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Impact of climate change on hydro-meteorological trigger conditions for debris flows in Austria

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Abstract. Debris-flow activity is expected to change in a future climate. In this study we connect a susceptibility model for debris-flows on a regional scale with climate projections until 2100. We use this to assess changes of hydro-meteorological trigger conditions for debris flows in six regions in the Austrian Alps. We find limited changes on an annual basis, but distinct changes when separating between hydro-meteorological trigger types and regions. While regions in the east and in the south of Austria may experience less days susceptible to debris flows in summer, there is a general trend of increasing susceptibility earlier in the year for both, rainfall-related and snow-related trigger conditions. The outcomes of this study serve as a basis for the development of adaption strategies for future risk management from this debris-flow hazard.

1 Introduction

Debris flows initiate by a critical combination of abundant sediment, steep inclination, and water [1]. The water-component is mostly provided by rainfall, leading to slope failure- or runoff-generated debris flows (e.g. [2, 3]). The triggering rainfall can span from convective storms to stratiform precipitation (e.g. [4]). Sometimes intensive snow-melt or rain-on-snow events can play a significant role in debris-flow initiation (e.g. [5]).

For all emission scenarios, climate simulations project an increase of temperature and changes of the seasonal precipitation pattern in the European Alps (e.g. [6]). A common theme in the assessment of changing debris-flow activity is that a future climate with increased temperatures can store more water in the atmosphere, which results in more frequent and intense rainfall events [7] that may trigger such mass movements [8].

Up to now, there are only a few studies that investigate the impact of climate change on debris-flow activity in specific watersheds (e.g. [9]) or regions (e.g. [10-12]). In this study we aim to assess the impact of climate change on debris-flow trigger conditions in the Austrian Alps.

2 Methods

2.1 Study design

We feed a semi-distributed hydrological model with 28 down-scaled and bias-corrected climate change projections on a daily basis until 2100 [13]. The hydrological model was independently calibrated and validated for six study regions in the Austrian Alps over a period of 40+ years ([14, 15]). The resulting time series of hydro-meteorological variables of the reference period (1971-2000) as well as for the near future (2021 to 2050) and the far future (2071 to 2100) are subsequently fed into a trigger model for debris flows [14] that differentiates between the meteorological trigger types “long lasting rainfall” (LLR), “short-duration storm” (SDS), “snow melt” (SM) and “rain-on-snow” (RS). We subsequently assess the change in frequency of days susceptible to debris flows in the six study regions. We also analyse regional and seasonal changes of the different trigger types (Figure 1).

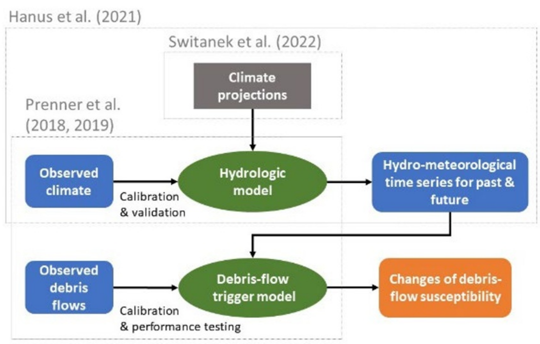

Fig. 1. Flowchart of the study design separately applied to all six study regions.

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2.2 Study regions

The study regions range from high-altitude valleys north and south of the alpine chain, to lower elevations in the east of the Austrian Alps (Figure 2).

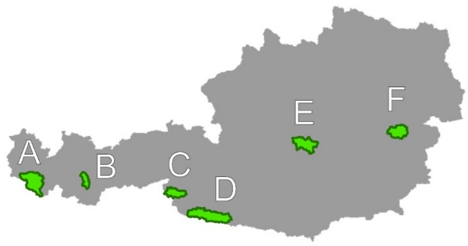

Fig. 2. Overview of the six study regions (west to east): A-Montafon, B-Pitztal, C-Defereggental, D-Gailtal, E-Paltental, and F-Feistritztal.

The Gailtal region occupies the largest area with 586 km², followed by the Montafon region with 510 km². The regions Pitztal and Feistritztal are the smallest with 133 km² and 115 km², respectively. The elevation range of the regions decreases from west to east. While the western catchments (Montafon, Pitztal, Defereggental) have a high-alpine character (exceeding 3000 m above sea level), the eastern catchments are sub-montane to montane with a narrower elevation range (e.g. Feistritztal 400 to 1600 m a.s.l.).

2.3 Climate projections

Projected station data were derived from regional climate simulations from the EURO-CORDEX initiative. The statistical downscaling approach considers the spatial correlation of all of the nearby weather stations within our study regions [13].

The projections are based on the “moderate” scenario RCP4.5, which assumes an additional forcing of 4.5 W m^{-2}, and the “business as usual” scenario RCP8.5, with a surplus loading of 8.5 W m^{-2} by the end of the 21st century. In total we use 28 climate time-series for each rain and temperature station from 1970 and 2100 as input for hydrological modelling.

To assess changes, we define three periods. The first represents our current and immediate future period (2021 to 2050), which we term “near future”, the second is the period 2071 to 2100 (“far future”). The historical period from 1971-2000 serves as reference period.

2.4 Trigger model

The trigger model differentiates between the trigger types long-lasting rainfall (LLR), short-duration storms (SDS), snow melt (SM), and rain-on-snow (RS). These trigger types have shown significantly different signatures in the hydro-meteorological timeseries on days when debris flows occurred in the past. For example, a long-lasting rainfall event is typically associated with decreasing temperatures and increasing soil moisture on the days preceding a debris-flow event in the regions. In contrast, a convective “short-duration storm” occurs when the landscape heats up, leading to a decrease of soil moisture and an increase of temperature span during a day. Debris-flow events associated with snow melt occur on consecutive days increasing soil moisture due to intensive snowmelt. In the current study we use a similar set of trigger criteria as presented by [14] and are detailed in [16].

3 Results

3.1 Changes of hydrological catchment states

The hydrological response of our study regions changes significantly by shifting precipitation and temperature patterns in a future climate, which is similar to the detailed analysis of changes of runoff signatures by [15]. Overall, catchments become wetter in winter (increased soil moisture, slightly more precipitation and less snow fall) and drier in summer (less precipitation and drier soils).

3.2 Changes of debris-flow trigger conditions

Averaged over all regions, we find no strong signal for changes of any trigger type. However, there are distinct regional as well as seasonal differences of trigger conditions. On an annual basis, the most distinct changes are predicted for the Paltental, a low-alpine region in the central to eastern part of Austria, and the Pitztal, a high-alpine valley in the western part (Figure 3). In the Paltental the annual number of days susceptible to debris flows are projected to decrease by -7 % (-4.3 d/yr) for RCP4.5 and up to 14 % (-5.7 d/y) for RCP8.5, mainly due to a decrease of LLR and SDS trigger types (Figure 3a). For the Pitztal region LLR events are expected to increase by up to 12% (2.7 d/yr) in the far future for emission scenario RCP8.5 (Figure 3b). For the regions south of the Alpine main ridge (Gailtal and Defereggental), there is a tendency of snow-related trigger conditions to decrease.

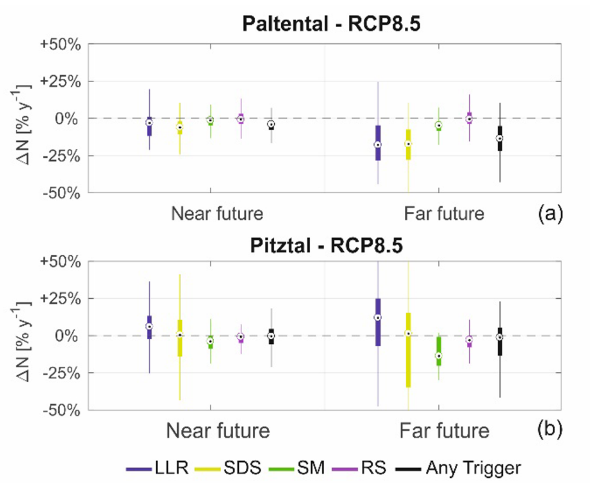

Fig. 3. Annual change of trigger type frequency (LLR, SDS, SM, RS as well as without trigger differentiation) for emission scenario RCP8.5 for the study regions Paltental (a) and Pitztal (b).

On a seasonal basis, there are strong variations of trigger types. In most regions, SDS conditions expand to spring months and – for some regions show a decreasing frequency during summer time. LLR conditions show similar patterns, but are not that distinct as SDS conditions. RS receives a more prolonged period than future conditions of SM [16].

4 Discussion and conclusions

For our study, predictions are made on a regional scale rather than on the scale of individual catchments, where debris flows actually initiate. This is a trade-off between resolution and data availability, but also guarantees that the model chain (climate-hydrology-trigger) is kept on the same scale. We rigorously accounted for the uncertainties and use 700 time-series of future hydrological catchment states that provide a broad representation of the range of combined uncertainties of the hydrological and climate model. The criteria of the trigger model were derived from (usually extreme) catchment states where debris-flows were observed in the past. The criteria sets were subsequently applied to both, projected future and past. Hence, results shown in this study are conditional on the assumption that the pattern pointing to debris flows in the past will also hold in the future.

Debris-flow activity is not only controlled by a certain intensity or duration of rainfall, but also by hydrological and geomorphological boundary conditions that may vary over time. This study covers the most important aspects of the hydrological component on a regional scale, however, the geomorphological aspects are not included, including changes of sediment production due to weathering [9], increased accumulation of debris in the channel during drier summers [11], or the retreat of glaciers and thawing of permafrost, which releases considerable amounts of debris. An elevation-resolved quantification of the extent and temporal variation of the geomorphological disposition is not yet available, but would be of importance for a more complete climate change impact assessment including predictions of future debris-flow event magnitude (i.e. volume), which is the most important quantity in engineering hazard assessment [17].

Our results show seasonal and spatial changes of hydro-meteorological conditions that were associated with past debris-flow occurrence in the Austrian Alps. We expect an extension of the debris-flow season from the summer months into spring. In some regions, rainfall-related triggers become less frequent in summer, but together with snow-melt related trigger conditions more frequent earlier in the year. Changes are more pronounced for the far future and RCP8.5 than for the near future and RCP4.5.

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