Critical Rainfall Conditions Triggering Shallow Landslides or Debris Flows in Torrents - Analysis of Debris Flow events 2012, 2013 and 2014 in Austria

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ABSTRACT

Generally, debris flows are caused by both small-scale intensive precipitation and long lasting rainfalls with lower intensity but high pre-wetting or both combined. The triggering mechanism of the debris flow events in Austria 2012, 2013 and 2014 were mass movements on steep slopes in the upper catchments. Those masses slide with very high velocity into the torrent beds provoking hyperconcentrated flows or debris flows. In areas of the geologically unstable Greywacke zone, the torrents were cleared up onto the bedrock and the debris was deposited in the storage areas of existing debris flow breakers or in torrents without technical protection measures the debris caused catastrophic damage on the alluvial fan. Following the events, comprehensive documentations and analyses were undertaken to support the understanding of the occurred processes to mitigate future hazards. Unfortunately, the small-scale heavy rain events are not detected by the precipitation stations. Therefore, weather radar data (INCA-Data) analysis was used to determine the - usually very local - intensities which caused those catastrophic landslides and debris flows.

KEYWORDS

critical rainfall conditions; debris flow; event analysis

INTRODUCTION

The knowledge of which precipitation intensities and durations are capable of triggering debris flows and landslides are of decisive importance to the effort of optimizing integrated protection concepts in torrent control. This knowledge is won through thorough event documentation and detailed analysis, here, of debris flow events that occurred in Austria in 2012, 2013 and 2014. These events were characterized by very localized precipitation events of high intensities, both with and without a high degree of pre-wetting. Most of the debris flow events were triggered by slope failures in the uppermost catchment areas, which in turn were caused by a high water saturation of the soil and a temporary increase in the pore water pressure. The slopes were therefore destabilized through a reduction in the soil's shear strength.

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PROBLEM STATEMENT

Determining the precipitation sums per unit of time which are capable of triggering debris flow events such as those considered here are problematic for two reasons. Due to the very small spatial extent of the precipitation events, an analysis of data from precipitation stations (which are often not situated directly in the catchment area in question) is difficult and needs rely on interpolations. In addition to this, factors such as the event‘s prehistory (e.g. degree of pre-wetting) and the area’s disposition due to its geology play a deciding role. Numerous published studies, beginning with Caine (1980), Crozier (1986) and Zimmermann (1997), can be found that report empirically determined threshold values based on the precipitation parameters of intensity i [mm/h] and duration D [h]. The data used to investigate the relationships of intensity and duration were drawn from events which occurred in areas that have a great diversity of climatological and geological characteristics, and as such, the databases must be considered as rather inhomogeneous. Crozier extended the method in a 1997 study to include precipitation data from rainfall events that did not trigger mass movement events. Guzzeti et al. (2008) employed the same method, but constrained the threshold values for a variety of climatic regions. MLIT (2004) expanded the methodology employed by Crozier (1986) by considering the prehistory (pre-wetting) of the events analysed, as well as the effective rainfall necessary to trigger slides and debris flow events. Strenger (2009) attempted to calculate precipitation threshold values for the triggering of debris flow events in the Vinschgau (South Tyrol, Italy) using the Antecedent Daily Rainfall Models after Glade et al. (2000). He was able to prove that although the model is generally well suited for such calculations, it is inadequate to capture the heavy rainfall events, which are usually of a very localized spatial extent, due to the poor spatial resolution of weather station data. Also Braun 2014 referred in his study to the inadequate detection of local heavy rainfall events with weather station data. Analyses of rainfall events using the highest available resolution for the whole dataset of one day lack the short term component.

METHOD

For this study, the analysis of a precipitation intensity and duration relationship was carried out using weather radar data (INCA data), limited spatially to a single geological unit in Austria, the Greywacke zone. The dataset was furthermore divided into mass movement events that occurred either with or without pre-wetting to take into account the catchment’s prehistory and disposition. The threshold values were empirically determined using the relationship found in measured precipitation data (weather station as well as weather radar data) between precipitation intensity i [mm/h] and duration D [h] ($I = \alpha \times D\beta$). The smallest precipitation sum which triggered a landslide or debris flow was selected as the threshold value.

DATA SOURCES

Weather radar data (INCA)

The INCA (Integrated Nowcasting through Comprehensive Analysis) System of the ZAMG (Zentralanstalt für Meteorologie und Geodynamik; Eng: Central Institute for Meteorology and Geodynamics) is used for spatial and temporal analyses of a high resolution, as well as for weather predictions on the order of a few hours, taking particular account of regional and local topographic effects. The precipitation analysis of the INCA System comprises a combination of interpolated weather station data (with elevation effects taken into account) and weather radar data. The combined use of radar and rain gauges provides the benefit of each of these instruments' respective strengths: the exactness of a point measurement on the ground (rain gauge) and the acquisition of a precipitation system's spatial structure with the aid of weather radar. On the other hand, the methodology is not without weaknesses or possible shortfalls: unrepresentative locations and/or low spatial density of weather stations and rain gauges on the one hand, as well as the uncertainty of indirect precipitation measurement via weather radar on the other hand. The available data raster has a horizontal resolution of 1 x 1 km and a temporal resolution of 15 minutes.

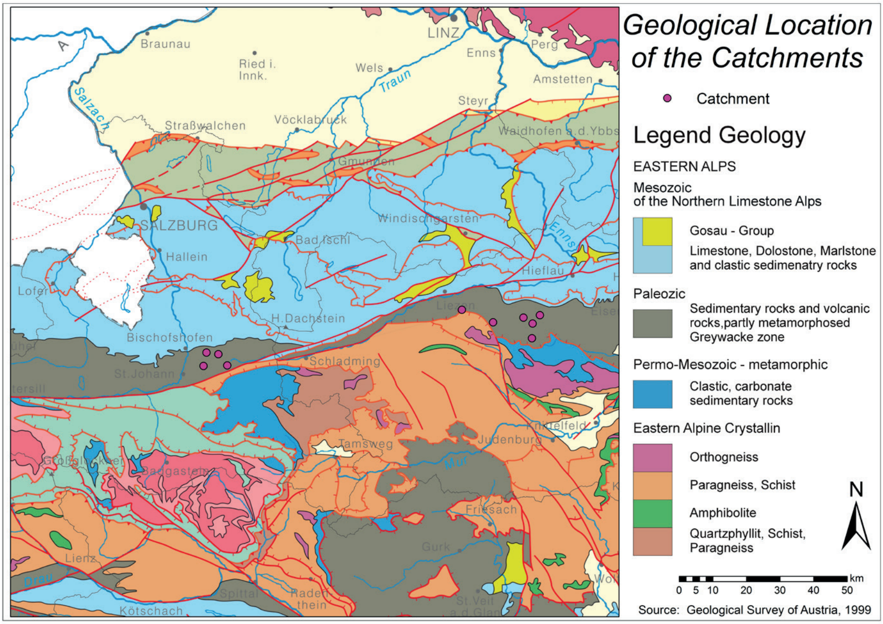

Figure 1: Geological map with catchment areas

Geological conditions

All of the investigated events occurred in the Greywacke zone (from Greywacke, the name of a Paleozoic sandstone). Geologically, this zone is located between the Northern Limestone Alps towards the north, of which it forms the geological base, and the Central Eastern Alps in the south. The bedrock consists of phyllite and the Paleozoic slate of the Greywacke zone, which are mostly extensively shattered and as a consequence prone to mechanical and chemical weathering. These rocks, especially the clay layers, produce a laminar, creeping scree material that covers the slopes in a substantial mantle of weathering debris of various thicknesses up to the ridges. This unconsolidated rock already becomes unstable at minimal levels of water uptake, which, upon further wetting produces large mass movements.

DATA SOURCES

Disposition – with and without pre-wetting

The following two examples serve to illustrate the importance of a catchment area's pre-history. The event which occurred in Klemmgraben in 2014 was a single event without any antecedent precipitation (0 mm precipitation in 3 days), whereas the event that occurred in the Lorenzerbach in 2012 followed three days of antecedent rain(200 mm precipitation in 3 days) with the resulting high degree of pre-wetting making for a higher disposition. The different wetting-situations result in different behavior of the catchments.

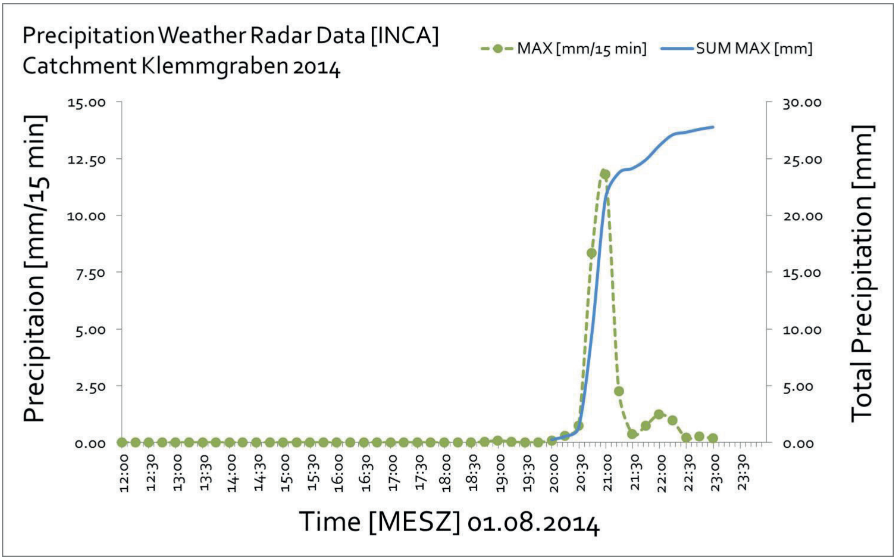

Figure 2: Precipitation and total precipitation – Klemmgraben 2014

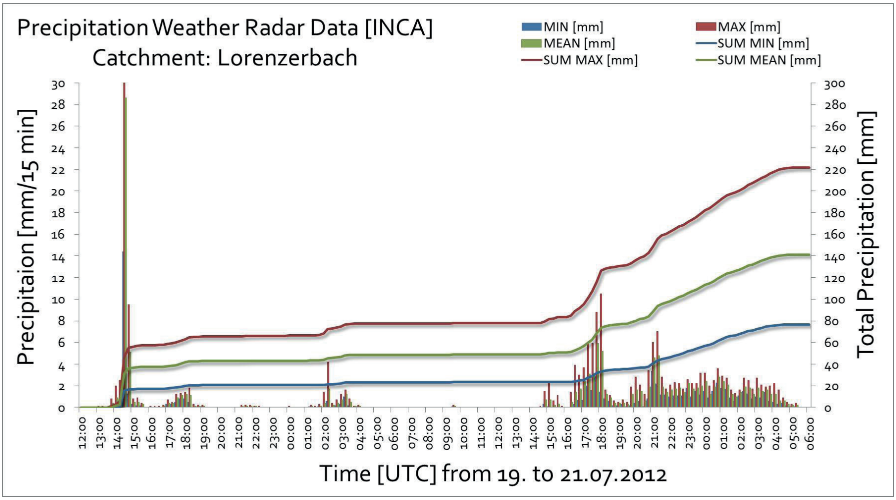

Figure 3: Precipitation and total precipitation – Lorenzerbach 2012

STUDY SITES AND EVENTS

Lorenzerbach, Paltental 2012

The muddy debris flow event of 21. July 2012 in St. Lorenzen was caused by a combination of high sums of precipitation in the preceding 4 weeks (430 mm, this equals to a return period of more than 300 years) and heavy rain on the night of the event. Since there are no precipitation stations inside the catchment area, the areal precipitation was determined with the aid of weather radar data (INCA analysis, raster data 1 x 1 km, 15 minute intervals.). The highest 15 minute precipitation rate within the catchment area was found to be nearly 40.4 mm/15 min and occurred on the 19th of July. In sum, from 14:00 UTC of the day before the event up to shortly after the debris flow, 96 mm of precipitation was registered in the catchment area of the Lorenzerbach torrent. These extreme precipitation sums led to a complete saturation of the groundwater reservoirs and to an activation of flow- and slide processes along the gorge sections.

Sattelbach 2013

A similar disposition could be reconstructed for the debris flow event in the Sattelbach torrent. A high pre-wetting since the beginning of May 2013, in combination with intensive rainfall toward the end of that month and on the 1st and 2nd of July, resulted in numerous debris flow and landslide events in the torrential catchment areas of Salzburg's Pinzgau and Pongau regions. A catastrophic debris flow occurred in the municipality of Hüttau on the morning of 2. June 2013. Following a three day period of rain, a marked increase in precipitation rates occurred in the night of 1. June to the morning of 2. June. Evaluation of the precipitation rates obtained from weather radar data revealed a precipitation sum of 80 mm in the catchment area up to the time of the debris flow. The trigger of the debris flow could be identified as a 2000 m^2 large landslide in the upper part of the catchment. The steepness of the ravine consequently enabled the development of a debris flow, which in its passing cleared the fore-filled sediment down to the bedrock. According to expert estimates, the fully developed debris flow transported 12,000 m³ of material.

Klemmgraben 2014

In terms of pre-wetting, a different disposition existed for the debris flows of 2014. Very short but intensive precipitation events were responsible for triggering these debris flows, a circumstance that was substantiated through analyses of weather radar data as well as data from surrounding weather stations. The Klemmgraben event on the 1st of August was likewise triggered by a very short but high intensity precipitation event. According to eye-witness reports, the heavy rain cell was situated above the upper portions of the catchment area. The analysis of the local precipitation was complemented by processing of INCA data, the sum of the precipitation was 28.3 mm/45 min with a peak of 12 mm/ 15 min. The surrounding precipitation stations registered from 16.9 mm (Flachau) to 33.2 mm (Radstadt) of rainfall on that day. The station Hüttau, in the north west of the catchment area, registered 60 mm/45 min.

RESULTS - CRITICAL RAINFALL CONDITIONS

A number of studies (Austria/BFW 1972 – 2000, Caine 1980, Caine in Dodt 2007, Giannecchi 2006, Braun 2014) have described critical rainfall conditions as a relationship between the intensity i [mm/h] and duration D [h] of a precipitation event that acts as a trigger for mass movements.

The precipitation intensities – values in 15 minute intervals, derived from INCA analyses – that were associated with the debris flow events were classified according to the type of event and displayed graphically in a precipitation intensity-duration diagram.

The following two event types were defined:

– Events with a high level of pre-wetting
– Events that occurred without any pre-wetting

A comparison reveals the high intensities associated with events that occurred without pre-wetting and the low intensities associated with events with pre-wetting.

The lowest precipitation values which triggered a debris flow were selected in order to obtain functions of rainfall intensity and duration thresholds for each event type in the Greywacke zone. Regression analysis yields the following relationship between threshold precipitation intensity and duration for events which occurred without pre-wetting:

$$i_{[mm/h]} = 21.803 \times D_{[h]}^{-0.378}$$

Formula 1: Regression equation for the relationship between precipitation intensity and duration for events without pre-wetting

For events with a high degree of pre-wetting, these precipitation parameters are related thus:

$$i_{[mm/h]} = 11.676 \times D_{[h]}^{-0.489}$$

Formula 2: Regression equation for the relationship between precipitation intensity and duration for events with pre-wetting

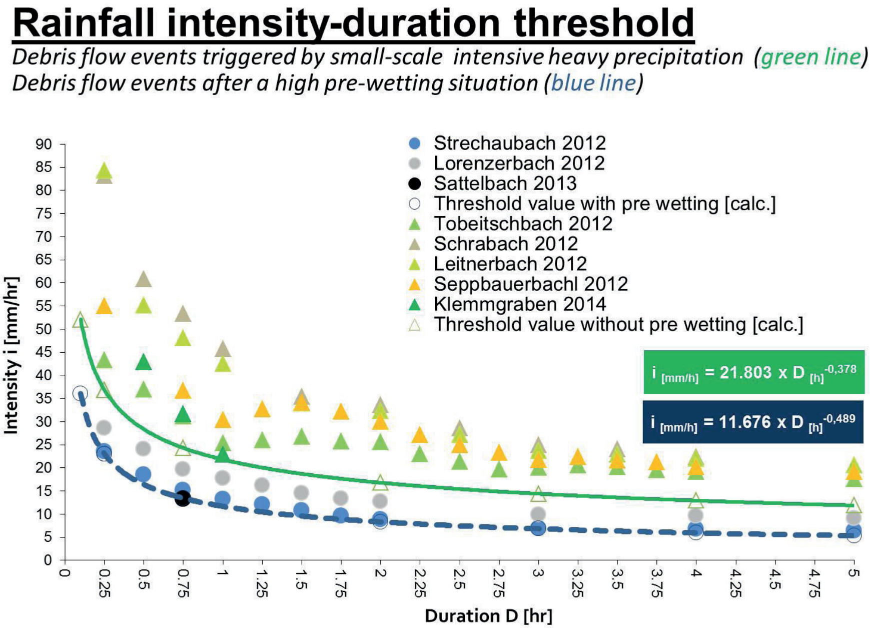

Figure 4 Rainfall intensity-duration thresholds of 8 debris flow events occurred 2012 - 2014 in the Greywacke zone, Austria

Table 1 Precipitation threshold values per duration, event type and difference between event types in %

Duration [hr]	a)Threshold value with pre-wetting [mm/h]	b)Threshold value without pre-wetting [mm/h]	% a/b
0.4	18.3	30.8	59
0.5	16.4	28.3	58
1	11.7	21.8	54
2	8.3	16.8	50
5	5.3	11.9	45
10	3.8	9.1	41

This comparison also confirms the generally valid statement that relatively low precipitation intensities are sufficient to trigger debris flows if a high degree of pre-wetting is given. The estimated threshold value for the short duration for example of 0.5 hours only 58 % from the threshold value without pre-wetting is needed. The highest precipitation intensities found for the events described above (in mm/h, mm/2h, and so forth) correspond well to the values quoted in literature, as being critical, debris flow triggering rainfall conditions.

DISCUSSION

The advantage of the method introduced here, using weather radar data, is that it also allows precipitation threshold values to be calculated for very locally occurring intense rainfall events which cannot be sufficiently resolved using the existing weather station network. It is however important to not only consider the immediate time period of the mass movement in question, but to also include and analyse the event's pre-history within its catchment area. Those different pre-wetting situations are the reason for a different behavior of the catchments and result in a higher disposition for catchments with a high degree of pre-wetting. Dividing a given dataset into events with and without pre-wetting is a first step and the examples provided here clearly illustrate that the results may differ quite substantially. Since different catchment areas may have significantly different dispositions for producing landslides and debris flows, based on their geology. Therefore only events in geological similar catchment areas were selected. An even more detailed data acquisition will be necessary for further investigations; this example may constitute an applicable approach for such research ventures.

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