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Channel scour and fill by debris flows and bedload transport

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ABSTRACT

In steep channels, debris flows are known to dramatically increase in volume under the effect of channel erosion. However, the critical factors controlling channel erosion by debris flows are not well documented by field studies. This is particularly true for the effect of slope on the depth at which erodible beds are scoured during debris flows and during bedload transport. This topic has been addressed by intensive cross section resurveys (54 cross sections) of debris flows ($n = 5$) and flow events ($n = 9$) that occurred in two torrents of the French Prealps, the Manival and Réal torrents, between 2009 and 2012. This study provided evidence that debris-flow scouring increases with slope, whereas this is not the case for bedload transport (no slope effect detected during floods). A functional relationship defined from a piecewise regression model is proposed as an empirical fit for the prediction of channel erosion by debris flows with a critical slope threshold at 0.19 (95% confidence interval: 0.17–0.21). This slope threshold is interpreted as the transition between the transport-limited and supply-limited regimes, associated with the upstream decreasing erodible bed thickness. The erodible bed was also characterized by quantifying erosion, deposition, and surface roughness with multidate terrestrial laser scans (TLSs) in a short reach of high sensitivity of the Manival torrent. Debris-flow erosion occurred preferentially on smooth surfaces corresponding to the unconsolidated gravel deposits from bedload transport. A 20-cm resolution roughness profile from an airborne laser scan (ALS) and a slope profile of the whole channel were used to detect the unconsolidated sediment deposits that can potentially feed future debris flows.

1. Introduction

Although steep-slope channels represent a considerable length of upland stream networks, our understanding of geomorphic laws that govern these channels is less advanced than for lowland fluvial systems. The variety of sediment transport processes encountered in this environment (debris flows and bedload transport) and the strong influence of hillslopes on sediment supply conditions interact to produce a specific geomorphic behavior in headwaters. This situation limits our ability to propose reliable tools for assessing the transfer of sediment from mountains to piedmont rivers, whereas at the same time, stakes related to the protection against natural hazards in mountains, and to the preservation of sediment continuity in aquatic ecosystems, are becoming more and more important. Debris flows are surges of saturated nonplastic debris traveling in steep channels at a range of 2–20 m s^{-1} with sediment concentrations generally higher than 50% by volume (Hungr et al., 2001; Jakob and Jordan, 2001). In contrast, bedload transport occurs during flow events with low sediment concentrations (<20% by volume) and consists of the stochastic motion of individual particles that are traveling in a series of step and rest periods at a velocity that is much lower than the fluid velocity.

The geomorphic work of debris flows has been well documented over the past decades with several studies focusing on the quantification of magnitude and frequency and rainfall thresholds of debris flows (e.g., Innes, 1983; Kotarba, 1992; Jonasson and Nyberg, 1999; Vedin et al., 1999; Beylich and Sandberg, 2005; Decaulne et al., 2005). The sediment recharge of the channel from active erosion on hillslopes was found to be a critical factor of debris-flow magnitude and frequency (Bovis and Jakob, 1999; Marchi and D'Agostino, 2004; Jakob et al., 2005) as channel erosion is generally the most important contribution to the debris-flow volume (Hungr et al., 1984, 2005). Our study focuses on runoff-generated debris flows that are triggered by high intensity rainfalls; these surges progressively entrain the channel where erodible sediments are present, which in turn increases the sediment concentration (Rickenmann et al., 2003; Berti and Simoni, 2005; Godt and Coe, 2007; Coe et al., 2008; Gregoretti and Fontana, 2008).

One of the most striking characters of debris flows is their ability to dramatically cut and fill the granular bed during their propagation. These channel deformations can commonly reach several meters (Jakob et al., 2005; Remaître et al., 2005; Imaizumi et al., 2006). A classic way to predict erosion and deposition for a given reach is to use the conservation of mass (Exner equation) (Ashmore and Church, 1998). The rate of change of channel elevation per unit time is a function of the

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rate of change of sediment transport per unit length of stream. The sediment transport rate is controlled by the forces exerted by the fluid on the bed (shear stress) and also by sediment supply conditions (in terms of frequency, volume, and grain-size distribution), which are determined by channel conditions and also by external delivery from hillslopes. These drivers of channel deformations are extremely difficult to quantify in a deterministic way, which limits our understanding of the spatial variability of erosion and deposition in debris-flow channels.

Even though in-channel sediment deposits are known to be an important source of material for debris flows, our understanding of their entrainment is still limited. Recently, studies gave insights on channel conditions controlling the release of sediment from a steep bed during a debris flow, notably by looking at the effect of pore water pressure on channel scouring. This effect has been demonstrated in large-scale flume experiments, which show that a small increase of the bed sediment water content before the flow release had a considerable effect on the rate at which the bed is entrained by the flow (Iverson et al., 2011). These experimental findings were recently confirmed by field observations at the Chalk Cliffs debris-flow observatory, where it has been shown that the time-averaged bed sediment entrainment rate was faster when saturation of the bed prevails when the flow occurs (McCoy et al., 2012). Another study using erosion sensor column data has observed the timing of bed scouring during debris flows and showed that the majority of scouring occurs at the debris-flow front, during the shear stress peak (Berger et al., 2011); this was also observed at the Chemolgan field laboratory site (Rickenmann et al., 2003). Although these field and laboratory experiments provided insights into the instantaneous scour processes, they were not designed to address the spatial variation of scouring and notably the effect of slope and material properties on channel erosion by debris flows and bedload transport.

An experimental study has examined thoroughly the role of erodible sloping beds on granular flow dynamics with a tilting apparatus (Mangeney et al., 2010). It was found that the growth of granular flow momentum from scouring became insignificant when the slope is below half the repose angle of the bed material. This study also found that the presence of an erodible bed increases granular flow travel distance by 40%. Few field studies have attempted to look at the effect of slope. Post-event field measurements of maximum scouring for the 1987 debris flows in Switzerland revealed a broad linear relationship with slope (Rickenmann and Zimmermann, 1993). A database compilation of 174 debris flows and debris avalanches in the Queen Charlotte Islands (British Columbia) was used to look at the relation between slope and debris-flow yield rates, without any clear trend in the data (Hungr et al., 2005). This result has been partly attributed to the poorly constrained nature of erosion observations, which are not based on high-resolution topographic resurveys (Hungr et al., 2008). This is not the case of a recent study in Iceland, based on airborne laser scanning (ALS) and differential GPS surveys which showed a clear effect of slope on erosion and deposition patterns of first-order gullies entrenched into steep talus slopes (Conway et al., 2010).

Despite the many efforts for understanding debris-flow erosion, there is very little field observations using reliable topographic surveys across long reaches with high periodicity. More field data are needed to address the effect of slope on channel erosion by debris flows and by bedload transport. This is particularly true for steep-slope channels located on debris-flow fans because this is a critical zone where debris flows can dramatically grow in volume due to the presence of loose debris. The focus of this paper is to investigate the different scour and fill patterns for debris flows and bedload transport along steep-slope channels and to better define the controls on debris-flow erosion by assessing the effect of channel slope and channel conditions (roughness). Two study sites are investigated: the Manival and Réal debris-flow torrents in the French Alps, which frequently experience both debris flows and bedload transport.

2. Study sites

2.1. Manival torrent

Debris flows frequently occur in the Manival torrent (Peteuil et al., 2008), situated near Grenoble in the Chartreuse Mountains of the northern French Prealps, located at 45°17′ N, 5°49.75′ E (Fig. 1C). This torrent has been previously studied to quantify debris input and channel storage by using photogrammetry with historical aerial photographs (Veyrat-Charvillon and Memier, 2006). The torrent flows intermittently into a large sediment trap (25,000 m^3 capacity) that protects the urbanized fan from debris flows. The 3.6-km^2 catchment above the sediment trap has 1130 m of relief with a mean catchment slope of 0.81 (39°) (Table 1). The 1.8-km study reach extends from the apex of the debris-flow fan to the sediment trap (long profile shown in Fig. 1B).

The Manival area has a mean annual precipitation of 1450 mm and a 10-year daily rainfall of 88 mm (from monthly rainfall data of the Saint-Hilaire-du-Touvet Météo France station since 1964). The catchment typically experiences convective storms during the spring and summer (May to September) which trigger debris flows. During autumn (September to December), steady and long duration rainfall generates bedload transport. The upper catchment is typically covered by snow in the winter (January to March), thereby having a dormant channel.

The geology of the Manival catchment corresponds to the Mesozoic cover of the external alpine crystalline belt. The bedrock is composed of highly fractured, alternating sequences of marls and limestones from the Upper Jurassic to early Cretaceous with a bedding thickness ranging from decimeters to meters (Loye et al., 2012). Geomorphic processes are typical of upland prealpine catchments. Shallow landslides, hillslope debris flows, and snow avalanches form thick colluvial deposits below rockwalls and hillsides. Limestone rock faces are known to produce frequent rockfall that supplies debris to talus slopes (Fig. 2A).

Upstream from the sediment trap the mean channel slope is 0.16 (9°) over 1.8 km to the apex of the debris-flow fan. The channel has a mean active width of ~15 m (range: 10–20 m) with a typical morphology of a debris-flow scoured channel consisting of levees, boulder fronts, and coarse lags (Fig. 2B). It is formed within the wide debris-flow fan (40 to 250 m wide, increasing downstream). Along the main channel, bedload transport macroforms can be observed (Fig. 2C). They are defined as gravel deposits with well-sorted grain-size distributions that can fill the U-shaped debris-flow channel. These macroforms are an important part of the sediment input for debris-flows mass balance (Theule et al., 2012).

2.2. Réal torrent

The Réal torrent is a very active debris-flow torrent located in the upper Var River catchment of the Southern French Prealps, located 44°07′ N, 06°54.5′ E (Fig. 1A). It flows intermittently into the Tuébi River, a tributary to the Var River, near the small village of Péone. Debris flows occur 2–3 times every year and interact with bedload transport. The 2.3-km^2 catchment has 800 m of relief with a mean catchment slope of 0.58 (30°) (Table 1; Fig. 1B).

The Réal area has a drier climate, with a mean annual rainfall of 1050 mm, but it also experiences large storms with a 10-year daily rainfall of 102 mm (from monthly rainfall data of the Péone Météo France station since 1951). Convective storms occur in the spring and summer (May to September). During autumn (September to December), steady and long duration rainfall generates bedload transport. The catchment is also covered by snow in the winter (January to March).

Bedrock geology is composed of Paleogene sandstones and alternating sequences of Cretaceous and Jurassic marls and limestones. Quaternary