Sediment input from debris flows into mountain rivers: an event-based perspective

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ABSTRACT

Sediment transport in mountain streams is a function not only of upstream sediment input but also of sediment delivery from the steep lateral tributaries. In this study we analyzed a total of 32 debris-flow events which had occurred in the Swiss Alps. For 19 of the 32 studied events a sediment delivery occurred into the receiving stream. For the other 13 events no substantial part of the total event volume was transported into the receiving stream. We performed a statistical analysis to find a quantitative criterion for the question whether or not a debris flow with a given event magnitude will reach the confluence with the receiving stream. We developed a dimensionless index to respond to the above question. The index is based on the following three parameters: channel fan slope, length of the channel on the fan, and event volume.

KEYWORDS

debris flow; sediment input; mountain river; sediment connectivity; torrent fan

INTRODUCTION

Sediment transport in mountain streams is a function not only of upstream sediment delivery but also of sediment input from steep lateral tributaries. The amount of sediment potentially entering the main valley river from a tributary is likely to depend on the event magnitude of a debris flow in the torrent catchment as well as on the topographic conditions on the fan. These latter conditions may also be modified by man-made constructions such as bridges, houses, and protection structures.

During a debris-flow event in a torrent catchment, the sediment transfer and deposition in the fan area depends primarily on the presence of sediment retention basins, the channel conveyance capacity in relation to the size of the debris flow, and potential clogging locations on the fan (e.g. narrow cross-sections under bridges crossing the channel). The sediment load transported to the fan apex can is often deposited on the fan outside of the channel, if the transport capacity in the channel is insufficient, for example in a flat reach upstream of the confluence. Streams with a catchment area of less than 25 km^2 and an average longitudinal slope greater than 5-10% can be classified as torrents (Rickenmann and Koschni, 2010; Rickenmann, 2014).

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For the quantification of solid transport in a mountain river, the potential sediment delivery from individual tributaries (torrents) must be known. For the estimation of the sediment delivery in debris-flow prone torrents there are several field-based methods (Marchi and D'Agostino, 2004; Jakob, 2005; Gertsch, 2009; Frick et al., 2008, 2011; Kienholz et al., 2010). Typically, with these methods an expected sediment load is estimated for the fan apex.

There are many studies on the sediment connectivity of debris-flow fans with fluvial systems over longer time scales (Harvey, 2012). However, with regard to the important role of fans on the coupling or buffering of sediment cascades in the fluvial system, there are few quantitative investigations on the controlling factors of sediment delivery to the main valley river on an event-based time scale from debris flows in steep tributaries.

For this study we analyzed the sediment input to mountain rivers from steep torrents based on 32 debris-flow events which had occurred from 1987 to 2009 in the Swiss Alps. Based on a statistical analysis we identified several parameters which can be used to estimate whether or not a debris flow (of a given event magnitude) delivers sediment into the receiving stream. Using some of the identified parameters, we developed a dimensionless index that can help to distinguish between the two cases.

DATA AND METHOD

The majority of the 32 case study events were taken from the PhD dissertation of Gertsch (2009) in steep torrents. The study catchments have surface areas mostly smaller than 20 km^2 and mean channel gradients that are steeper than 10%. About a third of the study catchments have a sediment retention basin, mostly in the upper part of the fan near the apex.

For the analysis, the 32 events were divided into the following two groups: (i) events and fan situations for which some of the total debris-flow material reached the receiving stream, labeled here as yes cases (YC), and (ii) events during which no sediment entered the receiving stream, labeled here as no cases (NC). For the first group, the available dataset did not, unfortunately, include sufficient information to quantify the amount of sediment which had entered the main stream. However, based on photo documents and on experience from other debris-flow events it is likely that for most events in group (i) only a relatively small fraction of the total sediment volume entered the receiving stream.

In a first step, 18 parameters were determined for each event, characterizing the study catchment, the fan topography and the debris-flow event. Parameters characterizing the catchment and the fan were determined from the analysis of Digital Elevation Models (DEM 10m and DTM AV 2m of Swisstopo), the assessment of aerial photographs, and by field investigation. Event-related parameters were determined from the available event documentation and in some cases estimated with empirical formulas. The 18 parameters were: catchment area above fan apex, channel length from the apex to the confluence, mean fan slope, mean channel slope, mean channel slope according to Prochaska et al. (2008), mean channel slope until 25 m upstream of the confluence, mean channel slope for 100 m reach upstream of fan apex, Melton number (fan apex), Melton number (confluence), event volume, event volume without retention basin volume, maximum discharge (estimated from event volume), flow velocity (at maximum discharge), minimum cross-sectional area of channel on fan, estimated flow cross-sectional area, fan surface area, angle of fan channel to receiving stream (plan view), number of potential clogging sites.

We then used statistical methods to search for a quantitative criterion or rule to distinguish between the two groups (i) and (ii). Some parameters were found to provide a reasonable differentiation between the YC and NC. Finally, using a subset of the most useful parameters, a dimensionless index was developed that can help to distinguish between the two cases.

RESULTS

Main processes on the fan during large debris-flow events

For our dataset we compiled the main processes and fan situations which existed or occurred for large debris-flow events between the fan apex and the confluence with the main river (Fig. 1).

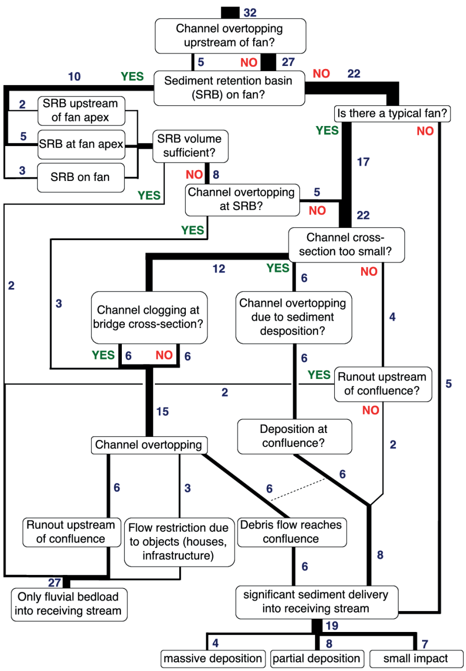

Figure 1: Flowchart of the main processes on a fan during the debris-flow runout process. The line width is proportional to the number of observed cases. Out of 32 investigated events sediment entered the receiving stream in 19 cases (bottom line).

Some important results can be described as follows:

- For 19 of the 32 studied events a sediment delivery occurred into the receiving stream (YC). For the other 13 events no substantial part of the total event volume was transported into the receiving stream (NC).
- For 21 events, an overtopping occurred out of the existing channel on the fan. Among these events there are 10 NC (not reaching the confluence) and 11 YC (reaching the confluence).
- Although for 10 study catchments a sediment retention basin (SRB) exists on the fan, debris-flow material reached the confluence in some of these cases.

A flow chart with the main processes occurring on the fan (see Fig. 1) could be used as a basis for the development of a decision tree that may eventually allow for a semi-quantitative estimation of the sediment delivery to the main stream. However, the number of possible sub-processes (many branching possibilities in the flow chart of Fig. 1) is very large in relation to the limited number of investigated events. Therefore, in the following analysis we mainly searched for criteria to distinguish between the two groups of events (i.e. YC and NC).

Analysis of selected parameters

Among the 19 pre-selected parameters we could identify five whose values allow a rough distinction between the NC and YC, in that there is no overlap of the quartiles of the value ranges (Fig. 2): (1) fan gradient, (2) channel gradient over 25 m horizontal distance upstream of the confluence, (3) mean flow velocity at maximum debris-flow discharge, (4) number of potential clogging locations, and (5) average channel gradient over 100 m horizontal distance upstream of the fan apex. Three of these parameters (2, 3, 5) are strongly correlated to the fan slope, and were therefore not used in the further analysis.

Regarding the parameter length of the fan, Lf, we found that there were 5 NC with Lf > 1230 m and 10 YC with Lf < 455 m, whereas the remaining 17 cases had intermediate LF values. This finding suggest that the longer is a torrential fan, the smaller is the probability that a debris flow reaches the receiving stream.

All debris-flow events on a fan with a mean gradient, Sf, larger than 18 % or with a magnitude greater than 40,000 m^3 reached the receiving stream (Fig. 3). The more potential clogging locations are present on the fan, the lower is the probability that a debris flow reaches the receiving stream (Fig. 2). On fans with six or more potential clogging locations, only NC occurred. In contrast, if there were zero or one potential clogging location, there were only YC.

We identified further parameters that may be suitable for a distinction between YC and NC: catchment area, mean channel gradient upstream of the fan, Melton number, ratio of calculated flow cross-section to minimum available flow cross-section, fan area, and angle of debris-flow channel to the receiving water. However, there is overlap of the quartiles of the value ranges between the two main groups (YC and NC).

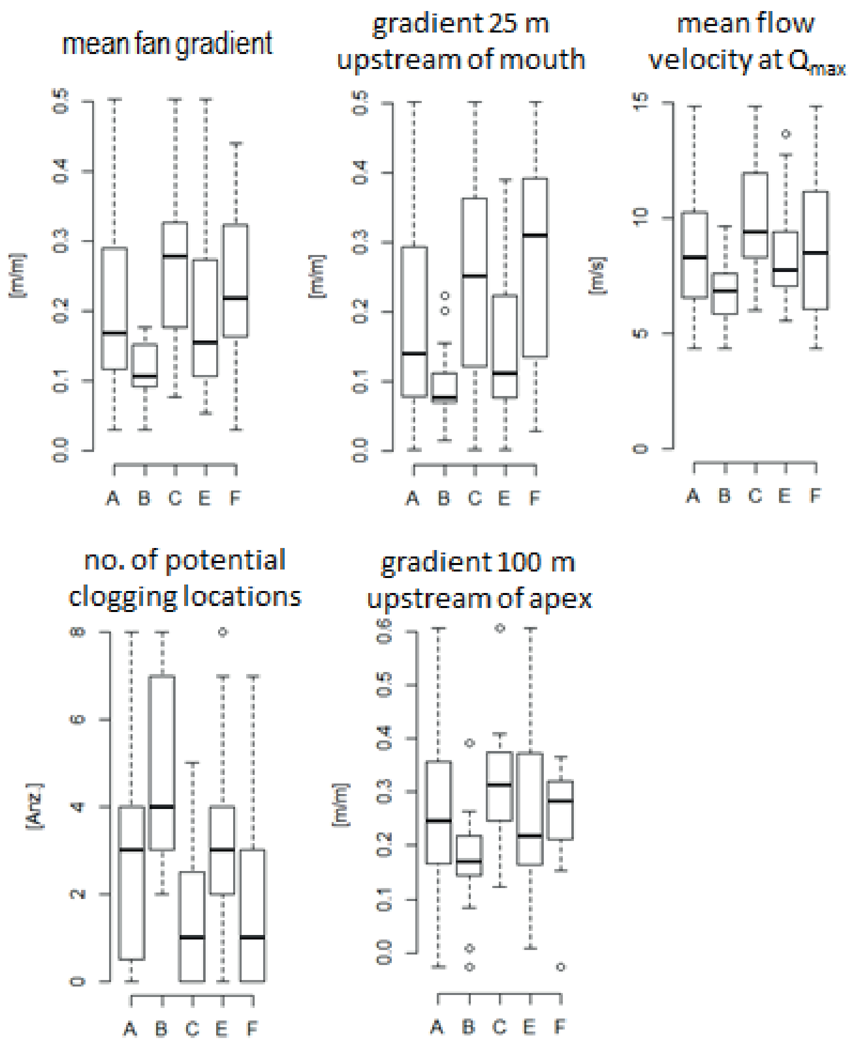

Figure 2: Range of values of five important parameters which may be related to the runout charac¬teristics. A = all events, B = no runout into the receiving stream (NC), C = runout into the receiving stream (YC), E =channel overtopping, F = no channel overtopping. Qmax is maximum debris flow discharge. A box includes the median value (thick line) and 50% of the data. It is limited by the upper and lower quartiles. Whiskers refer to the 5% and 95% values. Circles represent extreme values (not fully shown).

Regarding the sensitivity to channel overtopping on the fan, we identified several parameters that may be useful for a delineation of this process: channel length (from apex to confluence), fan gradient, channel gradient over 25 m horizontal distance upstream of the confluence, and number of potential clogging locations.

Dimensionless index

Based on the above analysis, we searched for a quantitative criterion to distinguish between the two groups of events (YC and NC). Considering all the investigated parameters, some important correlation was identified among several of them, as for example between fan area and length of the fan channel or between the upstream channel gradient and the gradient of the channel on the fan. Among the following parameter pairs, however, no clear correlation could be identified: (i) fan gradient and fan length; (ii) fan gradient and event volume; (iii) event volume and fan length.

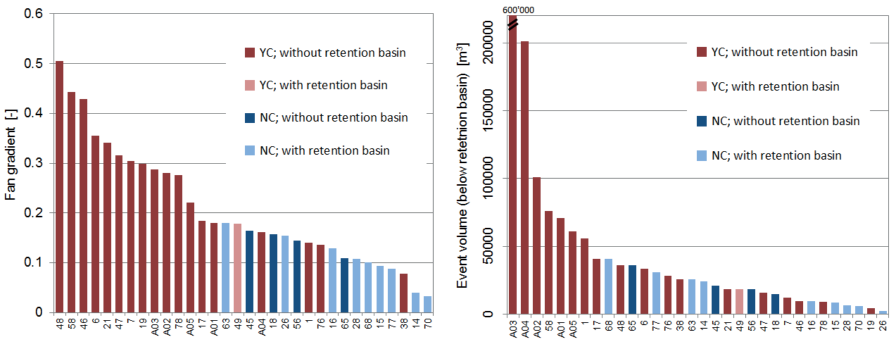

Figure 3: Separation of YC and NC cases as a function of mean fan gradient (left panel) and event volume (right panel).

As a result, we finally retained the three parameters fan gradient Sf, fan length Lf, and event volume Mexc for the development of a quantitative criterion. Here Mexc refers to the debris-flow event volume excluding the volume of the SRB if existing. By normalizing all three parameter values with the arithmetic mean of the parameter group (denoted by an overbar), a dimensionless index value was determined. By introducing a pre-factor of 0.42, the resulting range of index values lies between 0 and 1.

$$Index = 0.42 * \left(\frac{M_{exc}}{\overline{M_{exc}}}\right)^{0.33} * \left(\frac{\overline{L_f}}{L_f}\right)^{0.5} * S_f$$

Equation 1

The index permits a fairly good distinction between these events not reaching the confluence (NC) and those reaching the confluence (YC) (Fig. 4). Considering a fixed threshold of 0.06 for the critical index value, only three YC events are not correctly classified (i.e. they would be incorrectly classified as NC events). The exponents of the different factors constituting

Eq. 1 were determined by trial and error to obtain the best distinction between YC and NC events.

DISCUSSION

The torrent catchments included in our study are all prone to debris-flow occurrence. A limitation of our dataset is that there were few YC catchments with a natural fan, i.e. with only few anthropogenic structures. Among the catchments with NC, there was a relatively large proportion (69%) with a sediment retention basin on the fan. These two limitations, in combination with the relatively small number of 32 cases in total, may have influenced and biased our findings.

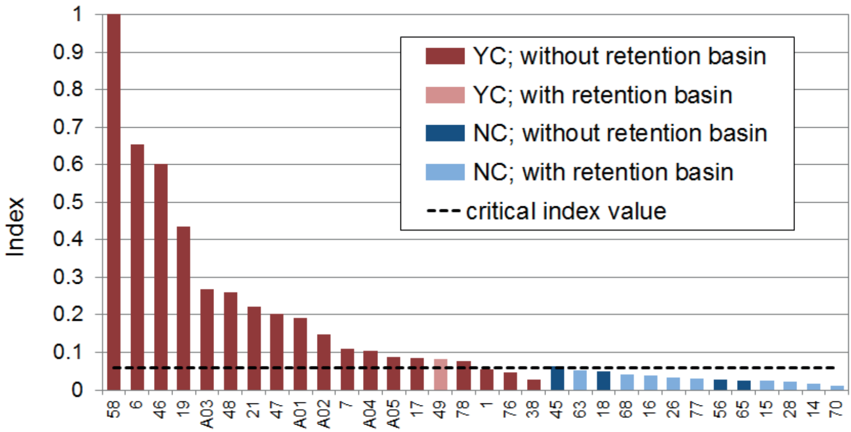

Figure 4: Dimensionless index to separate YC and NC cases. The proposed critical limit of 0.06 (dashed line) approach correctly identifies 16 out of 19 events of the YC cases, and all 13 events of the NC cases are correctly identified with this limit.

The proposed index allows for a reasonably good separation for debris-flow events and fan situations with or without sediment entering the receiving stream. It is possible that a more robust method could be developed by including more parameters such as the number of potential clogging locations in a detailed quantitative analysis. The index should be reviewed on the basis of further independent data.

An alternative approach could consist in developing a decision tree, which could eventually also allow to estimate the fraction of the total event volume that reaches the receiving stream. Such a decision tree could be largely based on the flow chart of the main processes as depicted in Figure 2. The decision tree would start with a given debris-flow volume at the fan apex, and this volume would be reduced due to partial deposition along the flow path down to the confluence with the receiving stream or it may be enlarged due to sediment entrainment by erosion on the fan. To develop and test such an approach, a more detailed data base on debris-flow volumes entering receiving streams would be necessary to determine quantitative criteria at the branching points of the flow chart. A similar approach was developed in the context of a practice guide on "Estimation of the average annual sediment delivery into receiving streams" (BAFU, 2014).

CONCLUSIONS AND OUTLOOK

In this study we analyzed a total of 32 debris-flow events which had occurred in the Swiss Alps. For 19 of the 32 studied events a sediment delivery occurred into the receiving stream. For the other 13 events no substantial part of the total event volume was transported into the receiving stream. We performed a statistical analysis to find a quantitative criterion for the question whether or not a debris flow with a given event magnitude may reach the confluence with the receiving stream. We considered several topographic parameters which characterize the fan and channel properties, and we also included the event-based parameters in our analysis.

We found that several of the pre-selected parameters were useful to discriminate between the two types of fan situations and events. We developed a dimensionless index, which is based on the following three parameters: channel fan slope, length of the channel on the fan, and debris-flow event volume. Selecting an optimal critical index value, this approach correctly identifies 16 out of 19 events in the first group (events with sediment entering the receiving stream); at the same time, all the 13 events in the second group (events without sediment reaching the receiving stream) are also correctly identified.

The two topographic parameters of our index can be determined easily from digital elevation models. Additional compilations of comprehensive documentations of past debris-flow events including an estimate of the event volume and runout characteristics are important prerequisites for any further testing of the proposed index and for an improved development of a similar method. Other catchment or fan parameters could also be considered to possibly improve the discrimination method with an enlarged dataset.

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REFERENCES

- BAFU (2014). Abschätzung der mittleren jährlichen Geschiebelieferung in Vorfluter – Praxishilfe. Hunziker, Zarn & Partner, Aarau; Lehmann, Hydrologie-Wasserbau, Urtenen – Schönbühl; belop gmbh, Sarnen; im Auftrag des Bundesamtes für Umwelt (BAFU), Bern, 75S.

- Frick, E., Kienholz, H., Roth, H. (2008). SEDEX - eine Methodik zur gut dokumentierten Abschätzung der Feststofflieferung in Wildbächen. Wasser Energie Luft 100 (2): 131-136.
- Frick, E., Kienholz, H., Romang, H. (2011). SEDEX (SEDiments and EXperts), Anwender-Handbuch. Geographica Bernensia P42, Geographisches Institut der Universität Bern, 128p., ISBN 978-3-905835-27-4.
- Gartner, J.E., Cannon, S.H., Santi, P.M., Dewolfe, V.G. (2008): Models to predict debris flow volumes generated by recently burned basins. Geomorphology 96: 339–354.
- Gertsch, E. (2009). Geschiebelieferung alpiner Wildbachsysteme bei Grossereignissen - Ereignisanalysen und Entwicklung eines Abschätzverfahrens. Dissertation (unveröffentlicht), Geographisches Institut der Universität Bern, Bern.
- Gerber, M. (2014). Entwicklung eines Klassifizierungsverfahrens für den Feststoffeintrag in den Vorfluter durch Murgänge. Bachelorarbeit (unveröffentlicht), Zürcher Hochschule für Angewandte Wissenschaften, Wädenswil und Eidg. Forschungsanstalt WSL, Birmensdorf.
- Harvey, A.M. (2012). The coupling status of alluvial fans and debris cones: a review and synthesis. Earth Surface Processes and Landforms 37: 64–76.
- Jakob, M. (2005). Debris flow hazard analysis. In Debris-flow Hazards and Related Phenomena, ed. M Jakob, O Hungr (Chichester: Springer Praxis Publishing, 2005), pp. 411–443.
- Kienholz, H., Frick, E., Gertsch, E. (2010). Assessment tools for mountain torrents: SEDEX© and bed load assessment matrix. Proc. International Interpraevent Symposium, Taipei, Taiwan, pp. 245–256.
- Marchi, L., D'Agostino, V . (2004). Estimation of debris-flow magnitude in the Eastern Italian Alps. Earth Surface Processes and Landforms 29: 207–220.
- Rickenmann, D. (2014). Methoden zur quantitativen Beurteilung von Gerinneprozessen in Wildbächen. WSL Berichte, Nr. 9, 105p. (www.wsl.ch/publikationen/pdf/13549.pdf)
- Rickenmann, D., Koschni, A. (2010). Sediment loads due to fluvial transport and debris flows during the 2005 flood events in Switzerland. Hydrological Processes 24: 993–1007.