 8.7), Obwalden (OW, 5.8), Nidwalden (NW, 5.7), Ticino (TI, 4.7) and Glarus (GL, 4.6). At the other end of this list were the urban cantons of Basel-Stadt (BL, 0.08) and Geneva (GE, 0.26) located in the regions Jura and Swiss Plateau.~~

4.4 Natural hazard fatalities classified by age and gender

The age of victims was provided for more than 93% of the natural hazard fatalities reported in our database (954 out of 1023). Overall, the age groups with the highest death toll were the 20-29 year-old (172 fatalities) and 30-39 year-old (177 fatalities) groups, followed by the 40-49 year-old group with 151 fatalities (Figure 11, Table S2 in supplementary material). These values correspond to a combined 500 victims (or 48.9%) between 20 and 49 years of age. While children and teenagers (0-19) accounted for 20.9% of natural hazard deaths, people above 60 years of age made up only 12.6%.

When focusing on age related patterns for the individual process types, several discrepancies from the overall numbers attract attention. For example, about one fifth of all flood victims were younger than ten years of age, compared to 7.5% for all hazard processes (Figure 11~~Table 2~~). Most of these very young victims drowned in the first half of the study period. In addition, the percentage of victims over 60 years of age was more than twice as high for flood fatalities (25.8%) as for all fatalities. Lightning rarely killed young children (2.4% in the 0-9 year-old age group) but seems to particularly affect teenagers. The 10-19 year-old age group constituted 23.2% of all lightning victims, which is much higher than the value for all processes (13.4%). The large majority of these teenagers were killed in the first part of our investigation period. Finally, windstorm victims below 20 years of age were underrepresented (10.5%) compared to the full data set (20.9%).

Gender was provided for practically all (99.5%) natural hazard fatalities in our database. Summarized for all process types, more than three quarters of all natural hazard victims were males, indicating that males were approximately three times as likely to become fatality victims as females (Table 1). Male fatalities greatly outnumbered female deaths for every process category (percentage of male fatalities between 74.2 and 79.3%), with the exception of landslides and processes in the *other* category (including ice avalanches) (Figure 11). While the proportions of male and female victims of landslides were quite similar (55.4 and 44.6%, respectively; Table 1), the victims killed by the ice avalanche of 1965, which destroyed a dam construction site, were practically all males (96.6%). Expressed differently, female landslide deaths represented 13.6% of all female natural hazard fatalities, whereas the same value for males was only 5.3%. Correspondingly, processes classified as *other* were the cause of death in 11.0% of male victims in our records, while this value was negligible for female victims (2.9%).

Regarding the ages of victims, the number of male victims in natural hazard fatalities was considerably larger than the number of female fatalities within every age group (Figure 11Table 2). This pattern is accentuated for young adults between 20 and 39 years of age, where the percentage of male victims was more than 80%, whereas for young children from 0 to 9 years of age the percentage of female victims was highest at 34%. Accordingly, the age distribution of male and female victims of natural hazard processes exhibits a few differences. Whereas 26.4% of female fatalities were younger than 20 years of age, this applied to only 19.4% of male victims (Table S2). In contrast, the percentage of young-adult victims between 20 and 39 years of age was much higher for males (37.2% of all deaths) than for females (25.2%).

4.5 Natural hazard fatalities in different accident circumstances

Accident circumstances, such as *activity* (work or leisure time), *locality* (on transportation routes, in open terrain, in or around buildings, on a lake, in the immediate vicinity of a stream channel) and *mode of transportation* (on foot, in a vehicle, on a boat, on skis, on a bicycle, in public transport) were analysed for the 1023 entries in our database (Figure 12, Table 23). Regarding the victims' activity, we found that 52% of all fatalities occurred during leisure time, 35% occurred during work, and the activity could not be assigned in 13% of the cases. The assessment of incident locality revealed that most of the fatalities occurred on transportation routes (33%), in open terrain (14%) or in or around buildings (home 20%, other buildings 6%, around buildings 3%). For all fatalities except those in buildings, the mode of transport was determined: 62% of victims were killed whilst on foot, 18% in a vehicle, 7% on a boat, 6% on skis and 1% or less in public transport or on a bicycle.

Avalanches killed more than twice as many people during leisure time (245) as during work (110). People killed by avalanches during work were mostly located on transportation routes (72), mainly travelling by foot (35) or in vehicles (16). People who died in avalanches during leisure time were usually at home (159) or were travelling on transportation routes (83). Similarly, for floods, windstorms, landslides and rockfall events, fatalities that occurred during leisure time were at least twice as frequent as those that occurred during work. The single hazard event with the largest number of people killed during work was the ice avalanche in Mattmark with 88 deaths (category *other*). People fatally struck by lightning were working in 43% of the cases (Table 2~~3~~).

Most victims of floods were killed in the stream channel sector (63) and were usually carried along by the high water. Flood related fatalities on transportation routes were also relatively common (31), with 11 victims travelling in vehicles, 16 by foot, two by bicycle, one in public transport and one case unclear. Regarding windstorm related incidents, most of the fatalities occurred on lakes with victims located in boats (44). Thirty-four windstorm related fatalities occurred on transportation routes, where 20 victims were killed in vehicles, 13 on foot and one on a bicycle. Loss of life caused by landslide processes occurred mostly in and around buildings (40). Twenty people were killed by landslides whilst on transportation routes, and 11 of these victims were in vehicles, eight on foot and one in public transport. Most people killed by rockfall were on transportation routes (58), of which 30 people were travelling by foot and 27 in a vehicle (one unclear), whereas 14 people were killed by rockfall on open terrain. Most of the lightning fatalities occurred on open terrain (95 victims, of which 90 were moving by foot), in or around buildings (33) or on transportation routes (28 victims, of which 13 were travelling by foot, 10 in or on a vehicle and 5 by bicycle; Table 2).

5. Discussion

5.1 Data quality

5.1.1 Completeness of the data set

Several factors influenced the integrity of our data set: (i) Fatal accidents caused by natural hazard processes during the 70-year study period could simply not have been reported in the Neue Zürcher Zeitung (NZZ) or in the additional data sources used. (ii) The NZZ is a German written newspaper. The coverage of the news includes all parts of Switzerland (e.g. regarding severe natural hazard events), but there might be a bias towards an underreporting in the other language regions (French, Italian, Rhaeto-Romanic), which represent roughly one third of the population. (iii) For practical reasons, we had to apply a limited number of keywords in our search. Thus, we could have missed reports on natural hazard fatalities in the data sources because our keywords were not used in the respective news coverage. (iv) There were a few small data gaps in our main data source. Some issues of the NZZ were not present in the data portal applied; hence, we possibly missed fatalities that occurred during such periods. (v) The NZZ archive was established by scanning all newspaper issues and applying a character recognition program (with the exception of all new editions available digitally since 1994). This procedure is susceptible to errors whenever the character recognition fails due to insufficient scan quality. We encountered this problem when searching for keywords in the first few decades of the study period, mainly for long keywords. (vi) Finally, media articles sometimes mix up technical terms and thus hazard processes (a problem already discussed in Badoux et al., 2014). For example, we suspect that several fatal debris flows were not exactly identified as such in the media during the first few decades of the study period because this process was not yet commonly understood.

All in all, we acknowledge that our database for the time period between 1946 and 2015 is not fully 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.The main reason for this is that graver events with several deaths were almost certainly reported in the NZZ. 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 34). 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~~5~~). 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~~5~~).

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~~ and 5~~).

Regarding the relative importance of single-fatality events, we detected two distinct categories of natural hazard process types. Flood, rockfall, windstorm and lightning incidents with one victim were responsible for more than 70% of the total fatalities associated with each of these process types. This value was much smaller for avalanches (26.2%) and landslides (31.1%) (Table 4~~5~~). This distinction is probably related to the fact that fatal victims of both avalanche and landslide process types are more often killed in buildings (around 50% of all cases) than victims of other hazard processes. Affected buildings are likely to be occupied or inhabited by more than one person, and thus, multi-fatality events are more frequent for avalanches and landslides. Lightning was associated with the highest percentage of deaths in single-fatality events in Switzerland (87.8%). This value is only slightly lower than percentages reported for the USA (90.9%, Curran et al., 2000) and Australia (92%, Coates et al., 1993).

5.3 Evolution of fatality numbers during the last 70 years~~ in Switzerland~~

General attempts to explain the decrease in natural hazard fatalities observed in other countries and globally have been made previously. For example, Goklany (2007) indicated that societies' collective adaptive capacities lead to reduced ~~fatality ~~mortality rates due to extreme weather. For the USA, Curran et al. (2000) attributed a decline in lightning related deaths over time to improved medical care, emergency communication and transportation, as well as better awareness of the serious threat posed by lightning. Improved forecasting, process detection and warning systems may have also contributed to the decrease in fatalities (Curran et al., 2000; López and Holle, 1996). Furthermore, fewer people currently work in open fields than in the past (Elsom, 2001)~~,~~. With the expansion of urban areas more people are spending a greater proportion of their time inside lightning-safe structures compared with decades ago (e.g. Curran et al., 2000; Holle, 2016). ~~and the expansion of urban areas has provided more buildings and structures to attract lightning away from people (Elsom, 2001).~~ These points also apply to Switzerland, which is confirmed by significant decreases in lightning fatalities in particular and total fatalities more generally.

A significant reduction in avalanche fatalities in settlements and on transportation corridors since the 1970's has been noted throughout the countries of the European Alps (e.g. Techel et al., 2016~~in prep.~~), as well as in other developed regions like in Scandinavia (Kristensen, 1998) and North America (e.g. Page et al., 1999; Jamieson et al. 2010). Explanations for this decrease, also detected in our data set for Switzerland, include (i) large investments into permanent avalanche defence structures, which reduce the potential for catastrophic avalanches (e.g. SLF, 2000); (ii) hazard mapping and risk assessment to evaluate appropriate measures for the protection or closure of avalanche-threatened sections of roads during winter (e.g. Wilhelm, 1997; Margreth et al., 2003); (iii) the preventive artificial release of avalanches (e.g. Stoffel, 2001); (iv) the improved avalanche education of local authorities responsible for avalanche safety (e.g. Bründl et al., 2004); and (v) an improved and more widely distributed avalanche forecast (Etter et al., 2008).

Many fatalities related to floods and inundations occur because people act imprudently and put themselves in dangerous situations. We assume that a substantial proportion ~~about half~~ of all flood deaths in our data set can be ascribed to such inappropriate behaviour.~~,~~ ~~f~~For example, outdoors, when victims are carried away by floodwaters because they were standing too close to a channel or inside a building, when victims intend to save belongings from flooded basements ~~surprised in their home by rapidly intruding surface water~~ or try to drive vehicles out of inundated underground car parks (see also section 5.5~~6~~). Similar observations were made abroad, e.g. in association with the use of motor vehicles, when people decided to cross floodwaters, often underestimating the depth and force of flowing water and thus taking significant risks (e.g. FitzGerald et al., 2010; Diakakis and Deligiannakis, 2013). Hence, although Swiss flood protection has been developed and refined considerably in the last decades (e.g. BWG, 2001), implying large financial investments, fatal events can only be prevented by such measures to a limited extent. This could partly explain the relatively moderate decrease in flood fatality over our study period. However, it has to be taken into consideration that deaths caused by floods were dramatically reduced since the middle of the 19th century in Switzerland, as showed e.g. in Petrascheck (1989). Still, it will be very important in the future to better inform and train people who regularly stay in or close to flood prone areas. A similar recommendation could be made for windstorms, as fatalities related to these events also often occurred due to negligent behaviour in dangerous situations.

5.4 Demography of fatality data

Our study revealed that male natural hazard fatalities have been much more frequent than female fatalities (75.9% male vs. 23.7% female). This pattern has also been observed in other countries, for example for fatal flood (Ashley and Ashley, 2008; Coates, 1999) and lightning (Singh and Singh, 2015; Navarrete-Aldana et al., 2014; Elsom, 2001; Curran et al., 2000) victims. To explain this striking gender difference, we first need to focus on work related deaths, which represent slightly more than one third of all recorded fatalities (Figure 12, Table 2~~3~~). A remarkable 93.5% of all natural hazard victims killed at work were men, and this percentage was at least 95% in the four first decades of the study period. This finding is probably mainly due to the fact that (i) during the study period, the ratio of men working full time was considerably higher than the ratio of women working full time, especially in the first half of the period; and (ii) many accidents were associated with occupations that are physically demanding and thus were, and to some extent still are, almost exclusively carried out by men, such as farm labour, forestry work, construction work, road maintenance (e.g. snow clearing) and rescue services. Thus, men have been more involved than women in employment (often involving outdoor work) that puts them at risk of dying in a natural hazard event.

More than half of all fatalities in our data set occurred during leisure time (Figure 12~~Table 3~~). Of these 536 victims, approximately two thirds were men and one third were women. Obviously, the predominance of male fatalities was not as strong as that observed in work related accidents, but it was still considerable. We assume that the gender difference observed for fatalities during leisure time activities was due to the higher risk perception of women compared to men (e.g. Bubeck et al., 2012; Lindell and Hwang, 2008; Tekely-Yesil et al., 2011). This effect probably leads to a more cautious and less adventurous behaviour of women, which could explain the difference between the number of male and female fatalities. What applies for recreational activities ~~work~~ might also be valid for work ~~recreational activities~~ and it seems that men have an overall greater disposition towards risk-taking than women. This is e.g. confirmed by Jensenius (2014) for lightning deaths in the USA. However, a growing recognition of the equality of the genders has led to a greater proportion of women being at risk relative to men (Coates, 1999). This trend is somewhat supported by our data, in that 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

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

5.6 Comparison of recent Swiss natural hazard fatality data with historic data

In our data set from Switzerland, less than 1% of all events caused more than 15% of the overall fatalities, and since 1946 no single natural hazard incident killed more than 88 people (section 5.2). Compared to some catastrophic historical events that occurred on Swiss territory, 88 victims is considerable but not exceedingly great. In this section, we briefly address three events that probably represent the most devastating natural hazard incidents of the last 1000 years in Switzerland: an earthquake, a rockslide, and a rockslide/flood wave combination.

On 18 October 1356 in the region of Basel, an earthquake occurred that is regarded as the strongest historically documented earthquake event in central Europe (Swiss Seismological Service, 2004). The inferred magnitude of the seism lies between 6.5 and 7.0. This event destroyed large parts of Basel, but the overall number of victims remains very uncertain (Fäh et al., 2009) and contemporary sources are sparse. While 300 deaths were associated with this incident in a chronicle from around 1580, miscellanies of the 16th century report a maximum figure of 2000 fatalities. However, , the latter number seems highly exaggerated (Fäh et al., 2009). If an identical earthquake occurred today, experts fear it would cause approximately1500 deaths (Katarisk, www.katarisk.ch).

Approximately 160 years later, during an intense rainfall period in September 1513, a massive rockslide 10 to 20 million m^3 in volume failed from Pizzo Magno and blocked the river Brenno at the end of the Blenio valley (canton of Ticino) just upstream of the village of Biasca (Heim, 1932). Due to this damming of the

~~Brenno, a shallow lake with a final length of 5 km was formed and two small villages were submerged. Roughly 20 months after the rockslide, in May 1515, the debris plug eroded and eventually collapsed. A massive surge of debris and water flooded Biasca and swept down the valley of the Ticino to the town of Bellinzona and further to Lago Maggiore (Eisbacher and Clague, 1984; Bonnard, 2011). Approximately 600 people were killed and some 400 buildings were destroyed.~~

~~On 2 September 1806, approximately 20 million m^3 of material (Eisbacher and Clague, 1984; other sources cite volumes up to 40 million m^3) failed on the southern slopes of Rossberg mountain in central Switzerland and subsequently destroyed and buried the villages of Goldau and Röthen, as well as parts of two adjacent hamlets. This so-called Goldau rock avalanche had a runout of about 1000 m and caused the destruction of more than 100 houses, 220 stables and barns, two churches and two chapels, and it killed 457 people. Several signs (e.g. tension crack formation and rockfall) predicted a failure several years before the event, but most people did not heed the warning and remained in the hazardous area (Heim, 1932; Eisbacher and Clague, 1984).~~

~~Further rockslides with catastrophic consequences occurred in the last centuries, such as an event in Elm in 1881 and an event in Plurs/Piuro (formerly Swiss territory, now Italy) in 1618. The latter event was exceptionally devastating and probably killed more than 2000 people. However, both events were to a large extent man-made, as intensive mining activity crucially destabilized the slopes that ultimately failed. Catastrophic events like the ones addressed above that seem to occur every 100 to 300 years in Switzerland and cause hundreds of victims would greatly change the fatality rates described in this contribution for the worse.~~

5.6~~7~~ Comparison of Swiss natural hazard fatality data with data from abroad

The EM-DAT International Disaster Database is a free and searchable source of information on world-wide victims of natural disasters (EM-DAT, www.emdat.be). In that database, we found 21 database entries for 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 ~~fatality~~ 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 ~~fatality~~ 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~~5~~). 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~~ (see section 5.6)~~, 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 ~~fatality~~ 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 ~~fatality~~ 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 ~~fatality~~ 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 ~~higher than that reported for India (0.25; Singh and Singh, 2015) and~~ 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, 2015). The decrease in lightning related fatalities we found over the last 70 years has also been observed in the USA (López and Holle, 1996) and in England and Wales (Elsom, 2001). In a comparative global summary of published lightning fatality estimates, Singh and Singh (2015) listed a value for 19th century Switzerland of 6.0 deaths per million population per year, which is more than ten times the value estimated in our study. Even though this figure was based on only two years of data (1876-1877), it illustrates the various improvements (e.g. better medical care, increased awareness) and the socio-economic changes that have occurred in Switzerland over the past 150 years.

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

5.78 Comparison of natural hazard fatality data with data from other accidental deaths

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

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

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

6. Conclusions

In this study, we compiled data from the Swiss flood and landslide database, the destructive avalanche database, and information collected in an in-depth newspaper search to establish a new database of fatalities caused by natural hazard processes in Switzerland. For a 70-year period from 1946 to 2015, we were able to assemble detailed data on 635 events during which 1023 people were killed by processes we summarized into seven hazard types (flood, landslide, rockfall, lightning, windstorm, avalanche, and *other* processes). Fatalities that occurred in connection with high-risk sports or certain popular summer and winter outdoor sport activities were not considered. Snow avalanches claimed 378 victims and clearly represent the deadliest natural hazard process in Switzerland. With 164 deaths, less than half as many fatalities were caused by lightning. Floods, windstorms, rockfall events and landslides killed 124, 105, 85 and 74 people, respectively.

Natural hazard fatalities were considerably variable over time. The number of people who died in one single year varied by one to two orders of magnitude. In 1951 and 1965, fatal events resulted in 112 and

108 deaths, respectively, whereas five years had only two fatalities each. For the 70-year study period, the average and median number of people who died due to natural hazards amounted to 14.6 and 9.0, respectively. Annual loss of life data showed a decrease over time, which was primarily induced by a marked decrease in deaths due to avalanches and lightning strikes. The reduction in avalanche fatalities in settlements and on transportation routes is a trend that has also been observed in other European countries and elsewhere. The decrease is due to improvements in both technical (defence structures, preventive artificial release) and organizational (e.g. hazard mapping, emergency planning) measures and to significant progress in avalanche education and forecasting. A reduction in lightning victims during the last century also occurred in many other countries around the world. In Switzerland, the main reasons for this distinct decrease might be that today fewer people work outdoors and there is a much improved awareness of the threat posed by lightning.

Most people were killed by natural hazard events in summer (JJA, 41.7% of fatalities) and winter (DJF, 32.2%). Accordingly, the four months with the largest number of victims were August (20.2%), January (14.2%), February (13.2%) and July (12.9%). While the summer peak mainly occurred due to flood and lightning events (together with one catastrophic ice avalanche in August 1965), the winter peak was caused by snow avalanche incidents. Furthermore, almost two thirds of the fatalities took place in the afternoon and evening.

Natural hazard fatalities were quite homogenously distributed over Switzerland. However, mountainous parts of the country (Prealps, Alps) were somewhat more prone to fatal events compared to the Swiss Plateau and the Jura. The reason for this is that avalanche fatalities, and to a slightly lesser extent rockfall and landslide fatalities, occur mainly in the alpine parts of Switzerland. In contrast, deadly events associated with floods and lightning were observed in practically all regions of Switzerland, with a definite maximum occurring along the Swiss Plateau. Finally, windstorm related fatalities were mostly observed on the Swiss Plateau, especially on lakes.

The age groups with the largest number of natural hazard victims were the 20-29 and 30-39 year-old groups (172 and 177, respectively), and almost 50% of all victims were between 20 and 49 years of age. Young children (0-9 years of age) were the age group that was most underrepresented in the fatality data compared to the Swiss age distribution. Three quarters of all fatalities were men, and men outnumbered women in all process types except landslides. We assume that this large gender difference was strongly influenced by two factors: first and probably more importantly, virtually all work related fatality incidents involved physically difficult occupations that put workers at risk and where the majority of workers are men; second, we speculate that women have a considerably higher risk perception compared to men and that, accordingly, men have a greater disposition towards risk taking than women. Both of these points are (probably) especially relevant for the first half of the study period.

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

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

	Total fatalities		**Normalized fatalities**	**Female fatalities**		**Male fatalities**		**Gender unclear**	**Percent female deaths**	**Percent male deaths**	**Altitude** [(A)]
Process type	**[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**

[(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 underestimation in comparison with the other processes.

Table 2: Natural hazard fatalities in Switzerland (1946-2015) classified by age groups.

Process type	Age group	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	Age un-known	Total
Flood	[deaths]	25	15	10	19	13	8	16	13	3	0	2	124
	[%]	*20.2*	*12.1*	*8.1*	*15.3*	*10.5*	*6.5*	*12.9*	*10.5*	*2.4*	*0*	*1.6*	*100*
Landslide	[deaths]	1	13	6	14	13	10	4	7	1	0	5	74
	[%]	*1.4*	*17.6*	*8.1*	*18.9*	*17.6*	*13.5*	*5.4*	*9.5*	*1.4*	*0*	*6.8*	*100*
Rockfall	[deaths]	4	13	11	11	8	14	15	1	1	0	7	85
	[%]	*4.7*	*15.3*	*12.9*	*12.9*	*9.4*	*16.5*	*17.6*	*1.2*	*1.2*	*0*	*8.2*	*100*
Windstorm	[deaths]	3	8	17	18	13	14	5	7	1	0	19	105
	[%]	*2.9*	*7.6*	*16.2*	*17.1*	*12.4*	*13.3*	*4.8*	*6.7*	*1.0*	*0*	*18.1*	*100*
Lightning	[deaths]	4	38	29	25	24	18	12	7	1	0	6	164
	[%]	*2.4*	*23.2*	*17.7*	*15.2*	*14.6*	*11.0*	*7.3*	*4.3*	*0.6*	*0*	*3.7*	*100*
Avalanche	[deaths]	39	48	74	68	66	44	18	11	2	1	7	378
	[%]	*10.3*	*12.7*	*19.6*	*18.0*	*17.5*	*11.6*	*4.8*	*2.9*	*0.5*	*0.3*	*1.7*	*100*
Other	[deaths]	1	2	25	22	14	3	2	1	0	0	23	93
	[%]	*1.1*	*2.2*	*26.9*	*23.7*	*15.1*	*3.2*	*2.2*	*1.1*	*0*	*0*	*24.7*	*100*
All processes	**[deaths]**	**77**	**137**	**172**	**177**	**151**	**111**	**72**	**47**	**9**	**1**	**69**	**1023**
	[%]	***7.5***	***13.4***	***16.8***	***17.3***	***14.8***	***10.9***	***7.0***	***4.6***	***0.9***	***0.1***	***6.7***	***100***
Male	[deaths]	51	99	144	144	115	83	53	34	6	1	46	776
	[%]	*6.6*	*12.8*	*18.6*	*18.6*	*14.8*	*10.7*	*6.8*	*4.4*	*0.8*	*0.1*	*5.9*	*100*
Female	[deaths]	26	38	28	33	36	28	19	12	3	0	19	242
	[%]	*10.7*	*15.7*	*11.6*	*13.6*	*14.9*	*11.6*	*7.9*	*5.0*	*1.2*	*0*	*7.9*	*100*

Table 2~~3~~: Natural hazard fatalities in Switzerland (1946-2015) classified by victims' activity, accident locality and victims' mode of transport.

		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**

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

Table 34: Quality of the data describing the circumstances of fatal natural hazard events and the victims (certain = information regarding this variable is fully reliable; probable = information regarding this variable was deduced but is very probable; unknown = no information available).

	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

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

Table 45: Fatal natural hazard events in Switzerland (1946-2015) classified by number of victims. The last two columns indicate the percentage of people that died 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 deaths for all process types.

	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**

Figure 1: Study area showing the Swiss stream network, the Swiss cantons (red polygons with abbreviations, see 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 (areas with different background colours), and several key cities (DHM source: dhm25 © 2016 swisstopo (5704 000 000)).

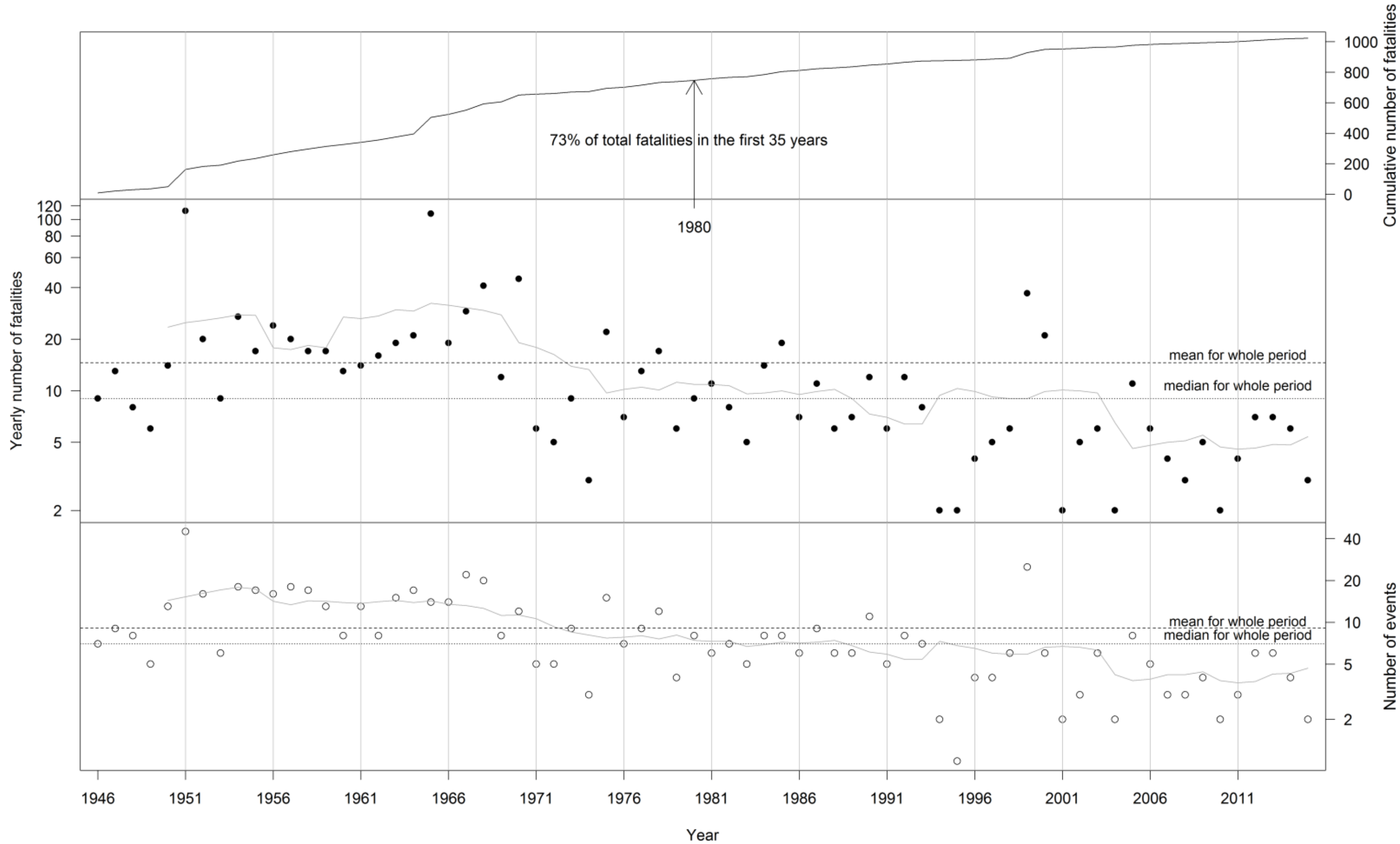


Figure 2: Total number of natural hazard deaths in Switzerland from 1946 to 2015: Cumulative number of fatalities (top) and ~~A~~a**nnual frequency of** ~~total natural hazard~~ **fatalities** ~~in Switzerland from 1946 to 2015~~ (middle)**.** At the bottom of the figure, the number of fatal natural hazard events is displayed. ~~The thin black line indicates the population increase during the study period.~~ **The** dashed and dotted **horizontal lines** in the middle and bottom panels **indicate the mean and median annual fatality frequencies** and annual event frequencies, respectively. The thin ~~black~~grey lines in the middle and bottom panels show a 10-year running mean.~~over the entire study period.~~

~~**Figure 3: Decadal sum of natural hazard fatalities in Switzerland from 1946 to 2015. The different colours indicate the seven process categories defined for this study (see section 3.4).**~~

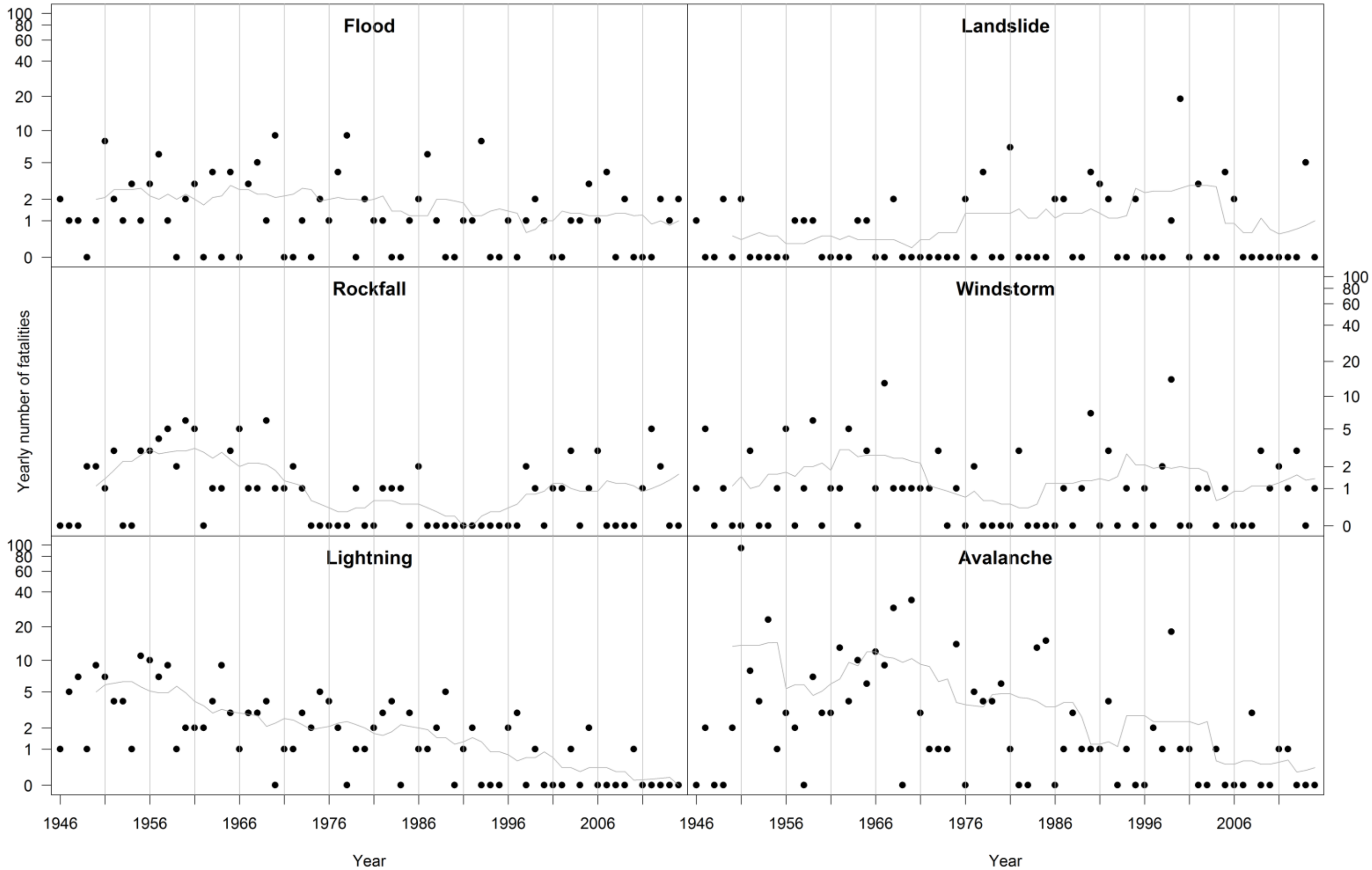
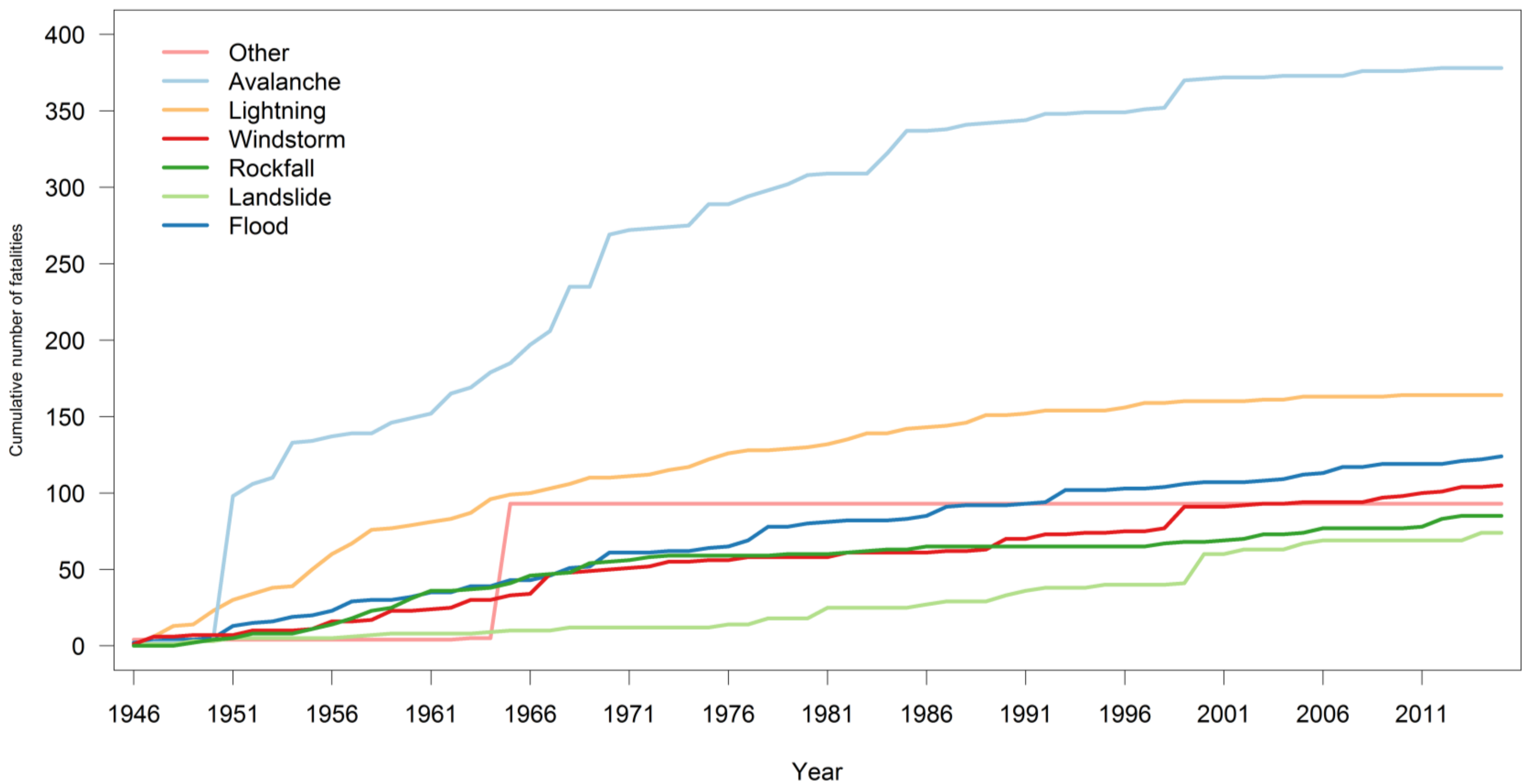


Figure 34: Annual frequency of fatalities in Switzerland for the different natural hazard categories considered in this study (except the category other). The thin blackgrey lines in all panels the show a 10-year running mean. Note that years with no fatalities were assigned an arbitrary value of 0.5 for plotting purposes and are labelled “none” on the y-axis. Note that the y-axis for avalanche ranges from 0 to 100 fatalities while the y-axis for all other process categories ranges from 0 to 20 fatalities.

~~**Figure 5: Annual frequency of natural hazard fatalities in Switzerland from 1946 to 2015, normalized by population (per million population). While the transparent bars show the overall normalized fatalities, the coloured dots represent the different process categories. The thin black line indicates the population increase during the study period.**~~



1138
1139 **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.**

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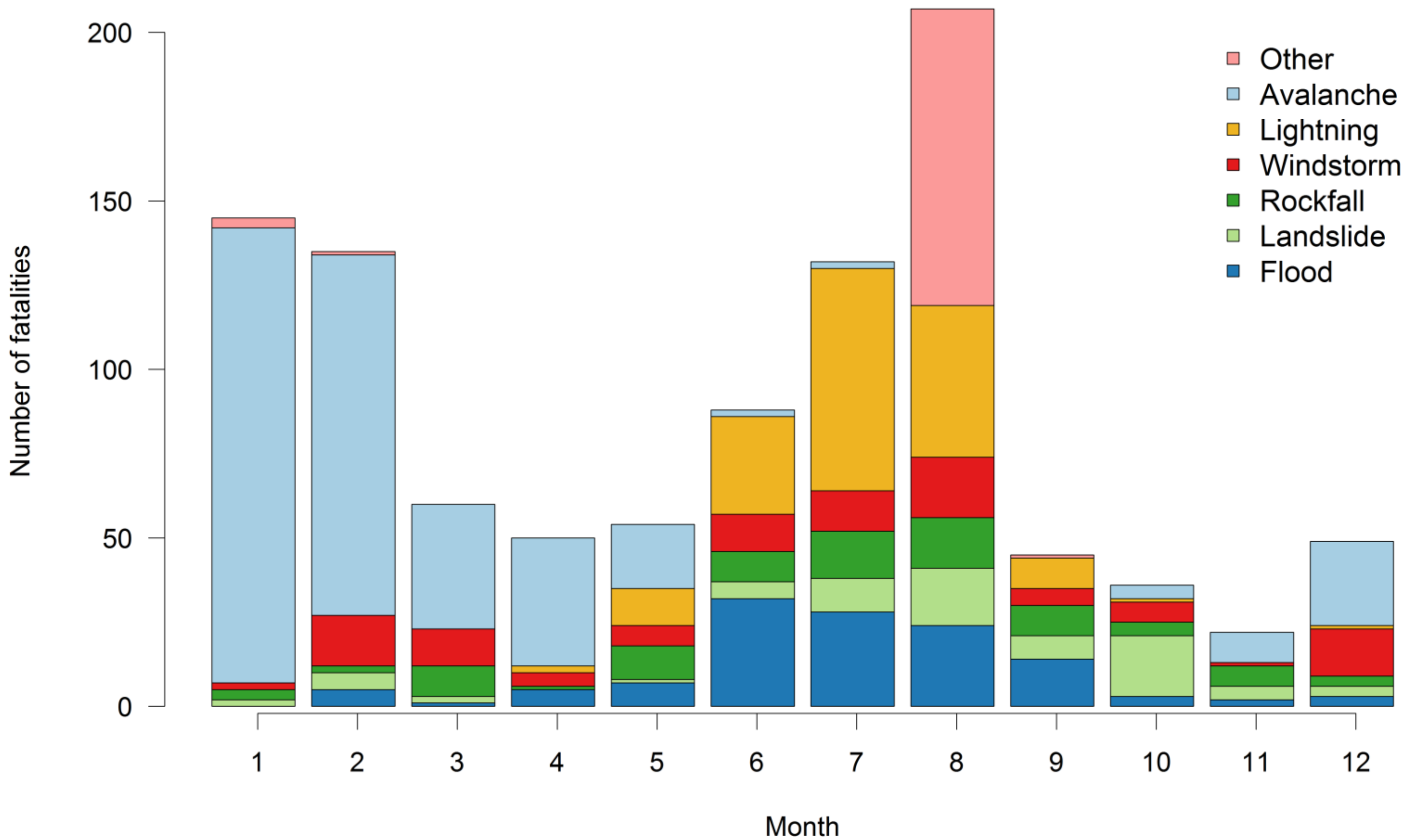

Figure 56: Monthly distribution of natural hazard fatalities in Switzerland from 1946 to 2015 (sum over study period). The different colours indicate the seven process categories defined for this study.

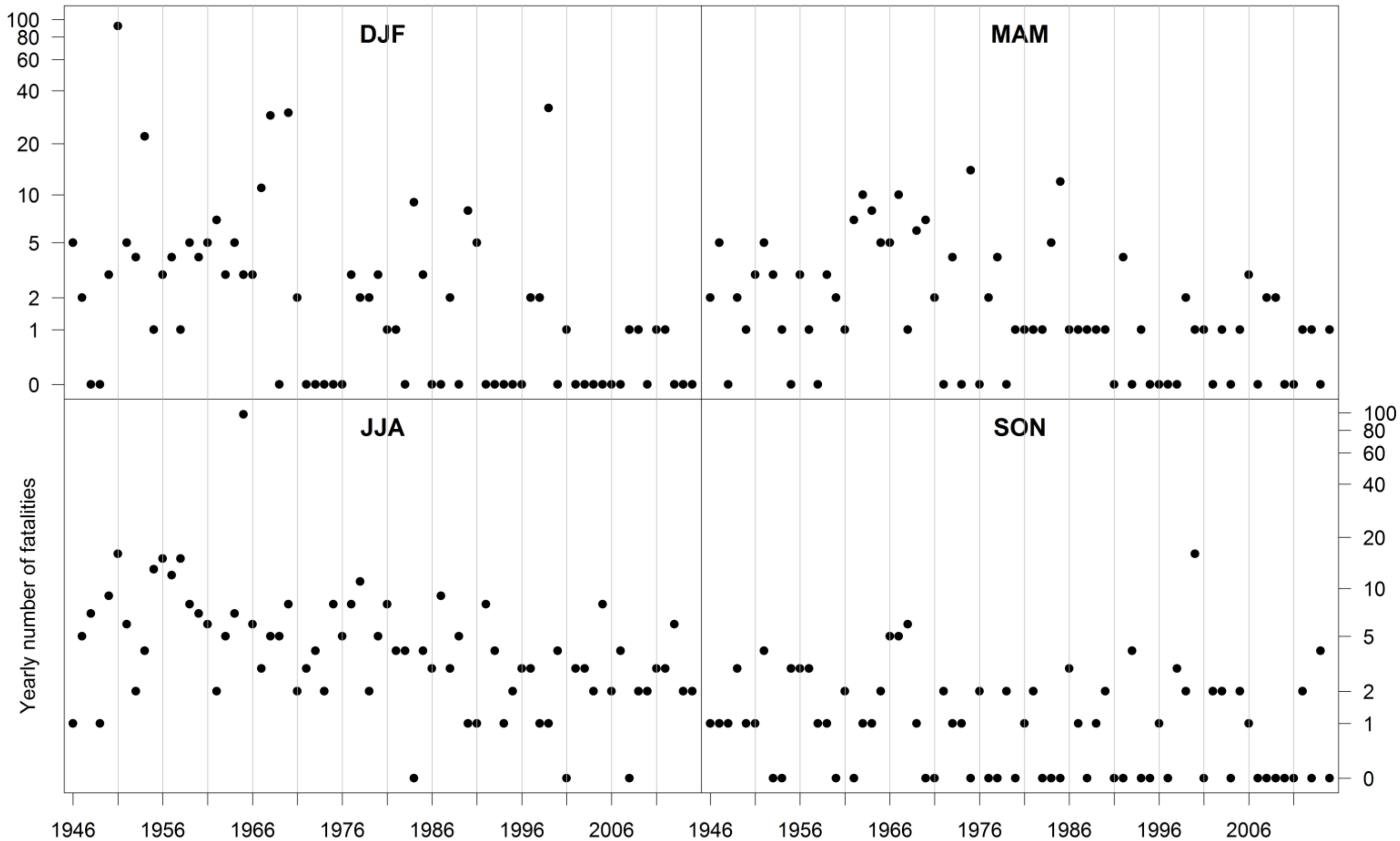

Figure 6: Annual frequency of total natural hazard fatalities in Switzerland from 1946 to 2015 for the four northern hemisphere seasons winter (DJF, top left), spring (MAM, top right), summer (JJA, bottom left) and autumn (SON, bottom right). Note that years with no fatalities in a certain season were assigned an arbitrary value of 0.5 for plotting purposes and are labelled "none" on the y-axis.

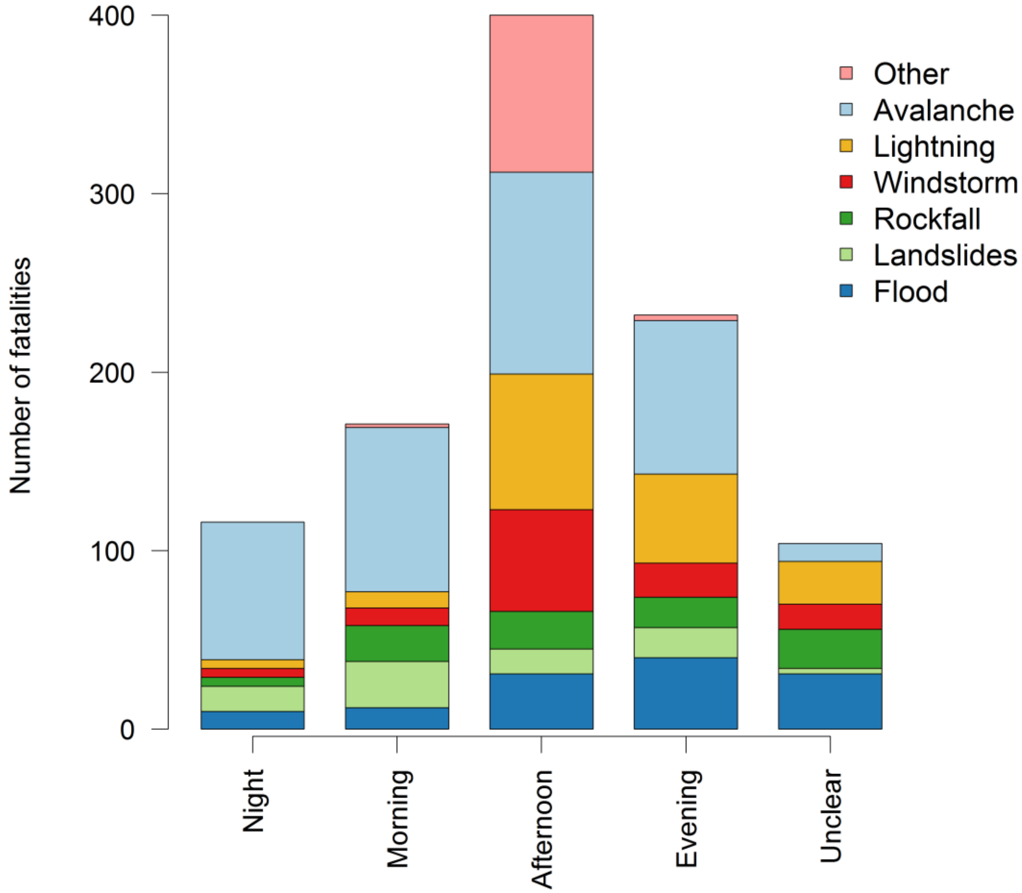

Figure 7: Distribution of natural hazard fatalities in Switzerland from 1946 to 2015 by time of day (sum over study period); morning (06:00-11:59 local standard time), afternoon (12:00-17:59), evening (18:00-23:59) and night (00:00-05:59). The different colours indicate the seven process categories defined for this study.

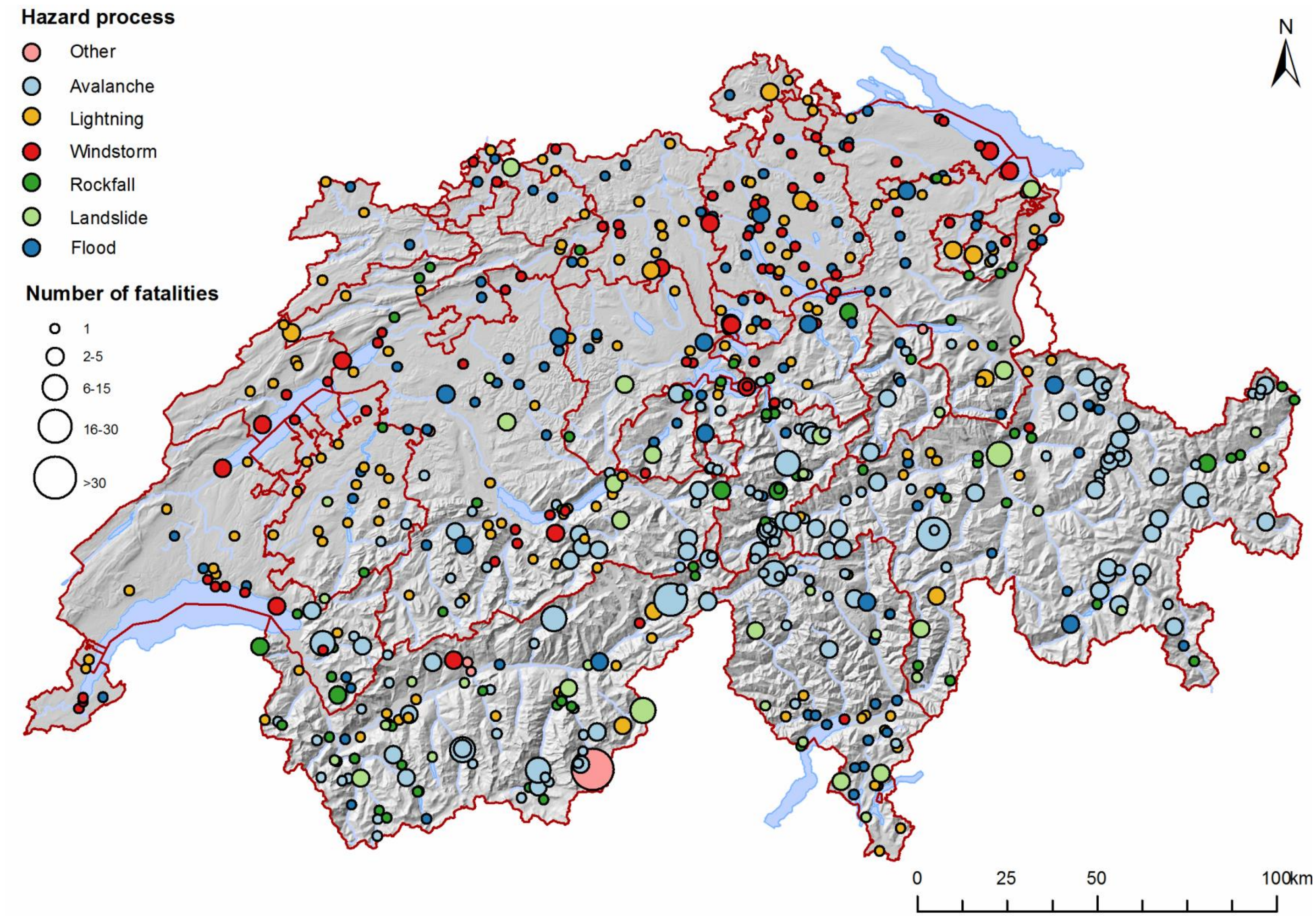

Figure 8: ~~(a)~~ Spatial distribution of fatalities caused ~~by~~ during natural hazard ~~processes~~ events in Switzerland from 1946 to 2015. The colour of each data point indicates the process type, and the size of the symbol shows the number of deaths per fatal accident (DHM source: dhm25 © 2016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

~~Figure 8: (b) Spatial distribution of normalized natural hazard fatalities (per year and per million population) over the 70-year study period at the cantonal level. The bars indicate the total number of deaths for each canton over the entire period.~~

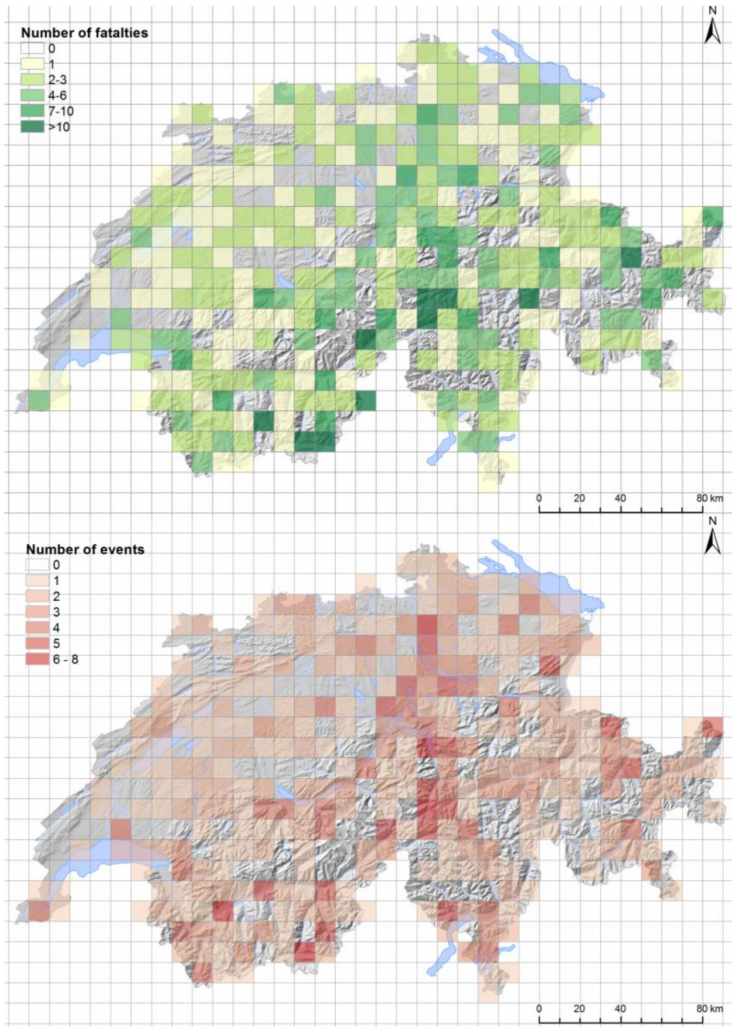

Figure 9: Spatial distribution of natural hazard fatalities (above) and fatal natural hazard events (below) in Switzerland over the 70-year study period using a 10x10 km raster grid (DHM source: dhm25 © 2016 swisstopo (5704 000 000)).

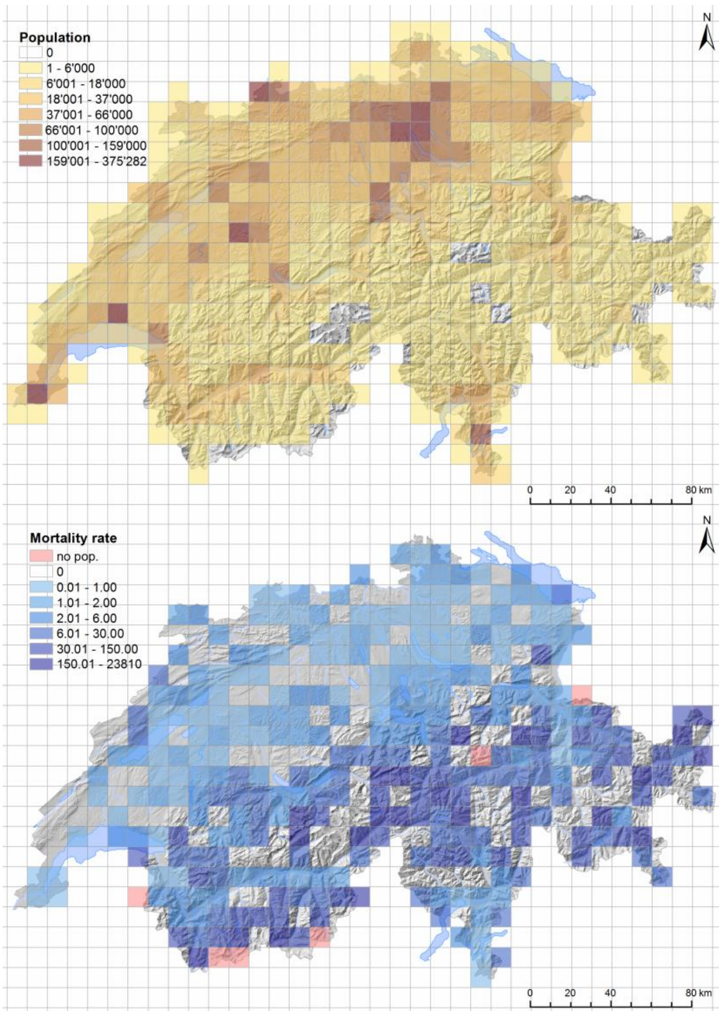

Figure 10: Spatial distribution of population as of 2015 (above) and normalized natural hazard fatalities per year and million population (below) in Switzerland over the 70-year study period using a 10x10 km raster grid (DHM source: dhm25 © 2016 swisstopo (5704 000 000)). Note that the gridded mortality 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 rate was calculated for the red grid cells because they are not populated (even though fatalities occurred there).

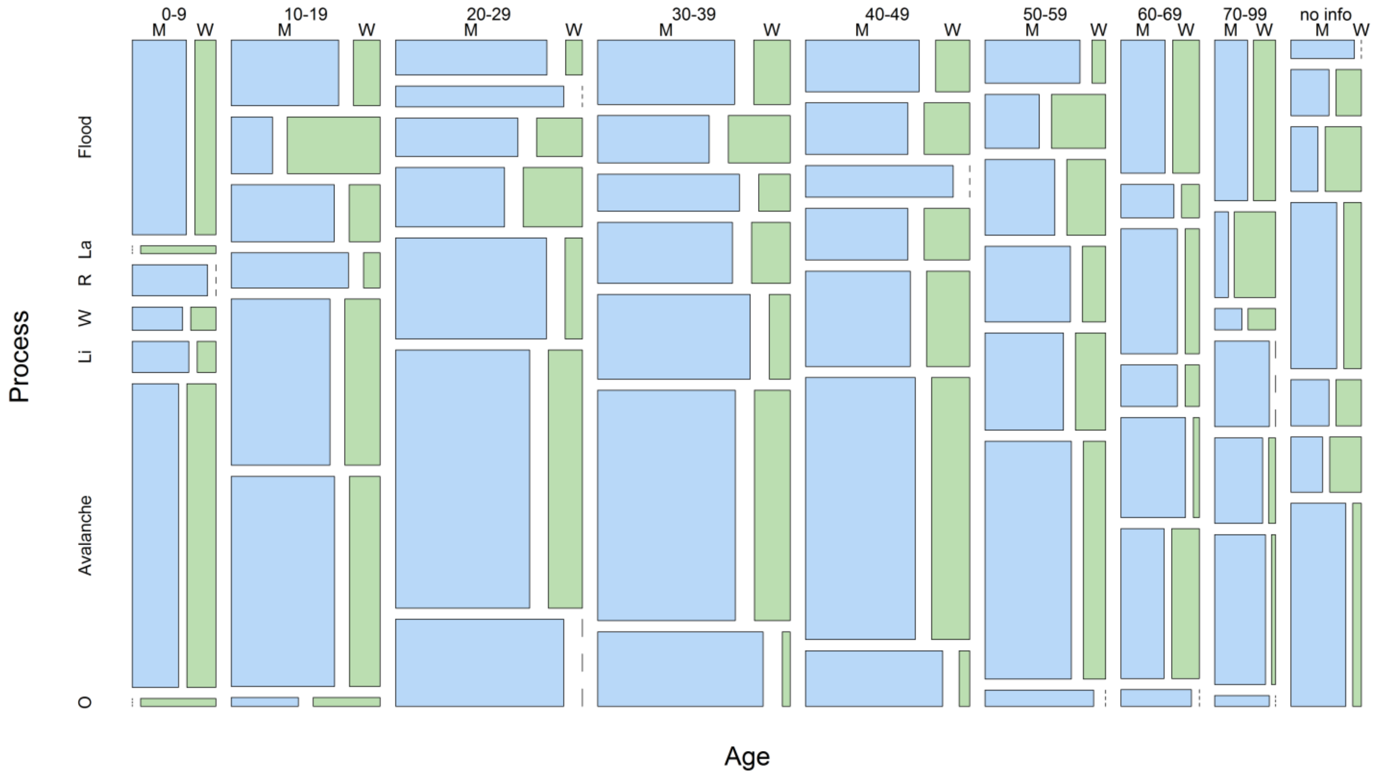

Figure 11: Mosaic plot showing age groups and gender for natural hazard fatalities in Switzerland (1946-2015). Fatalities are subdivided according to the hazard type (flood, La=landslide, R=rockfall, W=windstorm, Li=lightning, avalanche, and other). Also see Table S2 in the supplementary material.

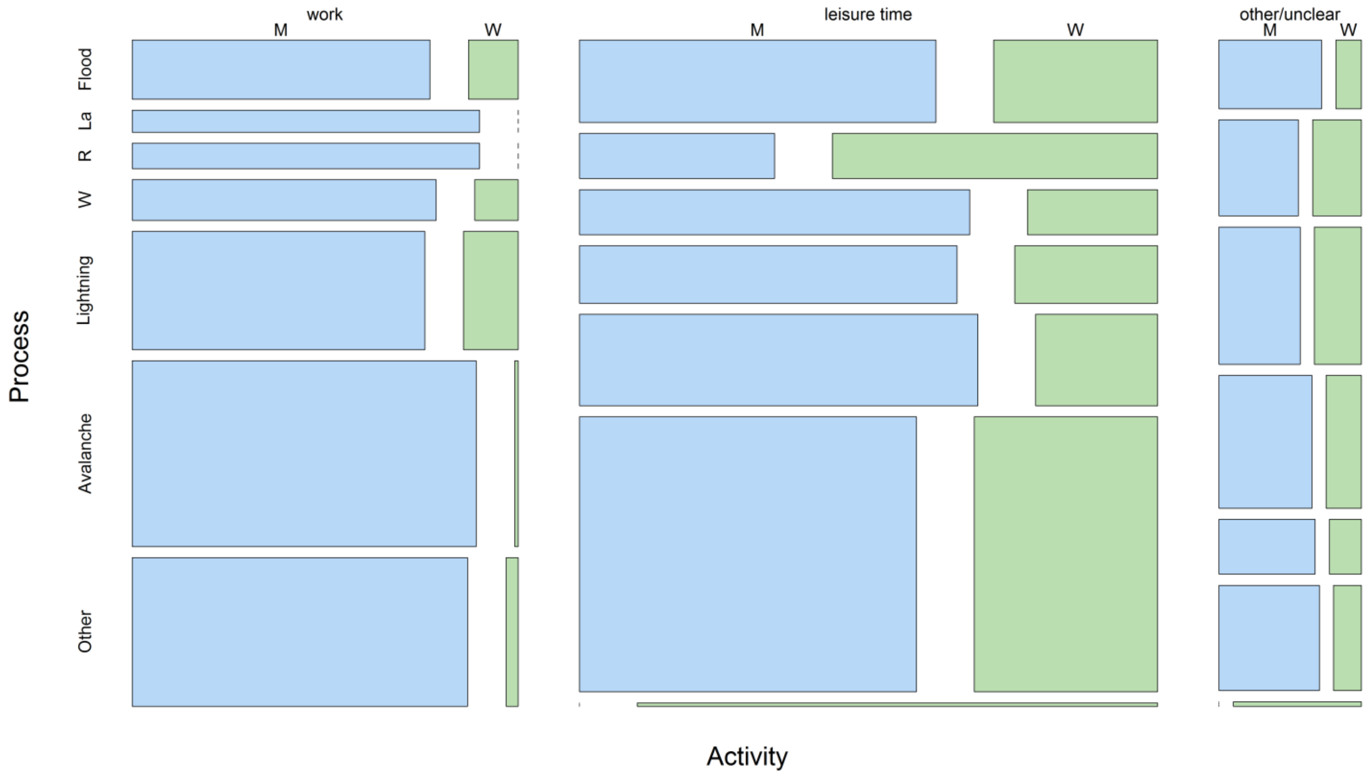

Figure 12: Mosaic plot showing victim's activity and gender for natural hazard fatalities in Switzerland (1946-2015). Fatalities are subdivided according to the hazard type (flood, La=landslide, R=rockfall, W=windstorm, lightning, avalanche, and other). Also see Table 2.