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Analysis of rainfall and runoff for debris flows at the Illgraben catchment, Switzerland

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Abstract

For hazard analysis, scenario design and mitigation there is a need to accurately and objectively predict the volume of debris flows. One approach is to base the calculation on rainfall properties. Herein we present an analysis of rainfall and debris-flow volume using data from the Illgraben catchment in Switzerland. The Illgraben debris-flow observation station, operated starting in the year 2000, has successfully recorded 75 debris flows and debris floods, with volume and bulk density estimates available for most of these events since 2000 and 2004, respectively. Here we describe results for 52 debris flows with sufficient data. Runoff coefficients determine the proportion of precipitation discharged from a catchment and support estimates on flow magnitudes. For each debris flow, runoff coefficients were determined by considering the event rainfall and the water contained in the debris flow. The events can further be characterized by the 14-day antecedent wetness. Runoff coefficients comprise a wide range from near 0 to close to 1. Clear trends are apparent, such as larger runoff coefficients during the snowmelt season. Furthermore, the debris-flow volumes are more sensitive to the antecedent rainfall than to the rainfall amount that triggered the event, likely because a wet channel bed enhances entraining. This study gives insights on which climate variables control the debris-flow volume. This will be further investigated and incorporated into the *SedCas* (Sediment Cascade) model (Bennett et al., 2014) to improve prediction of debris-flow activity.

Keywords: Runoff coefficient; Volume; Frequency

1. Introduction

Objectively quantifying debris-flow volumes and frequencies is unavoidable for the hazard analysis. The debris-flow volume indicates the severity of an event and can be a supportive parameter when planning mitigation measurements such as retention basins (Marchi and D'Agostino, 2004). Other magnitude parameters naturally also play a key role, such as the peak flow discharge for the planning of bridges crossing a torrent. Peak flow discharge is the most common parameter to assess flood magnitudes. For debris flows, however, volumes have shown to be a more robust measure. This is because there is more uncertainty in the friction parameter, which depends on the water-sediment proportions and grain sizes, and consequently affects the rheology of the flow (Pierson, 2005).

Several methods have been developed in the past to estimate debris-flow volumes. For example, Marchi and D'Agostino (2004) applied regression techniques and proposed a volume dependency on catchment area, mean gradient of the stream and a dimensionless geological index derived from the lithological classes present in the catchment. Their data set was not very sensitive to the latter parameter, which can be excluded (when the coefficients are adjusted). Stoffel (2010) reconstructed a debris-flow time series of the past ~140 years by performing tree-ring analysis and volume estimation on fan deposits. The added value of this technique is that time-series can be approximated for hazard assessment. In theory, once the volume has been estimated, it can be used to

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infer parameters like peak discharge, velocity and cross-sectional area by applying empirical relations e.g. as presented by Rickenmann (1999).

Although empirical formulations overcome common limitations such as the lack of magnitude-frequency distributions, a range of factors affecting the geology, land use, geomorphology and hydrology play a role for debris-flow volumes and cannot easily be taken into account (Marchi and D'Agostino, 2004). Thus, debris flows can alter their composition, depending on the material they entrain from the bed (Takahashi, 2014). How much sediments are entrained, at which point in the channel entrainment starts and where it ends (i.e. stagnation or start of deposition) has not been uniquely defined and likely depends on parameters such as slope, sediment characteristics and discharge (Hungr et al., 2005).

In the Illgraben catchment in the Swiss Alps, each year three to four debris flows have been observed on average in the most recent two decades. A world-wide unique debris-flow record including information on the time of occurrence and the volume, gives the opportunity to compute runoff coefficients and investigate how rainfall influences the debris-flow volume. Thereby, we intend to enhance the understanding of how climatic measures – primarily rainfall – control the debris-flow volume.

2. Study site

The Illgraben is located in the Rhône Valley in southwest Switzerland. The catchment spans from the Illhorn at 2716 m a.s.l in the south to the meeting point with the Rhône river at 610 m a.s.l in the north and covers an area of 9.6 km^2. The catchment can be divided into two sub-catchments, the Illgraben and the Illbach. whereas only the Illgraben (4.8 km^2) is susceptible to debris flows and is the focus of this study. Little direct runoff from the Illbach has been observed, and the tributary channel is comparatively small. The Illsee is an artificial reservoir and hydrologically disconnected from the study site (Fig. 1).

The climate is comparatively dry and mild (Hürlimann et al., 2003). Yearly precipitation ranges from 600 mm in the valley to 1000 mm in the summit region (Hydrological Atlas of Switzerland). Precipitation can be twice as much in summer as in winter and often of a convective type, causing high-intensity rainfalls (Swiss Meteorological Service). In the catchment, rainfall is measured at three locations with tipping-bucket rain gauges at 10-minute and 0.2 mm resolution. Although, only one of them (RG1) is representative for the initiation zone (Badoux, 2009).

In the initiation zone, an area southeast above the channel mainly characterized by quartzites, mean hillslope erosion rates amount to 0.39 m/y mainly caused by landslides and rockfalls (Bennett et al. 2012). This material is transferred to the outlet primarily by debris flows. The sediment discharge when debris flows are excluded makes up less than 1% compared to the sediment discharge by debris flows (Schlunegger et al., 2009).

The debris-flow frequency increased in the years after a large rock avalanche in 1961. As a consequence, a large retention dam was built in the torrent followed by multiple smaller check dams. The large dam and the check dams are now backfilled and do not serve as retention basins anymore but stabilize the channel. The Illgraben differs from other catchments in terms of its sediment discharge which exceeds Alpine standards by two orders of magnitudes (Schlunegger et al., 2009). Therefore, the catchment has been subject to a variety of studies on sediment transfer patterns (e.g. Schlunegger et al. 2009; Berger et al., 2011b; Bennett et al., 2013; Bennett et al., 2014). Between 2 and 8 debris flows, 3 to 4 on average, have been observed per year (including debris floods) since the installation of a force plate in 2003 (McArdell et al., 2007). The force plate is located close to the catchment outlet.

The Illgrabenbach has no base flow and after rain storms, runoff is not necessarily observed in the lower part of the stream, indicating that large parts of the rainfall are stored. Only in spring substantial amounts of water from snowmelt contribute to continuous runoff.

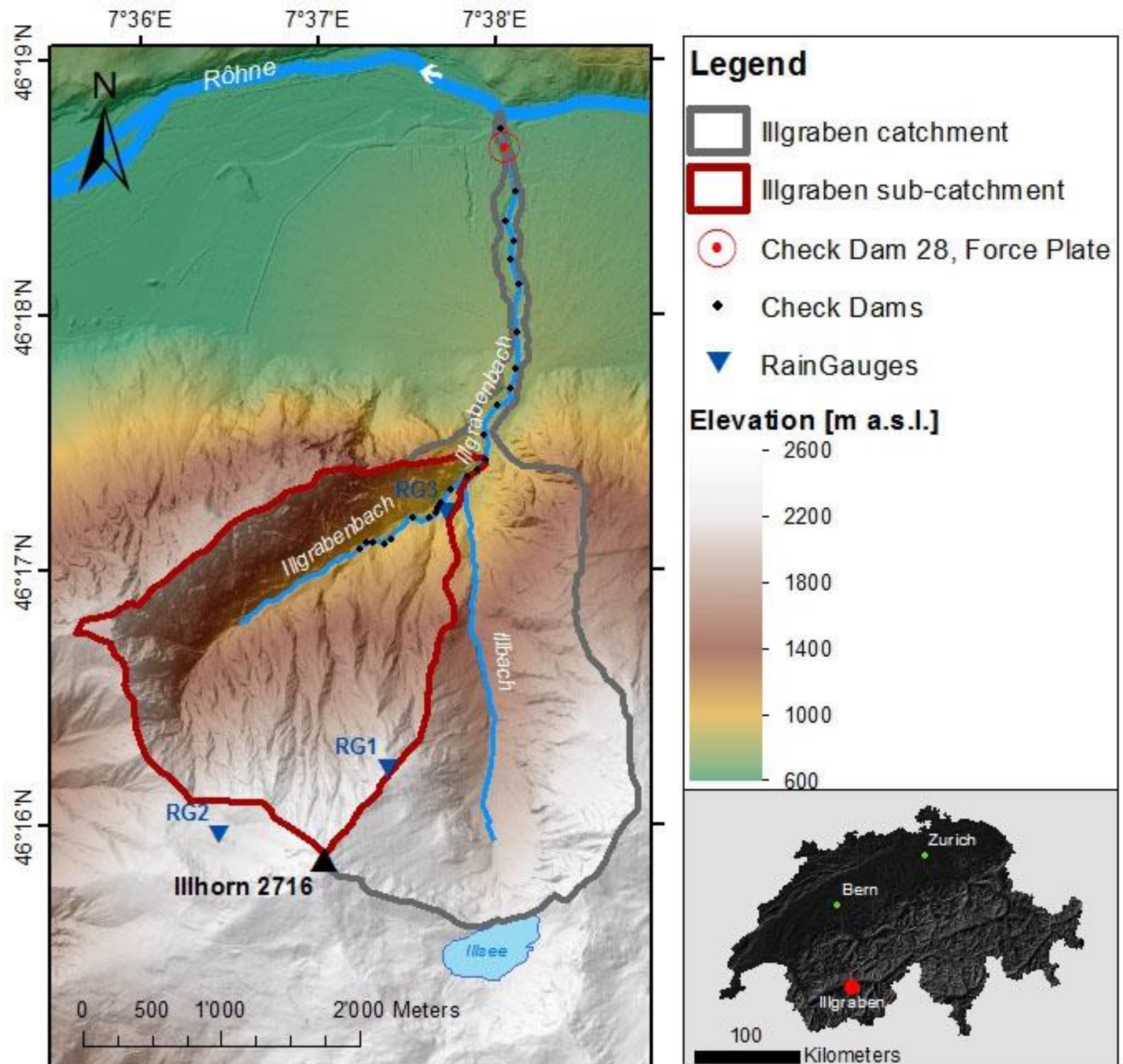

Fig. 1. Overview of the Illgraben catchment located in the Rôhne valley in Switzerland. The hillshade image and the digital elevation model have a spatial resolution of 2 m (Federal Office of Topography Swisstopo). Only the western Illgraben sub-catchment is susceptible to debris flows and is covered by 44% exposed bedrock, 42% forest and 14% grassland (Schlunegger et al., 2009).

3. Methods

We determine runoff coefficients by defining the cumulated rainfall amount that triggered a debris flow (or debris flood) and comparing it to the amount of water present in the debris flow. The rainfall record for RG1 is consistent for the years 2002 to 2017 and for the months of May to October. We assume that RG1 is representative for the entire catchment. Considering the steep gradients in elevation and the convective nature of storms in the summer, this assumption rarely reflects reality. Nevertheless, RG1 is the most representative for debris-flow triggering since it is located only 1-2 km away from the initiation zone and at similar elevation (2210 m a.s.l.).

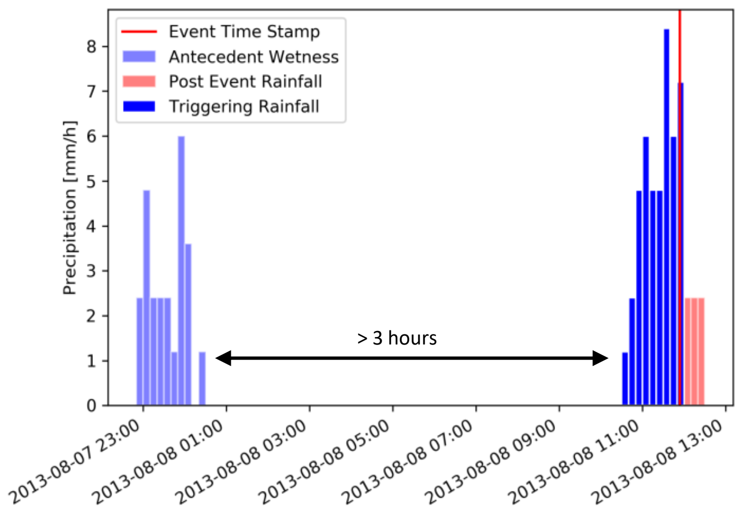

Fig. 2. Example of how an event is defined. Minimum-inter-event-time was set to 3 hours.

A rainfall event is defined by a minimum inter-event time of 3 hours (Fig. 2). In other words, if the gap between two rainfall pulses is less than three hours, they belong to the same rainfall event. If a debris flow occurred not immediately after but during a rainfall event, the instant of debris-flow occurrence was set as the last rainfall to be attributed to the particular debris flow.

The procedure for determining the debris-flow volumes was described in Schlunegger et al. (2009). The record in this study initially comprised 75 debris flows between 2000 and 2017. For some events, however, no volume could be determined and data on rainfall from RG1 is missing for large periods in 2000 and 2001. After excluding these cases the record consists of 52 debris flows.

To determine the amount of water per event, we assume that 50% of the total debris-flow volume consists of water, which corresponds to a bulk density of 1800 kg/m^3. Schlunegger et al. (2009) quantified bulk densities in the Illgraben to be in the order of 1400-1800 kg/m^3 for debris floods and 1800-2200 kg/m^3 for debris flows. We do, however, not differentiate between flow types and assume 1800 kg/m^3 to be the average bulk density. Hereafter, we will use the term *debris flow* for both types throughout the text. Finally, runoff coefficients (Ψ) are determined as follows:

$$\Psi = \frac{f \cdot V_{DF}}{\int_{t_0}^{t_e} p(t)dt} \qquad (1)$$

where V_{DF} is the total debris-flow volume, f is the fraction of water (50%), $p(t)$ is the 10-minute rainfall at a given point in time t and t_0 and t_e mark the start and the end of the rainfall event which can be attributed to the triggering of the debris-flow event. In Fig. 2, t_0 and t_e would be defined by the first and the last rain pulse of the triggering rainfall.

4. Results and Discussion

Fifty-two debris flows which occurred in the Illgraben catchment were analyzed considering their volumes, triggering rainfalls, runoff coefficients and antecedent wetness conditions (Fig. 3). The debris flows occurred between May and October, with highest frequency in July (25) and fewer in the shoulder seasons in May (7) and September and October (6). Debris-flow volumes range between 4 000 and 90 000 m^3 (median 25 000 m^3). Runoff coefficients have a median value of 0.3 but vary between 0.003 and 4.6. Although, 50% of the values lie between 0.01 and 0.09. Four of the nine largest runoff coefficients were observed in May during the snowmelt period. Events with larger volumes have larger runoff coefficients and occur until the beginning of August. Triggering rainfall amounts varied between 0.2 and 34.6 mm and have a median of 9.6 mm. For all events, the catchment experienced rainfall in the 14 days prior to the triggering event. Smaller events can have both high or low antecedent wetness during all seasons. While large events in May do not necessarily show increased antecedent wet conditions, large events occurring later into the year do.

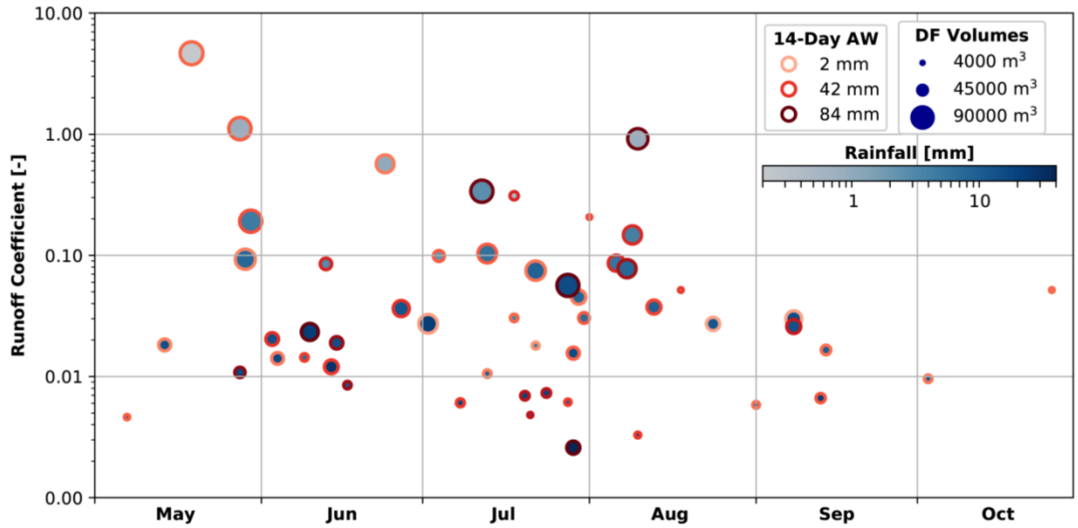

Fig. 3. Runoff coefficients (y-axis), debris-flow volumes (marker size), cumulated triggering rainfall (marker fill) and 14-day antecedent wetness (marker edge) of 52 debris flows (x-axis) that occurred in the Illgraben catchment between 2002 and 2017 in the period susceptible to debris flows between May and October.

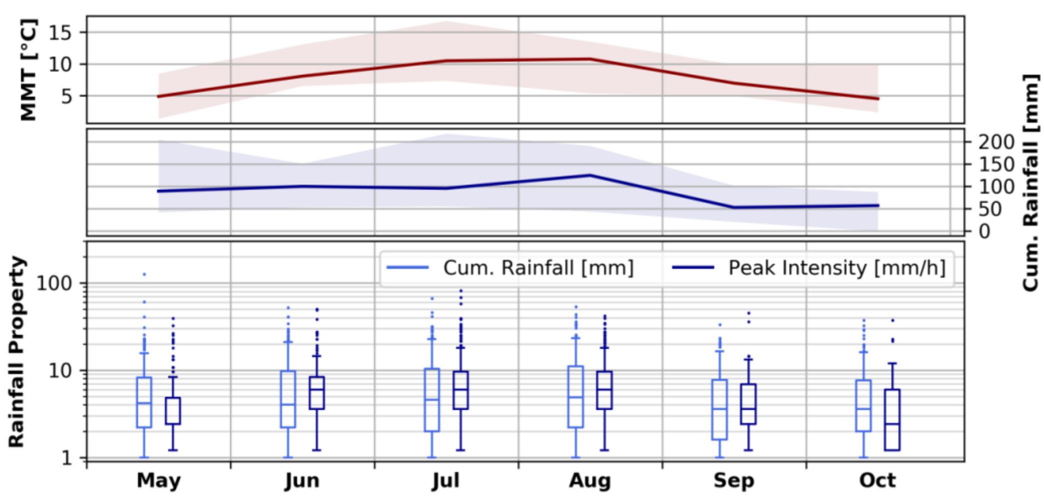

Fig. 4. Climate variables. Median, highest and lowest Mean Monthly Temperature (MMT) and cumulated monthly precipitation is shown in the upper two boxes. In the bottom, box plots for event cumulated rainfall (left) and rainfall peak intensity between 2002 and 2017 are presented.

The higher event frequencies during the summer months coincide with an increase in mean monthly temperatures and peak rainfall intensities (Fig. 4). In September and October, the decrease in debris-flow occurrence is accompanied by decreases in temperature, rainfall amounts and peak rainfall intensities.

In May, debris flows can be triggered by very small rainfall amounts, and runoff coefficients can even exceed 1. This strongly indicates that snowmelt plays a key role early in the season. Schneider et al. (2010) also evaluated snowmelt to be an important factor for debris flows triggered in a catchment of similar altitude as the Illgraben in the

Italian Dolomite Alps. Prenner et al. (2018) identified 6 of 41 debris flows where snowmelt fostered the triggering in an Austrian catchment also of similar altitude. Hence, our observation is consistent with others in similar catchments in terms of location and altitude.

In general, the Illgraben runoff coefficients increase with event volume. This is in line with the expectations, since we determine the water volume as 50% of the debris-flow volume. We also expect runoff coefficients of events with high cumulated rainfall amounts to be lower because of its definition (Eq. 1). A surprising result is that the largest debris flows were not initiated by the heaviest rainfalls (in terms of rainfall amounts). Rickenmann and Koschni (2010) highlighted that debris-flow volumes can have a large variability for a given runoff volume, in an analysis of a large storm event in Switzerland in 2005. Excluding catchments which were affected by landslides, this variability could be decreased. Consequently, it implies that there are other factors adding substantial uncertainty to the debris-flow magnitude, while rainfall and the resulting runoff only enhances the probability of triggering.

While the initial debris-flow volumes can be small, they can evolve to be a multiple thereof by entraining material along their flow paths (Berger et al., 2011a). Thereby, entrainment experiences positive feedback from the soil moisture in the flow path, because the pore water pressure increases as the debris-flow front approaches which can reduce the friction (Iverson et al., 2011; McCoy et al., 2012). Furthermore, the 14-day antecedent wetness can be considered as a proxy for the average soil moisture condition in the catchment. Debris flows in the Illgraben occur at all states of antecedent wetness, which therefore is not a good predictor for the actual event volume (Fig. 5). Nevertheless, out of the six largest debris flows, three occurred in May with modest antecedent wetness (~30 mm) while the other three took place later in the season under the highest observed antecedent wetness conditions (~80 mm). This exemplifies that there is a need to quantify the effects of snowmelt on the catchment, in order to make the climatic and hydrological conditions comparable. Furthermore, the results indicate that while events with smaller volumes can occur for the entire range of antecedent wetness, larger events with higher return periods are conditioned by antecedent wetness (except in May and June). Therefore, it is conceivable that there is an upper debris-flow volume limit for a given wetness condition (Fig. 5). These results are in line with McCoy et al. (2012) who observed substantially larger debris flows when the channel bed was wetter. It has also been noted that antecedent wetness is not necessarily required for debris-flow triggering (e.g. Coe et al., 2008; Abancó et al., 2016).

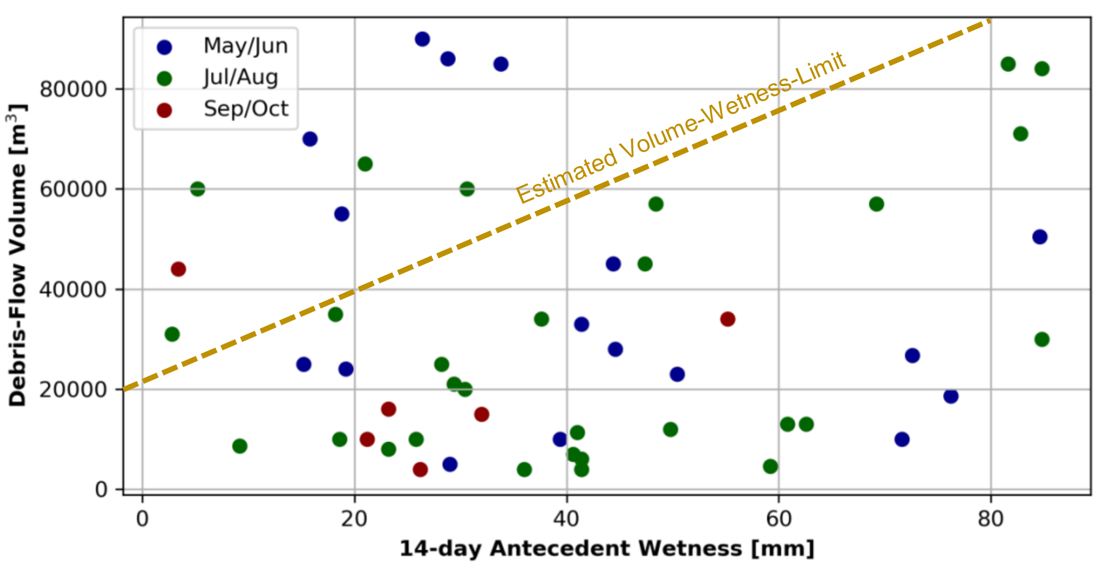

Fig. 5. Scatter plot of antecedent wetness, which corresponds to the cumulated rainfall in the 14 days before the event (excluding the triggering rainfall) and the debris-flow volumes for the 52 studied events. In color, the months during debris-flow season is indicated. There are indications that larger events are conditioned by antecedent wetness, which is exemplified by the dashed threshold line. The points above the line are likely due to snowmelt effects and uncertainties in the actual wetness conditions, among others.

In the case of sediment entrainment from the bed during an event, interstitial water stored in the soil is also entrained. This theory would explain the increased runoff coefficients for larger debris-flow volumes. In this study, we are not able to determine runoff coefficients as usually defined in hydrology, because an unknown amount is added into the fluid component of debris flows. Therefore, the runoff coefficients illustrate that the amount of water exiting the catchment as discharge can be altered by debris flows.

Naturally, there are other factors enhancing the debris-flow volumes, which were not considered here. Even though the Illgraben catchment has indications of being transport-limited (Schlunegger et al., 2009), Bennett et al. (2014) modelled the long-term sediment output and only characterized 55% of the debris flows to be transport-limited. Therefore, it is likely that for a significant number of cases, the debris flows were supply-limited and sediment availability should also be considered as a variable controlling the debris-flow volume.

Finally, residual uncertainties remain in the rainfall measurements. Measuring precipitation with a rain gauge is a point measurement and upscaling to areal rainfall comes along with uncertainties. Nevertheless, the gauge RG1 is situated comparatively close to the initiation zone and at a representative altitude. Some uncertainty also exists in the synchronization in the timing of the force plate and the rain gauge, since the latter is operated by the cantonal authorities. An uncertainty assessment, however, revealed that even a time shift of two hours would not change the runoff coefficients significantly (p-value = 0.1). There is also uncertainty in the assumption of the bulk density. If variations in this parameter would be considered, the range of runoff coefficients would be squeezed, but not alter the general pattern.

5. Conclusions and Outlook

We determined volume, triggering rainfall, runoff coefficients and 14-day antecedent wetness for 52 debris flows in the Illgraben catchment. Runoff coefficients varied greatly and increase with increasing debris-flow volume. We conclude that the cumulated rainfall amount is not a proxy for the debris-flow volume. In fact, debris flows with the largest volumes were triggered by comparatively small rainfall amounts. Antecedent wetness, however, seems to be a key factor for the volume. Antecedent wetness has at least two effects. First, it enhances entrainment along the channel by increased pore-water pressure and second, in the process of entrainment, the interstitial water is also entrained, contributing to substantially larger runoff coefficients.

Furthermore, seasonal variations in the debris-flow volumes and frequencies are apparent. In spring, snowmelt likely enhances the triggering and entrainment of sediments, leading to some of the largest debris-flow volumes. In the summer months, the increased frequency of debris-flow occurrence is accompanied with an increase in high rainfall intensities. In autumn, only few and small debris flows happen because of lower rainfall amounts and intensities. Another reason is possibly the occurrence of supply-limited conditions in autumn because sediments have been washed out earlier in the season.

This study gives insights on which climate variables are likely to control debris-flow volume. Nevertheless, the variables discussed here are only indicators and do not replace the actual conditions which led to the formation of a debris-flow of a given volume. Therefore, it motivates future investigations on hydrological (snow, runoff, soil water content, etc.) and geomorphological variables (available sediments for mobilization) in more detail. Especially in a changing climate and for possible hazard mitigation adaptation, it would be interesting to explore debris-flow generation in a more quantitative approach. *SedCas*, a probabilistic sediment cascade model which has been developed for the Illgraben (Bennett et al., 2014), offers an ideal framework for the suggested investigations.

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References

Abancó, C., Hürlimann, M., Moya, J., and Berenguer, M., 2016, Critical rainfall conditions for the initiation of torrential flows. Results from the Rebaixader catchment (Central Pyrenees): Journal of Hydrology, v. 541, p. 218–229, doi:10.1016/j.jhydrol.2016.01.019.

Badoux, A., Graf, C., Rhyner, J., Kuntner, R., and McArdell, B. W., 2009, A debris-flow alarm system for the Alpine Illgraben catchment: Design and performance: Natural Hazards, v. 49, p. 517–539, doi:10.1007/s11069-008-9303-x.

Bennett, G. L., Molnar, P., Eisenbeiss, H., and Mcardell, B. W., 2012, Erosional power in the Swiss Alps: Characterization of slope failure in the Illgraben: Earth Surface Processes and Landforms, v. 37, p. 1627–1640, doi:10.1002/esp.3263.

Bennett, G. L., Molnar, P., McArdell, B. W., and Burlando, P., 2014, A probabilistic sediment cascade model of sediment transfer in the Illgraben: Water Resources Research, v. 50, p. 1225–1244, doi:10.1002/2013WR013806.

Bennett, G. L., Molnar, P., McArdell, B. W., Schlunegger, F., and Burlando, P., 2013, Patterns and controls of sediment production, transfer and yield in the Illgraben: Geomorphology, v. 188, p. 68–82, doi:10.1016/j.geomorph.2012.11.029.

Berger, C., McArdell, B. W., and Schlunegger, F., 2011, Direct measurement of channel erosion by debris flows, Illgraben, Switzerland. Journal of Geophysical Research: Earth Surface, v. 116, p. 1–18, doi:10.1029/2010JF001722.

Berger, C., McArdell, B. W., and Schlunegger, F. 2011, Sediment transfer patterns at the Illgraben catchment, Switzerland: Implications for the time scales of debris flow activities: Geomorphology, v. 125, p. 421–432, doi:10.1016/j.geomorph.2010.10.019.

Coe, J. A., Kinner, D. A., and Godt, J. W., 2008, Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado: Geomorphology, v. 96, p. 270–297, doi:10.1016/j.geomorph.2007.03.017.

Hungr, O., Mcdougall, S., and Bovis, M., 2005, Entrainment of material by debris flows, *in* Debris-Flow Hazards and Related Phenomena, p. 135–155, doi:10.1007/3-540-27129-5_7.

Hürlimann, M., Rickenmann, D., and Graf, C., 2003, Field and monitoring data of debris-flow events in the Swiss Alps: Canadian Geotechnical Journal, v. 40, p. 161–175, doi:10.1139/t02-087.

Iverson, R. M., Reid, M. E., Logan, M., LaHusen, R. G., Godt, J. W., and Griswold, J. P., 2011, Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment: Nature Geoscience, v. 4, p. 116–121, doi:10.1038/ngeo1040.

Marchi, L., and D'Agostino, V., 2004, Estimation of debris-flow magnitude in the Eastern Italian Alps: Earth Surface Processes and Landforms, v. 29, p. 207–220, doi:10.1002/esp.1027.

McArdell, B. W., Bartelt, P., and Kowalski, J., 2007, Field observations of basal forces and fluid pore pressure in a debris flow: Geophysical Research Letters, v. 34, doi:10.1029/2006GL029183.

McCoy, S. W., Kean, J. W., Coe, J. A., Tucker, G. E., Staley, D. M., and Wasklewicz, T. A., 2012, Sediment entrainment by debris flows: In situ measurements from the headwaters of a steep catchment: Journal of Geophysical Reasearch, v. 117, doi:10.1029/2011JF002278.

Pierson, T. (2005). Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds: U.S. Geological Survey Fact Sheet, 2004-3142. 4 p.

Prenner, D., Kaitna, R., Mostbauer, K., and Hrachowitz, M., 2018, The Value of Using Multiple Hydrometeorological Variables to Predict Debris Flow Susceptibility in an Alpine Environment: Water Resources Research, v. 54, p. 6822-6843, doi:10.1029/2018WR022985.

Rickenmann, D., 1999, Empirical Relationships for Debris Flows: Landscape, v. 19, p. 47–77, doi:10.1023/A:1008064220727.

Rickenmann, D., & Koschni, A., 2010, Sediment loads due to fluvial transport and debris flows during the 2005 flood events in Switzerland: Hydrological Processes, v. 24, p. 993–1007, doi:10.1002/hyp.7536.

Schlunegger, F., Badoux, A., McArdell, B. W., Gwerder, C., Schnydrig, D., Rieke-Zapp, D., and Molnar, P., 2009, Limits of sediment transfer in an alpine debris-flow catchment, Illgraben, Switzerland: Quaternary Science Reviews, v. 28, p. 1097–1105, doi:10.1016/j.quascirev.2008.10.025.

Schneider, H., Höfer, D., Irmler, R., Daut, G., and Mäusbacher, R., 2010, Correlation between climate, man and debris flow events - A palynological approach: Geomorphology, v. 120, p. 48–55, doi:10.1016/j.geomorph.2009.09.014.

Stoffel, M., 2010, Magnitude-frequency relationships of debris flows - A case study based on field surveys and tree-ring records: Geomorphology, v. 116, p. 67–76, doi:10.1016/j.geomorph.2009.10.009.

Takahashi, T., 2014, Debris flow: mechanics, perdictions and countermeasures. press CRC.