Debris Flow Activity in Permafrost Regions in Austria During the 20th Century

Roland Kaitna and Thomas Huber

Abstract

Debris flows typically result from a critical combination of relief energy, water, and sediment. Hence, besides water-related trigger conditions, the availability of abundant sediment is a major control on debris flows activity in alpine regions. Increasing temperatures due to global warming are expected to affect the periglacial environment and by that the distribution of alpine permafrost and the depth of the active layer. This might lead to increased debris flow activity and increased interference with human interests. Here we assess the importance of permafrost on documented debris flows in the past by connecting the modeled permafrost distribution with a large database of historic debris flows in Austria. The permafrost distribution is estimated based on the model PERMAKART 3.0, which mainly depends on altitude, relief, and exposition. The database of debris flows includes more than 4500 debris flow events in around 1900 watersheds in the Austrian Alps. We find that around 10% of documented debris flows occurred in watersheds having a permafrost fraction larger than 5% in their headwaters. Only around 50% of historic debris flow events were documented in watersheds where permafrost is clearly absent. Our results indicate that watersheds without permafrost experience less, but more intense debris flow events than watersheds with modeled permafrost occurrence. We find no trend of increased debris flow occurrence rate from permafrost regions in recent years. Our study aims to contribute to a better understanding of geomorphic activity and the impact of climate change in alpine environments.

Keywords

Debris flow • Permafrost • Climate change • Eastern alps

Introduction

Debris flows represent a severe hazard in alpine regions. The occurrence of such mass flows is typically associated with a critical combination of relief energy, water, and sediment. Several studies focused on the identification of critical rainfall conditions at different spatial scales by searching for deterministic threshold conditions in the relation between rainfall intensity and rainfall duration, or between cumulative rainfall and rainfall duration (e.g. Caine 1980; Crosta 1997; Corominas and Moya 1999; Guzzetti et al. 2008) or probabilistic thresholds based on an Bayesian approach (e.g. Berti et al. 2012; Turkington et al. 2016). Besides these water-related trigger conditions, the availability of abundant sediment is a major control on debris flows activity in alpine regions (Kienholz 1995). In high alpine regions, where the ground (rock or soil) is permanently frozen, sediment availability is expected to be at least partially controlled by

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glacial and periglacial processes. Increasing temperatures due to global warming (IPPC 2013) lead to glacier retreat and are also expected to affect periglacial regions (Harris et al. 2009). The change of distribution of alpine permafrost and the depth of the active layer, as well as increased deformation rates of rock glaciers might lead to increased debris flow activity and increased interference with human interests (e.g. Harris et al. 2009; Stoffel and Huggel 2012). To what extend permafrost occurrence and debris flow activity were connected in the past is not well known. In this contribution we assess the importance of permafrost occurrence on documented debris flows in the past by connecting the modeled permafrost distribution with a large database of historic debris flows in Austria. The research questions of this contribution include:

- How many/what fraction of the documented debris flows were released in permafrost regions?
- Are debris flow events from permafrost regions more intense?
- Can we detect a change of occurrence rate over the last century?

Methods

Permafrost Modeling

To assess the permafrost distribution, we applied the model PARMKART 3.0 suggested by Schrott et al. (2012) on a 10 × 10 m digital elevation model of Austria. Here a permafrost index assessing the probability of permafrost occurrence is derived from topographic parameters like slope class, elevation, and exposition. Based on the permafrost index we derive a map of areas with “permafrost probable” and “permafrost possible”. In the subsequent analyses shown here we combined both areas. For details and model evaluation see Ebohon and Schrott (2011) and Schrott et al. (2012).

Historic Events and Data Analysis

The Austrian database of historic torrential events includes more than 4500 debris flow and debris flood events which occurred in 1907 watersheds since the year of 1900 (Hübl et al. 2008). For most of these events a qualitative classification of event intensity (S, M, L, XL) was available (Fig. 1).

As we expect an uncertainty of the modeled permafrost distribution, we differentiate between permafrost-prone watersheds with a permafrost area larger than 5% and watersheds with permafrost area smaller than 5%. Events that occurred in the latter were excluded from further analysis. The following analysis focuses on the

- “permafrost rate” (the rate of permafrost area to total watershed area)
- “event density” (ratio of average events per watershed)
- “event intensity” for events from permafrost regions and event from no-permafrost regions
- “event frequency” based on a Gaussian kernel density estimate (Mudelsee 2003; Braun 2014).

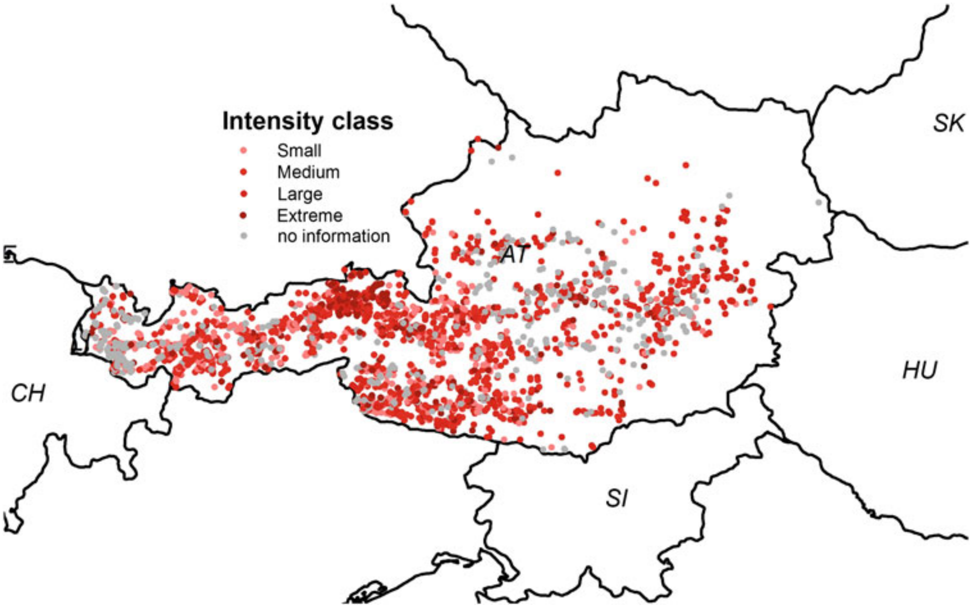

Fig. 1 Documented debris flow events since 1900 in Austria (modified from Hübl et al. 2008)

Results

The map of the modeled permafrost distribution for the Austrian Alps shows that a total area of around 1300 km^2 is likely to be permafrost ground (Fig. 1), which corresponds to about 1.5% of the Austrian territory. The occurrence of alpine permafrost is concentrated in the high altitude regions of southern Tyrol and southern Salzburg and some small amounts around the Hochkönig and the Dachstein area (see Ebohon and Schrott 2011).

After overlaying the modeled permafrost distribution with the watersheds that were prone to debris flow activity, we find that only about 49.3% of watersheds (2224) that experienced debris flow events in the past had no modeled permafrost area in the upper catchments. On the other side, 9.2% of the watersheds (415) have an area of modeled permafrost >5% of the catchment area (Fig. 2). The rest, about 41.5% of the watersheds (1871) have an area smaller than 5% of the catchment area (Table 1). As mentioned earlier, the following analysis concentrates on contrasting watersheds with a high certainty of permafrost occurrence with watersheds that for sure are not affected by permafrost (Fig. 3).

Interestingly, we find that watersheds that include more than 5% permafrost experience significantly more debris

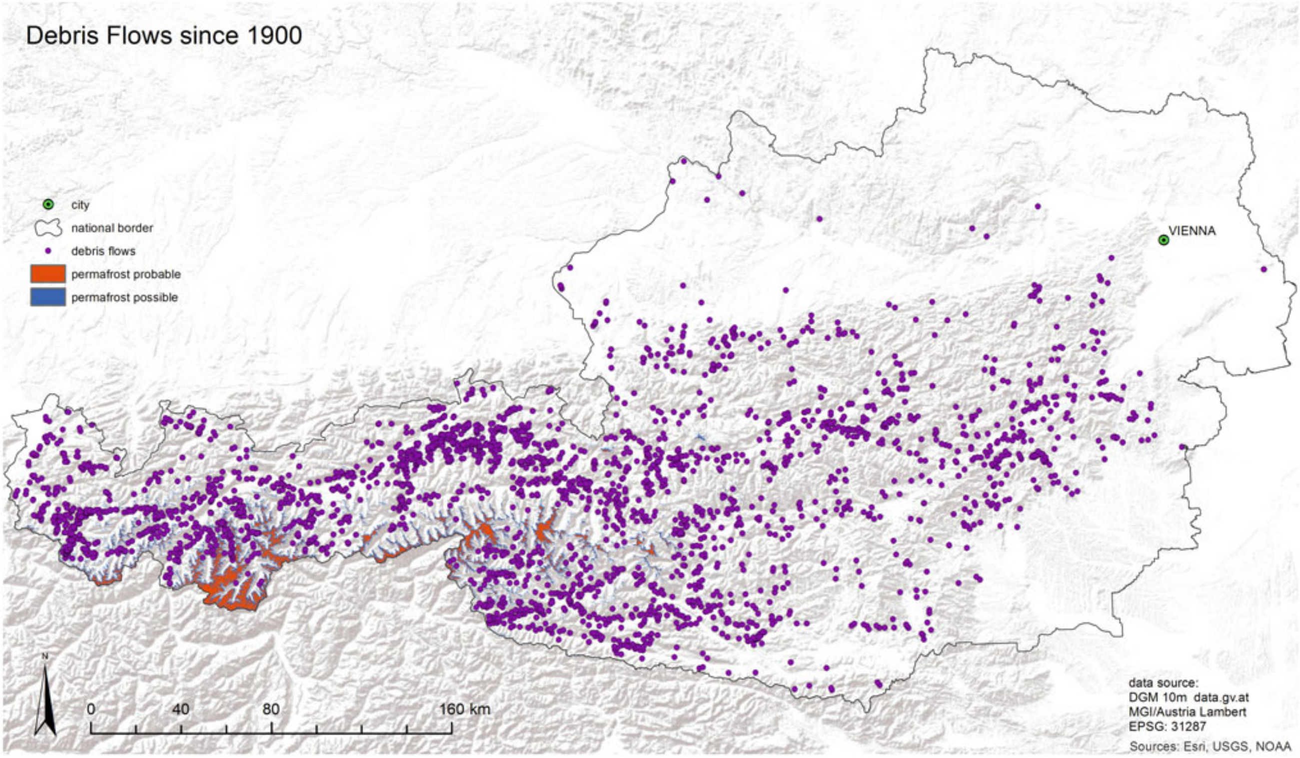

Fig. 2 Map of modeled permafrost distribution and debris flow events since 1900

Table 1 Events per watershed

	Events since 1900	No. of watersheds	Average events per watershed
Total	4510	1907	2.4
$\geq$5% p.f.	415	139	3.0
w/o p.f.	2224	1254	1.8

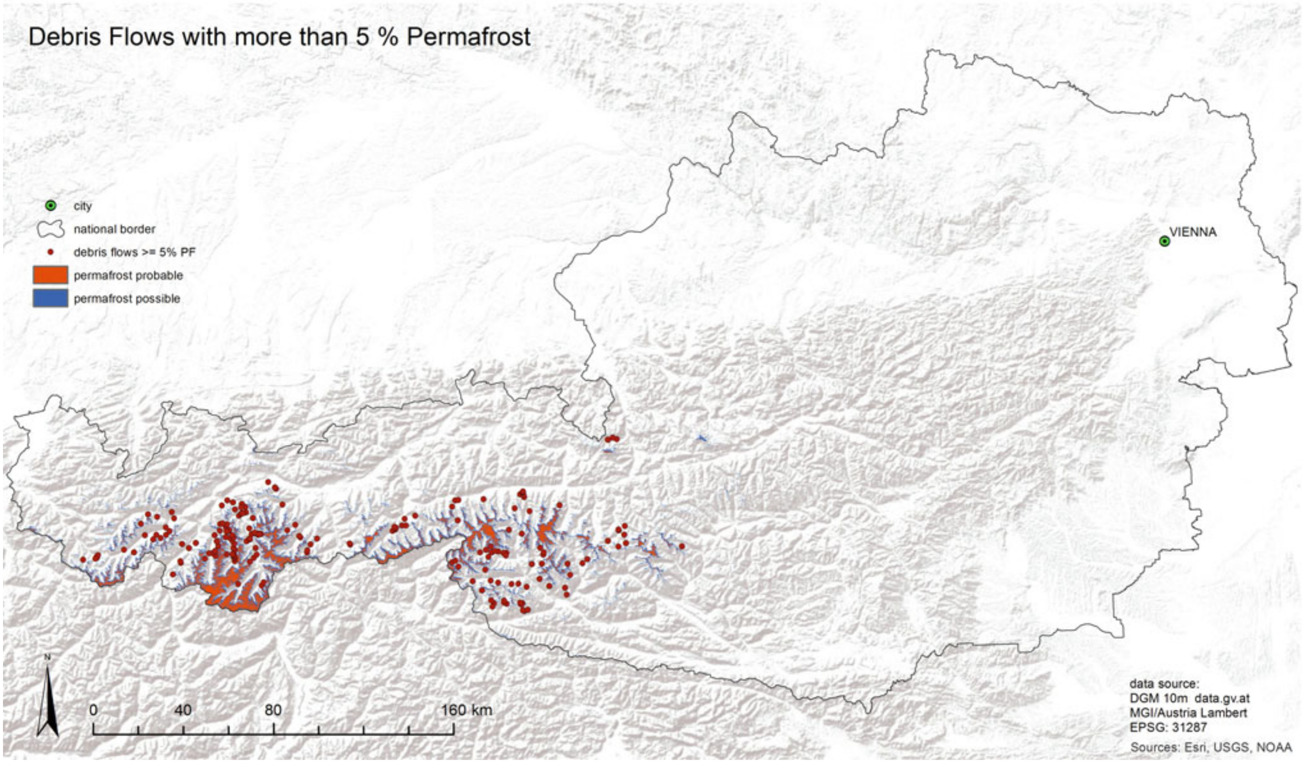

Fig. 3 Map of modeled permafrost distribution and debris flow events since 1900 from watersheds with a permafrost area larger 5% of total area

flow events (3.0 events per watershed) than watersheds without modeled permafrost occurrence (1.8 events per watershed, see Table 1). Scrutiny reveals that some areas with very high permafrost rates show almost no events (e.g. the area around the Wildspitze-peak in Tyrol). We assume that increased debris flow activity is not necessarily conditioned to permafrost occurrence but probably also to other topographic factors that are typical for regions with permafrost (e.g. high relief energy/Melton numbers).

Analyzing the frequency distribution of debris flow events and corresponding watersheds in dependence of modeled permafrost area (Fig. 4), we find that the occurrence rate of debris flows is highest in watersheds with a fraction of permafrost area between 5 and 10%. For permafrost fractions above 10% the exponential decline of number debris flow events and corresponding watersheds is quite similar.

When considering the qualitative description of debris flow intensity in the history documents, we find that debris flows from watersheds with more than 5% modeled permafrost tend to be less intense than events from watersheds without modeled permafrost occurrence (Fig. 5).

Applying a kernel-density analysis (Mudelsee et al. 2004; Braun 2014), and separating watersheds with a permafrost fraction larger 5% and watersheds not affected by permafrost, we cannot detect a significant increase of debris flow occurrence rate in recent decades that could be attributed to increased temperatures in the course of climate change (Fig. 6).

Conclusions

In this contribution we connect the modelled permafrost distribution with historic data of debris flow activity in Austria over roughly the 20th century. Our results indicate following concluding statements:

- Around 10% of documented debris flows occurred in watersheds having a permafrost fraction larger than 5%. Only around 50% historic debris flow events were documented in watersheds where permafrost is clearly absent.
- Watersheds with a significant fraction of permafrost tend to produce more debris flow events than watersheds

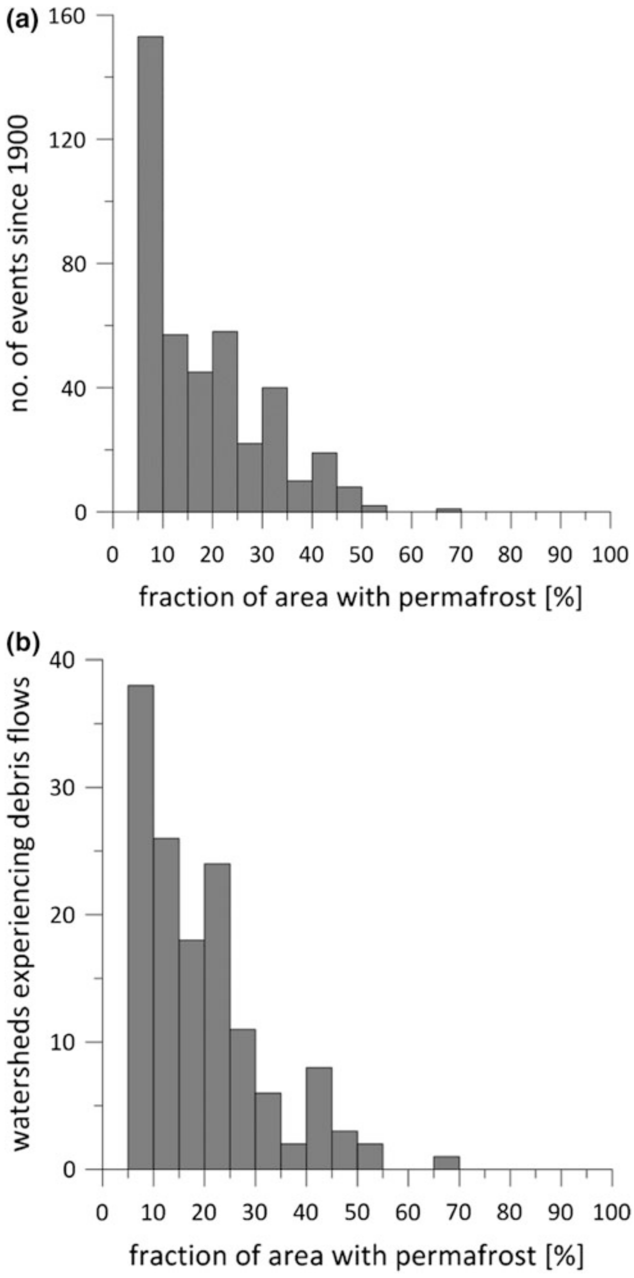

Fig. 4 Frequency distribution of **a** debris flow events and **b** watersheds in relation to the fraction of permafrost area

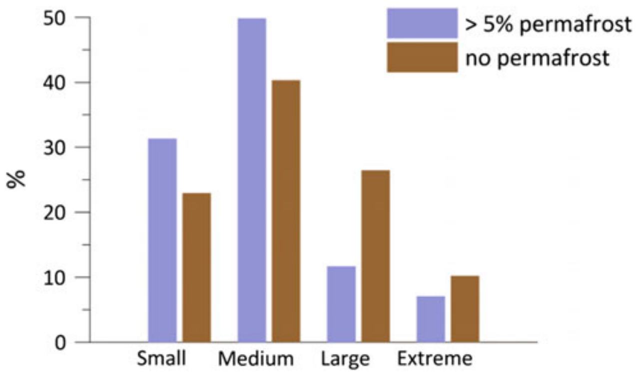

Fig. 5 Event intensities for debris flows from watersheds with a high fraction of permafrost area and watersheds not affected by permafrost

without permafrost (which is not necessarily conditional).

- Debris flows from watersheds affected by permafrost appear to be less intense.
- There is no apparent long-term trend of increased debris flow occurrence rate from permafrost regions in recent years.

We assume that a limitation of the presented results is connected to the uncertainty of permafrost modeling. In this study we do not differentiate between permafrost possible and permafrost probable. Due to the large region of interest we did not go into detail of investigating the real sources of sediment and the location of model permafrost areas. Another important limitation of this study is the incompleteness of the event database of debris flows in Austria, which is expected to be especially true in remote areas in high alpine regions (i.e. regions with permafrost). Additionally historic debris flow activity might be affected by changes in land use and construction of technical mitigation (especially since the second half of the 20th century) is expected to affect debris flow activity in Alpine Austria.

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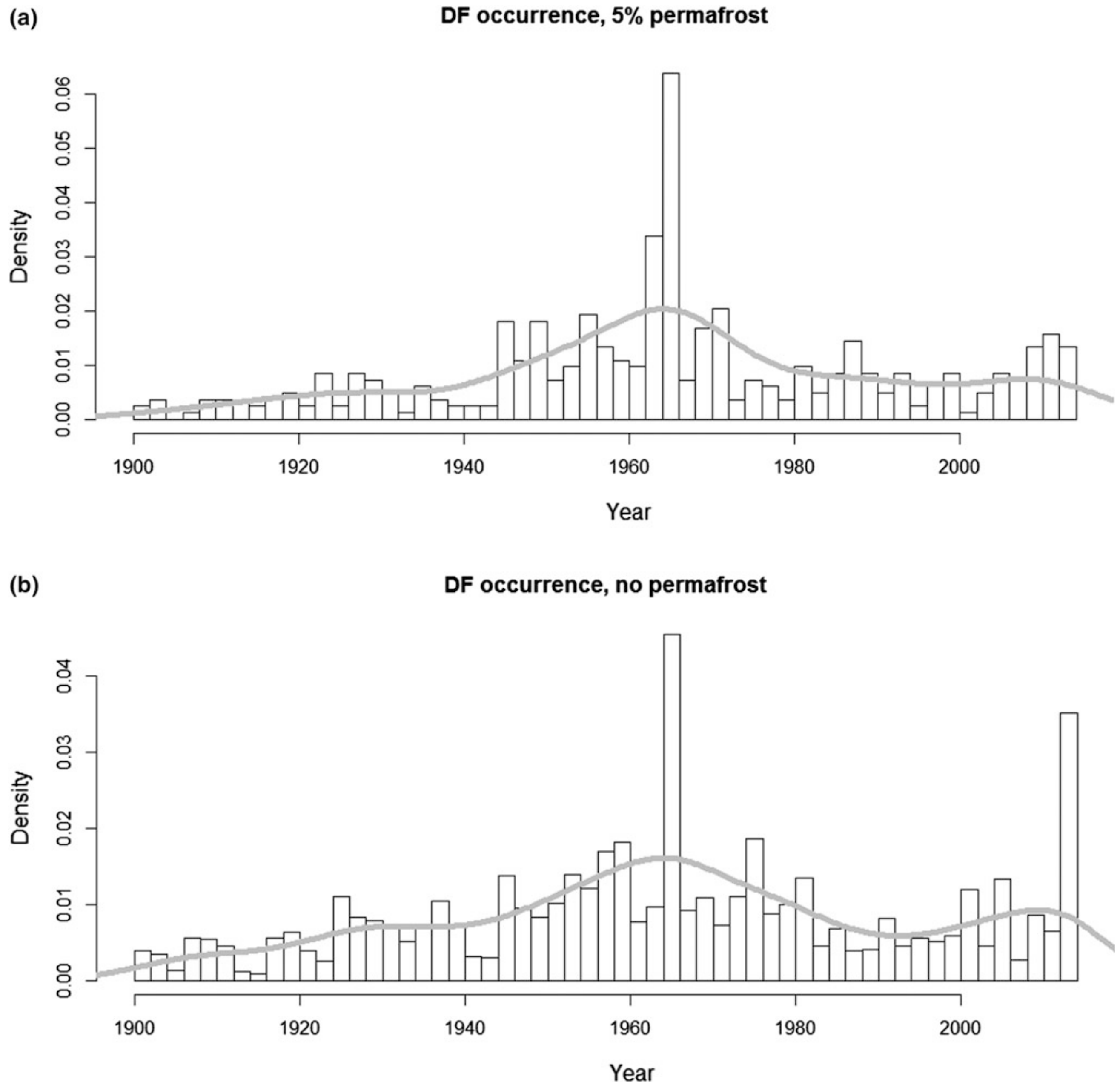

Fig. 6 Event density of historic debris flows occurring in **a** watersheds with a modeled permafrost fraction larger than 5%, and **b** watersheds not affected by permafrost

References

Berti M, Martina M, Franceschini S, Pignone S, Simoni A, Pizziolo M (2012) Probabilistic rainfall thresholds for landslide occurrence using a bayesian approach. J Geophy Res Earth Surf 117:F04006. doi:10.1029/2012JF002367

Braun M (2014) Hydrometeorological triggers of debris flows: evolution of the temporal occurrence of debris flows between 1900 and 2008. Masterarbeit, Institut für Alpine Naturgefahren (IAN), Universität für Bodenkultur, Vienna

Caine N (1980) The rainfall intensity: duration control of shallow landslides and debris flows. Geografiska Annaler. Series A. Phys Geogr, 23–27

Corominas J, Moya J (1999) Reconstructing recent landslide activity in relation to rainfall in the Llobregat river basin, eastern pyrenees, Spain. Geomorphology 30:79–93

Crosta G (1997) Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environ Geol 35:131–145

Ebohon B, Schrott L (2011) Modelling mountain permafrost distribution. A new permafrost map of Austria. Department of Geography and Geology, University of Salzburg, Salzburg

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5:3–17. doi:10.1007/s10346-007-0112-1

Harris C, Arenson LU, Christiansen HH, Etzelmüller B, Frauenfelder R, Gruber S, Isaksen K et al (2009) Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. Earth-Sci Rev 92(3):117–171

Hübl J, Totschnig R, Sitter F, Mayer B, Schneider A (2008) Historische Ereignisse—Band 2: Auswertung von Wildbach Schadereignissen in Westösterreich auf Grundlage der Wildbachaufnahmeblätter, IAN Report 111. Vienna

IPCC (2013) Summary for policymakers, In: Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Kienholz H (1995) Gefahrenbeurteilung und-bewertung-auf dem Weg zu einem Gesamtkonzept. Schweizerische Zeitschrift für Forstwesen 146:701–725

Mudelsee M, Börngen M, Tetzlaff G, Grünewald U (2003) No upward trends in the occurrence of extreme floods in central Europe. Nature 425:166–169

Schrott L, Otto JC, Keller F (2012) Modelling alpine permafrost distribution. In: The Hohe Tauern region, Austria. Austrian J Earth Sci (105/2), S. 169–183

Stoffel M, Huggel C (2012) Effects of climate change on mass movements in mountain environments. Prog Phys Geogr 36:421–439. doi:10.1177/0309133312441010

Turkington T, Remaitre A, Ettema J, Hussin H, Westen C (2016) Assessing debris flow activity in a changing climate. Climatic Change 1:1–13. doi:10.1007/s10584-016-1657-6