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Hydro-meteorological trigger conditions of debris flows in Austria

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Abstract

Different factors influence the disposition of a watershed for initiation of debris flows, including meteorological trigger conditions as well as the hydrologic and geomorphic disposition. The latter includes slowly changing factors like relief energy or sediment availability, whereas the hydrologic state of a watershed may vary over short time scales. This contribution summarizes the outcomes of a long term project to quantify meteorological and hydrological trigger conditions leading to debris flows at different temporal and spatial scales in the Austrian Alps. The analysis employs a database of more than 4,500 debris flows over the last 100+ years, which is the period for which systematic rainfall data is available. A Bayesian analysis was carried out for determining occurrence probabilities for all Austria. For selected regions, hydrological trigger conditions were assessed using a semi-distributed, conceptual rainfall-runoff model, which was calibrated to measured runoff data. As expected we find increasing trigger probabilities with increasing rainfall amounts and intensities. However, the additional information of regional hydrological parameters as well as their temporal evolution over days prior to a debris-flow event, enables to capture different trigger conditions, including short duration rainstorms, long lasting rainfall events, and snow melt. We also find that a trigger-type resolved prediction of debris-flow susceptibility based on the hydro-meteorological catchment information is superior to simple rainfall-only approaches. The results of this analysis shall improve our understanding of long-term trigger conditions and trends of extreme mass wasting processes in the Alps and aim to become a valuable tool in engineering hazard assessment.

Keywords: initiation conditions, probabilitic thresholds, hydrologic modeling, susceptibility

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1. Introduction

Debris flows occurring in the European Alps are often triggered by rainfall events. Over the last decades a lot of work has been done to identify triggering rainfall amounts, intensity, or intensity-duration thresholds, mostly in conjunction with shallow landslides (see review by Guzzetti et al., 2007; 2008). To overcome the uncertainties that come with deterministic thresholds, Berti et al. (2012) outlined a probabilistic approach and derived conditional probabilities for shallow landslide initiation in the northern Apennine mountains. In the recent years also remote sensing techniques like radar or satellite data have been employed to derive rainfall thresholds at high spatial and temporal resolution (e.g. Marra et al., 2014; Salio et al., 2015). For the Austrian Alps the only published work is the case study of Moser and Hohensinn (1983).

Besides the triggering rainfall event also other factors, like sediment availability and hydrologic conditions within the watershed are expected to influence debris-flow initiation (Kienholz, 1995). As a proxy for the wetness state of a catchment the antecedent water was analyzed which consists of the rainfall inputs reduced by evapotranspiration and drainage losses within the last 10 days (e.g. Crozier, 1999; Wieczorek and Glade, 2005). The sum of the antecedent water and the rainfall input at the actual day were considered to conclude whether to expect a landslide or not. A more complex model was provided by Ciavolella et al. (2016), who simulate the water cycle of a catchment by using a conceptual hydrological model that was calibrated to the catchments observed runoff. Result of the work was a threshold curve based on catchment water storage and precipitation as a tool to evaluate landslide susceptibility of the

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catchment. For events that were triggered in connection to snow melt, Meyer et al (2012) developed an intensity-duration threshold that considers two sources of critical water – melt water and rainfall water.

In this study we determined triggering rainfall events for more than 4,500 documented debris-flow events between 1901 and 2014 on a daily basis. Following the method of Berti et al. (2012) we also determined non-triggering rainfall events to calculate conditional probabilities for debris-flow triggering in Austria. At a regional scale we quantified the hydrological state of six contrasting regions when debris flows occur in the headwater catchments (Mostbauer et al., 2018; Prenner et al., 2018a,b). For that a semi-distributed rainfall-runoff model was setup covering periods of 40-60 years. Based on the temporal evolution of storage components and fluxes, we differentiated between three typical hydro-meteorological trigger conditions for debris-flow initiation in Austria.

2. Methods

2.1. Triggering rainfall

For 4,620 debris flows of the database of the Federal Ministry for Tourism and Sustainability (www.bmnt.gv.at/), the information of the data and the location (of damage) was available. In this database the definition of torrential processes follows the Austrian standard rules ONR 24800 (ONR, 2009) that separates between fluvial flows (floods and intensive bedload transport) and debris flow-like flows (debris floods and debris flows). Due to a sometimes unclear distinction between different processes (Bel et al., 2017), we only considered debris flows. The meteorological data was derived from the Hydrological Service (“HD”, ehyd.gv.at/) and the “Zentralanstalt für Meteorologie und Geodynamik” (“ZAMG”, www.zamg.ac.at). In total 790 time series of daily precipitation, daily temperature (mean, minimum and maximum), snow fall, and pressure were available. Here we used only the rainfall information.

For each observed debris-flow event the nearest active meteorological station was identified and the triggering event rainfall (TER) determined manually on a daily basis between 1901 and 2014 and on a sub-daily basis between 1993 and 2014. In the following we concentrate only on daily data. Events, for which meteo-station data exceeded a distance of 10 km and for which the determination of the rainfall event was unclear, were excluded from further analysis, reducing the number of TERs to 1,417. The database of TERs are (1) a direct result available for the community, but were (2) subsequently used to calibrate a detection algorithm for automatically identifying triggering and non-triggering rainfall events in all available time series from meteo-stations. For that we used an adapted algorithm provided by Matteo Berti (personal communication) and explained in Berti et al. (2012).

The probability Pr of a debris-flow event E conditional of a rainfall variable R in class $k = 1,2, \dots, n$ was calculated with

$$Pr(E|R_k) = \frac{Pr(R_k|E) \times Pr(E)}{Pr(R_k)} \tag{1}$$

2.2. Hydro-meteorological trigger conditions

We setup a semi-distributed, process-based rainfall-runoff model for six contrasting regions in Austria (Fig 1) and analyzed the hydrological system state of the watershed on days were debris flows were observed in the steep headwater catchments and compared it to the days were no event was observed. The hydrologic model include several storage components that represent snow and glaciers, unsaturated soil, interception, as well as fast and slow responding system components. Within a catchment different precipitation and elevation zones were modelled separately on a daily basis. For model calibration a likelihood-based differential evolution adaptive metropolis sampler (Vrugt, 2016) was used to derive posterior distributions of 43 calibration parameters. A detailed description of the model and the rigorous uncertainty assessment can be found in Prenner et al. (2018; 2019). A simplified analysis is described in Mostbauer et al. (2018). The modeling period for the six watersheds ranged from 46 to 71 years, including 3 to 43 days were debris flows were observed.

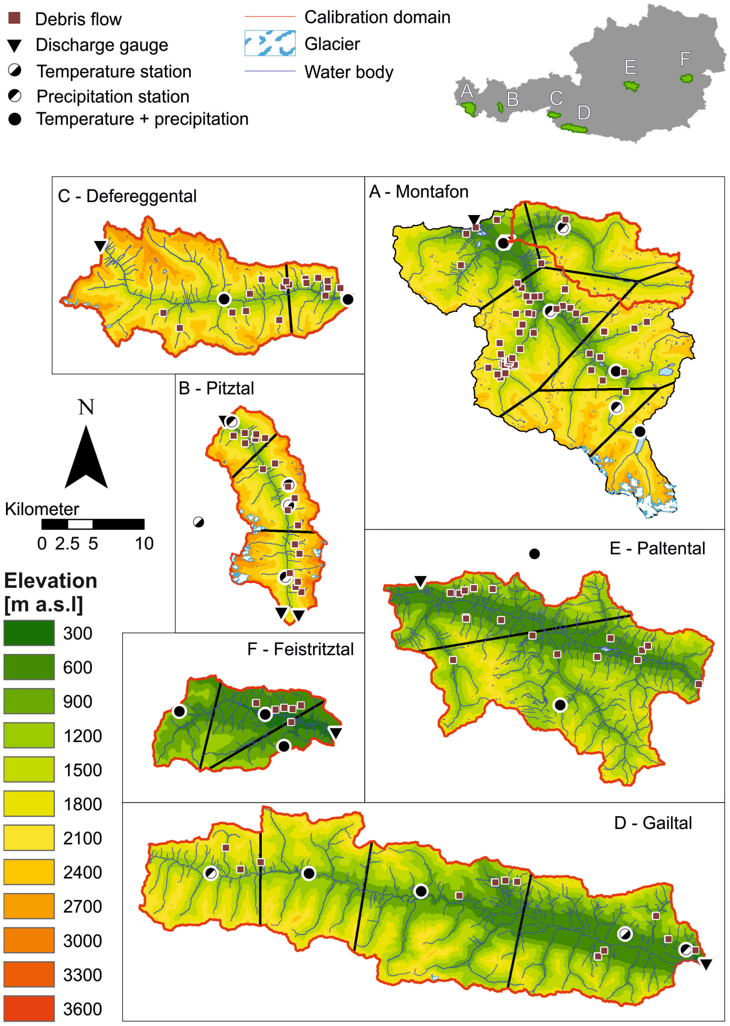

Fig. 1. Overview of the six study regions for the hydro-meteorological analysis

Table 1. Hydrological signals for identifying different trigger types for debris flows

Observation	Signal for LLR	Signal for SDS	Signal for SM
Increasing soil moisture in the prior days of event	X		
Decreasing potential evapotranspiration in the prior days of events	X		
Narrow air temperature span at the event day	X		
Decreasing soil moisture in the prior days of the event		X	
Constant high or increasing potential evapotranspiration in the prior days of events		X	
Large air temperature span at the event day		X	
Intense snow melt at the event day			X

Hydro-meteorological trigger conditions were analyzed for each watershed separately by comparing the distributions of modeled and measured variables like precipitation, soil moisture, (potential and actual) evapotranspiration, or runoff. Based on the notion that trigger conditions leave distinct signals in the hydrological time series, we ex-post differentiate between the trigger type long-lasting rainfall events (LLR), short-duration storms (SDS), and snow melt (SM). The hydrological signals for these simplified trigger types are given in Tab 1. Importantly, direct rainfall recordings were not used as criteria to avoid epistemic uncertainties from single point precipitation measurements. Here we try only to capture a general weather pattern, neglecting all different types of meteorological events. To also avoid a-priori definition of thresholds for these criteria, we sampled a 1000 times from a uniform distribution of plausible parameter values. Finally, the most frequent trigger type for each debris-flow event was selected (Prenner et al., 2018; 2019).

3. Results

3.1. Triggering rainfall

The median triggering rainfall amount for the analyzed debris-flow events was 40.0 mm, with a median intensity of 22.4 mm/d. Fig 2 compares derived triggering rainfalls and all automatically detected non-triggering rainfalls with the intensity-duration (I-D) thresholds for an Austrian case study of Moser and Hohensinn (1983), estimated by Guzzetti et al. (2007), and a global threshold for landslides and debris flows derived by Guzzetti et al. (2008, I-D threshold #6). Additionally we plot a quantile regression for the 5th percentile for the triggering rainfall. We see a wide range of measured trigger intensities. The 5% quantile regression plots below both thresholds. Especially for short triggering durations we expect that this daily analysis has limitations.

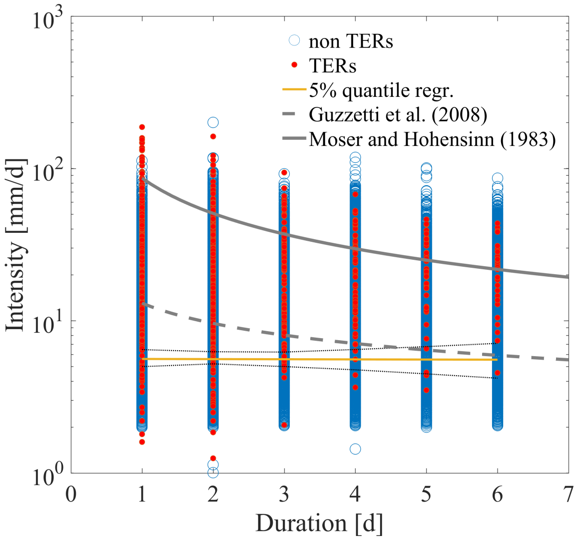

Fig. 2. Triggering and automatically detected non-triggering rainfalls for debris-flow events between 1901 and 2014 in Austria; the solid line represents the thresholds of Moser and Hohensinn (1983) as estimated by Guzzetti et al. (2007), the dashed line is a global threshold derived by Guzzetti et al. (2008).

As expected debris-flow occurrence probability increases with increasing precipitation. We find that the highest probabilities are associated with rainfall intensity, the total amount of rainfall, and the 3-day antecedent rainfall. The latter are shown in Fig 3. The two dimensional analysis of debris-flow probabilities in Austria conditional to the combination of rainfall intensity and duration shows that the highest probability emerges from high intensities > 24 mm/d.

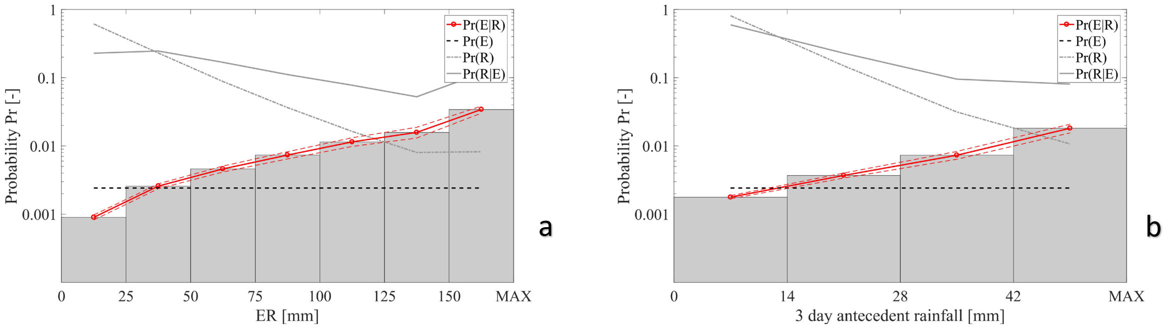

Fig. 3. (a) Probability of debris-flow occurrence conditional of total amount of rainfall (grey bars and red lines); (b) probability of debris-flow occurrence conditional of 3-day antecedent rainfall. In both plots dashed red lines refer to the 5th and 95th percentile of an assumed Poisson distributed counting error of debris-flow events; additionally the prior debris-flow probability $Pr(E)$ and prior rainfall probability $Pr(R)$ as well as conditional rainfall probability $Pr(R|E)$ are plotted.

It is important to note that our analysis is biased towards long rainfall event durations. Especially one-day intensities maybe strongly underestimated, as rainfall events may only last for few hours or minutes. Additionally, these mostly very local convective processes might not have been captured by the nation-wide rain-gauge network. In other words, we expect that our analysis does not capture debris-flow events that were triggered by short duration storms (SDS). As shown in the next section, our analysis might therefore be representative only for roughly 1/3 of the debris flows occurred in Austria.

3.2. Hydro-meteorological trigger conditions

Modeling performance after calibration of the six study regions were measured with different metrics and reached satisfying results (e.g. Nash-Sutcliffe efficiency indexes varying between 0.7 and 0.89). Fig 4 exemplarily shows modeling results for the study region Defreggental, a high alpine valley in the southern part of the alpine chain, for the year 2012. We see highest runoff during summer and a high fraction of melt water input into the soil and channel system during spring and late fall. Soil moisture gradually builds up during spring.

In the lower part of Fig 4 we show examples of the hydrologic state for three debris-flow event days. In the first example there is significant rainfall prior to the event day, leading to a continuous buildup of soil moisture. At the same time temperature and especially the difference between daily minimum and maximum temperature decreases, which is typically associated with a frontal rainfall of long duration (LLR). The second example shows a contrasting picture. Though some rainfall was measured on the days prior to the event, the temperature differences are high, indicating strong solar energy input during the day. Soil moisture slightly decreases. On the event day no significant rainfall was recorded. We classified this event trigger as a convective storm event of short duration (SDS). Finally, in the third example rainfall in conjunction with intensive snowmelt (SM) triggered the debris-flow event. We note that we also found debris-flow event days without any recorded rainfall but very intense snowmelt.

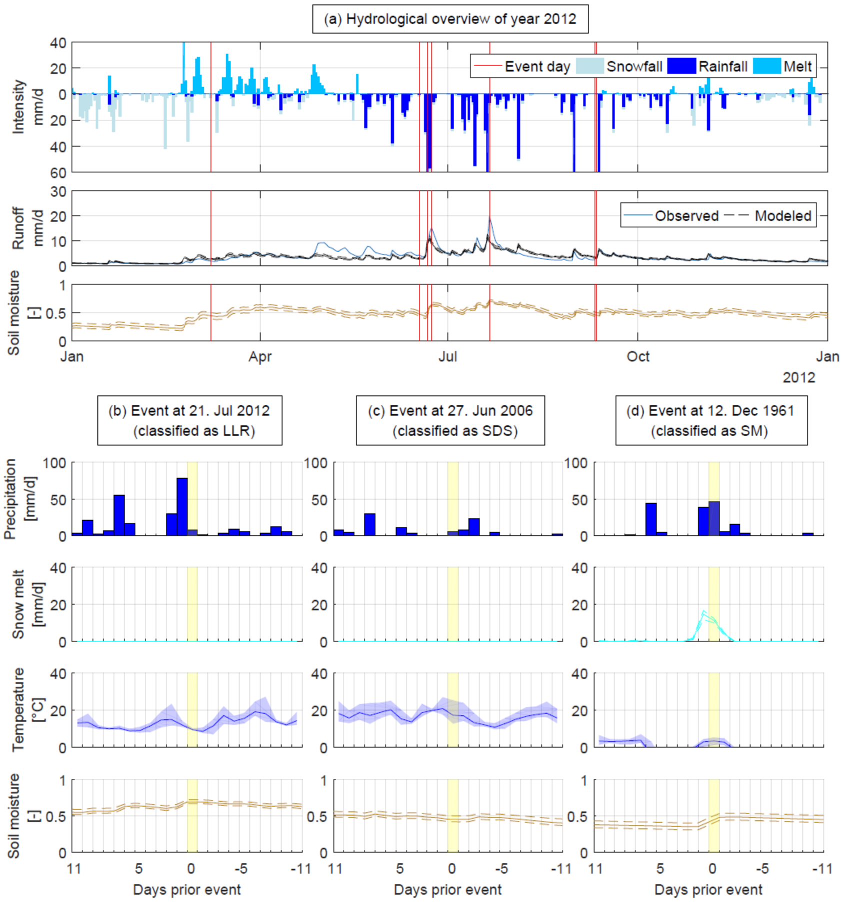

Fig. 4. (a) Example of selected modeling results for the study region Defreggental for the year 2012; (b) example of a debris-flow trigger that was classified as LLR, (c) as SDS, and (d) as an event were SM was important.

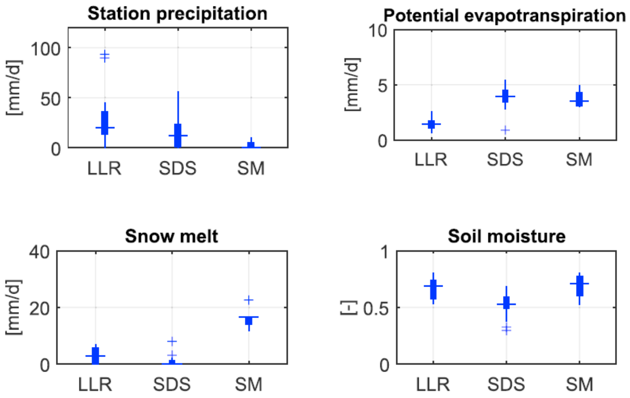

Fig. 5. Distribution of event day precipitation (which was not used for trigger classification), potential evapotranspiration, snow melt, and soil moisture at event days in the Montafon region (modified after Prenner et al., 2018).

Selected hydro-meteorological variables associated with the roughly separated trigger types are shown in Fig 5. We find that the registered event rainfall on the daily basis (which was not used for classification) supports our classification. LLR events have higher total rainfall sums than SDS events. (SDS events might have higher intensities, but this is probably not captured by the station network). For SM events sometimes no rainfall was measured. Similarly, also other variables are statistically different between the three groups (tested with the method of Kruskal and Wallis, 1952), which strongly supports the notion that different hydro-meteorological trigger types can be found in our study region.

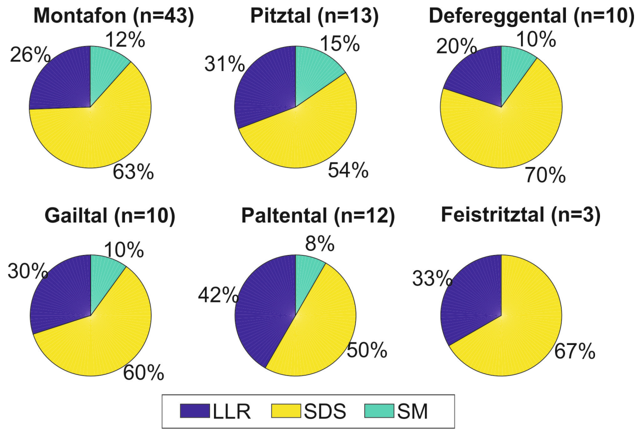

Fig. 6. Trigger of debris-flow events in the study regions.

In summary, we find the 50-70 % of the documented debris flows in the six study regions were triggered by SDS events, 20-44% due to LLR, and for up to 15 % snowmelt played are significant role (Fig 6). We think that for a better forecasting of debris-flow events, the combined information of rainfall forecasting and a real-time modeling of the hydro-meteorological history of a region, will be useful to capture these different trigger types.

4. Conclusions

A new database of triggering event rainfall for debris flows in Austria on a daily and sub-daily basis was created. The probabilistic analysis of triggering rainfall on a daily basis showed that probabilities for debris-flow occurrence increase with increasing rainfall amount, intensity and antecedent rainfall. The investigation of the hydro-meteorological trigger conditions in six contrasting study regions indicated a strong variability of hydro-meteorological trigger conditions of documented debris flows. The initial soil moisture as well as the rainfall on the event day, was higher for events associated with long-lasting rainfall events (LLR) than with short duration storms (SDS) across all study regions. Initial soil moisture and event day precipitation sums strongly vary across the regions for the same trigger type. Importantly, the temporal change of hydrological watershed state before events show similar signals across the regions and allows to draw more general conclusions about the susceptibility of regions to debris-flow release and might allow the development of a forecasting tool similar to the model suggested by Prenner et al. (2018). A major limitation of such a hydro-meteorological assessment, however, is the missing geomorphological component, e.g. temporal variation of sediment availability.

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