HEADWATER SEDIMENT DYNAMICS IN DEBRIS FLOW CATCHMENT: IMPLICATION OF DEBRIS SUPPLY USING HIGH RESOLUTION TOPOGRAPHIC SURVEYS

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Abstract

Debris flows have been recognized to be linked to amounts of material temporarily stored in torrent channels. Hence, sediment supply and storage changes from low-order channels of the Manival catchment, a small tributary valley with an active torrent system located exclusively in sedimentary rocks of the Chartreuse Massif (French Alps), were surveyed periodically for 16 months using terrestrial laser scanning (TLS) to study the coupling between sediment dynamics and torrent responses in terms of debris flow events, which occurred twice during the monitoring period. Sediment transfer in the main torrent was monitored with cross-section surveys. Sediment budgets were generated seasonally using sequential TLS data differencing and morphological extrapolations. Debris production depends strongly on rockfall occurring during winter – early spring season, following power law distribution for volumes of rockfall events above 0.1 m^3, while hillslope sediment reworking dominates debris recharge in spring and autumn, which shows an effective hillslope-channel coupling. The occurrence of both debris flows is linked to recharge from previous debris pulses coming from the hillside and from bedload transfer. Headwater debris sources display an equivocal behaviour in sediment transfer: low geomorphic activity occurred in the production zone, despite of rainstorms inducing debris flows in the torrent. Still, a general reactivation of sediment transport in headwater channels was observed in autumn without new debris supply, suggesting no exhaustion of debris storages. The seasonal cycle of sediment yield seems to depend not only on debris supply and runoff (flow capacity), but also on geomorphic conditions that

destabilize remnant debris stocks. This study shows that monitoring torrent's in-channel storage changes coupled to debris supply can readily improve knowledge on recharge thresholds leading to debris flow.

1 Introduction

In steep mountain catchments, rainfall intensity and duration (incl. snowmelt) are insufficient to predict debris flow, despite that conditions of initiation for runoff-generated debris flow require a significant water inflow (Van Dine, 1985; Decaulne and Saemundsson, 2007; Guzzetti, 2008). In many cases, the main reason arises from the fact that the amount of debris that can be entrained in a channel reach is often more significant than mechanisms of initiation (Hungr, 2011; Theule et al., 2015). The frequency and magnitude of debris flow have been recognized to be linked to the amount of material temporarily stored in channel reaches (Van Steijn et al., 1996; Cannon et al, 2003; Hungr et al. 2005), such that hillside sediment delivery recharging those channels represents a key factor for the occurrence of debris flows (e.g. Benda and Dunne, 1997; Bovis and Jakob, 1999; Berti et al., 2000). This implies efficient hillslope – channel coupling (Hooke, 2003; Schlunegger et al., 2009; Johnson and Warburton, 2010). Therefore, the rate of sediment supply needs to be considered for predicting debris flow hazards (Rickenmann, 1999; Jakob et al., 2005). However, the difficulty results in quantifying sediment process activity from hillslopes and in-channel debris storage (Peiry, 1990; Zimmermann et al., 1997).

Recording of overall sediment production and transfer rate has increasingly relied upon multi-temporal digital stereophotogrammetry (Coe et al., 1993; Chandler and Brunsden, 1995; Veyrat-Chavillon and Memier, 2006) and elevation difference from High Resolution Digital Elevation Models (HRDEM) (Smith et al., 2000; Wu and Cheng, 2005; Roering et al., 2009; Theule et al., 2012). In terrain dominated by steep slopes, traditional aerial derived DEMs typically remain inappropriate to study geomorphic processes. Limitations concern not only to the too low rendering of small topographic changes (Perroy et al., 2010), this can be technically improved, but also the poor surface representation of steep terrain with small curvature radii and the data gaps in vertically oriented and overhanging topography. Even on gentler slopes, the sharp break of slopes, encountered in erosion scars for instance, was demonstrated to be insufficiently modelled by airborne HRDEM, leading to erroneous volume estimations (Bremer and Sass, 2011). This represents a serious drawback in budgeting steep terrain, where sediment activity comes mostly from rock walls and rugged gullies. Because of these issues, many hill- and rock slope process studies have been investigated with terrestrial laser scanner (TLS) (Jaboyedoff et al., 2012). The recent development of long range TLS devices provides an effective mean of acquiring high resolution topographic information that adequately reflect the morphology of steep bedrock-dominated areas. The practical disadvantage in data acquisition related to ground survey can be compensated by flexibility in transport, ensuring a full coverage with minimum shadow zones.

This paper presents a quantitative study of sediment recharge and channel response leading to debris flow, using 3-D digital terrain models provided by TLS. This is illustrated on the Manival (French Alps), a torrent that experiments runoff-generated debris flow almost every year (Péteuil et al., 2008). The entire hillslope processes and sediment dynamics from tributary channels to the torrent was surveyed periodically over 16 months. The spatio-temporal variability of debris production and subsequent transport and storage of sediment are analysed on a seasonal time scale, in order to discuss the debris supply dynamics and the implications in debris flow initiation. This study also complements the investigation about what controls debris flow erosion and bedload transport in the Manival's torrent (Theule et al. 2015).

2 Study site

2.1 General setting

The 3.9 km2 Manival catchment located at the edge of the Chartreuse massif (France) (Fig. 1) displays a rugged, 1200 m relief watershed, resulting from a deep headward entrenchment (Gidon, 1991). The topography consists of a narrowly-confined head and of a steep-sided colluvium-filled valley, delimited from the west side by a series of rock walls and scree-mantled deposits separated by rock couloirs, and on the east side by steep rock and talus slopes divided by gullies. The lithology ranges in age from late Jurassic to early Cretaceous (Fig. 2) (Charollais et al., 1986). In the heart of the basin, thick sequences of calcareous marl interbedded with layers of marl predominate. Towards the ridge, the bedrock evolves progressively from more stratified to massive limestone. The valley sides correspond to the fold limbs of an anticline, where secondary folding and minor faults induce local variations in structure (Gidon, 1991). This tectonic setting and the varying stratigraphic competency have strongly influenced the topographic development, providing a dynamic geomorphic environment supported by an important runoff as a response to heavy rainstorms that occur regularly (Fig. 3).

2.2 Characteristic of the headwater sediment dynamic

The contemporary geomorphic activity contributing to the torrent's recharge with debris concentrates exclusively in the headwater, where no remnant glacial deposits are found (Gruffaz, 1997). In the upper catchment, large old rock deposits flooring the west side hillslope (Fig. 4) have dramatically influenced the bottom topography, and thus the channel network, resulting in a conjunction of four first-order debris flow channels deeply incised in the deposit down to the bedrock in several reaches. The upper catchment can therefore be subdivided in five subcatchments in terms of sediment recharge (Fig. 2). Bed entrenchment is now much constrained by check dams. However, lateral erosion still occurs episodically by flooding and debris flow scouring.

The style of sediment production and delivery is somehow different throughout the headwater, according to the local morphology and the lithologic and structural setting. The major geomorphic processes, identified preliminary in details from aerial photographs observations and field investigations, were characterized in a map (Fig. 4) that describes the spatial distribution of geomorphic features and sediment transfer processes contributing to debris recharge in the first-order channels. The west and upper sides are dominated by rockfall. Large rock collapses delimited by persistent joints occur due to the progressive degradation of the slope underneath (Loye et al., 2011). Where the slope gradient allows scree and soil development, erosion scars can be observed; sediment sources are remobilized from discrete shallow landslides. Depending on the location and size, rockfall can reach the channels directly, or accumulate on slopes or in ravines, before being subsequently routed to high-order segments by a combination of gravitational and hydrological processes. Towards the east, the erosion seems to be more progressive through the formation of gullies (Loye et al., 2012). Near the ridge, the slopes display mostly talus and scree deposits lightly covered with vegetation, whereas the hillside below exposes steepened rock slopes. Many active erosion scars can be observed. They contribute to accumulate debris into gullies and talus slope deposits that are subsequently entrained in channels downslope.

Historical records of debris flows since the 18th century show a frequency of 0.3 events per year that reached the apex of the fan (Brochot et al, 2000). The largest event deposited approximately 60’000 m^3. However, the torrent experiences smaller fluxes of debris (<1000 m^3) usually not reported in archives. Such events can occur 2-3 times per year, when initiated by intense runoff (Veyrat-Charvillon, 2005). Volumes of debris deposited in the sediment trap for the last 25 years represents 2200 m^3/yr, reaching a maximum of 7000 m^3/yr in 2008 (RMT service).

3 Methods and data processing

3.1 Topographic monitoring using TLS

The terrain was surveyed with an ILRIS-3D laser scanner (Optech Inc.). This device provides a range up to 1.2 km for 80% reflectivity surface and the instrumental precision is about 7 mm/100 m range for both distance and position (Optech Inc.). The overall coverage of the upper catchment with TLS point clouds required 50 scans considering a 20% surface overlapping. They were collected over a 5-day survey from 9 individual viewpoints to ensure a 3-D rendering of the topography. A particular attention was carried in irregular regions and major break of slopes, such as rock couloirs and deep-cut gullies. Using multiple scanning locations allow to limit shadow zones and increase the point cloud density of the scanned area. A series of 4 surveys was performed on a seasonal basis during 2009 and one extra survey was performed in July 2010 to analyse the effect of the winter period (Table 1). The monitoring setup remained similar for all surveys. Post-processing of TLS raw data was done using Polyworks (InnovMetric). Erroneous points and vegetation were filtered manually, ensuring a total control of the removed data to preserve a high density of points in topographic features with small radii curvature. Although this procedure is time consuming, (semi-)automatic approaches to filter vegetation accurately still remain in a stage of development for dissected mountain morphology (Brodu and Lague, 2012). Each of the multiple scans of a survey were merged to one another using common tie points of permanent topographic features and set in 12 local subsets. Given the size of the monitored area, dividing the point cloud in smaller datasets allows to avoid propagation of inaccuracy through large co-registered scans series. ICP (iterative closest point) algorithms (Besl and McKay, 1992), that enable to minimize the distance between two sets of points, were used to determine the best alignment of multiple scans subset in order to obtain the best co-registration within a time series. The same procedure was applied between the generated subset point cloud and a commercial airborne laser scanner derived point cloud (mean density: 6.9 pts/m^2) acquired in June 2009 to get the TLS data georeferenced in the Lambert projection coordinate system. The initial survey point cloud data was set as the surface model of reference. Each successive survey was best georeferenced on this reference using the ICP processing steps herein. The topographic change occurring between two successive surveys are too localized to influence the global co-registration within two survey data subsets consisting of millions of data points, hence the alignment accuracy. More details about multiple scans registration techniques and point cloud time series comparison can be found in Oppikofer (2009). The generated surface produced by a survey possesses a point spacing ranging from 2.5 to 18 cm according to the distance of acquisition. A maximum range of about 800 m was reached on the top peak of the catchment with a point cloud density of 25 pts/m^2. The surface coverage represents 84% of the deforested area under investigation (Table 2).

3.2 Topographic changes identification and characterization

The active geomorphic features within two successive datasets were identified on a point to point approach using the short distance neighbouring point search algorithm (Bitelli et al., 2004) that computes in 3-D the shortest difference vectors between points of two datasets. The vector sign indicates the net change direction of topography, i.e. surface of erosion or deposition. A set of points (cluster) was considered as active if at least 8 adjacent points of similar sign displayed an absolute difference above the limit of detection (LoD). Each active feature was outlined visually using the point cloud of difference (Fig. 5a). The point clusters of both survey datasets, which correspond to the topography of the active features, were extracted according to their spatial extend coordinates and each detected geomorphic feature was labelled:

(1) Rock slope erosion characterises rockfall/-slide;

(2) Hillslope erosion concerns the reworking of loose/compacted debris on slopes, respectively in gullies and channels;

(3) Deposition delineates material aggradation initiated by both rock slope failure (new production) and remobilisation of debris.

Using the images captured by the TLS integrated camera, clusters of points not corresponding to geomorphic process activity, such as snow melt, were ignored.

3.3 Volume computation of each geomorphic feature

As the volume of active features cannot be directly computed from TLS datasets differencing, the active features of two successive point clouds must be interpolated into continuous surfaces (DEM). Gridded model (raster) is regarded as being most effective from irregularly distributed datasets containing in some parts only few or no point (El-Sheimy et al., 2005), as this can be the case for rockfall and erosion scar. The algorithm of interpolation has however minor impacts, as TLS data provide an extremely dense coverage of the detected objects (Anderson et al., 2005). So, they were interpolated using linear inverse distance weighting (Burrough and McDonnell, 1998) and generated in a regular grid separately. Grid spacing and direction of interpolation were designed in a specific way for each feature: the coordinate system of reference was replaced by a local orthogonal system where the x-y axes represent the average plane of topography nearby (Fig. 5b). This new reference frame was defined using eigen-value decomposition of the covariance matrix of the point cloud of reference (Shaw, 2003). Interpolating the surface elevation in the direction of local topography allows generating a highly realistic DEM independently of slope steepness and thus, a close realistic representation of topography in case of overhanging features. The cell size was defined according to the point spacing distribution of both datasets. A series of tests revealed that setting the grid spacing at 68 % of the cumulative frequency distribution of point spacing provides a continuous surface reconstruction while keeping a high degree of detail from the point cloud. This ensures an accurate volume computation of geomorphic features. The volume was computed as the sum of the cell difference in elevation between the successive DEM. Absolute cell differences lying below a given threshold were not considered. The processing of volume computation using local deterministic method of interpolation adopting the adaptive gridding approach was developed in Matlab numerical computing environment.

3.4 Point cloud accuracy and limits of detection of the geomorphic features

A reliable identification of erosion and deposition features requires the setting of a minimum LoD, where the change of elevation between successive point clouds can be considered as real in opposition to noise associated with each dataset. Each TLS data point has theoretically a unique precision depending on the range and laser incidence angle (Buckley et al., 2008). In practice, the individual point precision of a scan can be assumed to model a surface with a global uniform uncertainty, considering the very high point density (Abellan et al., 2009). Given the homogeneity of surface error, and considering that the distance between sequential points at a position (x,y) should tend to zero, the accuracy of TLS data can be estimated by substituting the precision of each data point by a singular measurement of the error associated with the entire point distribution across the surface (Lane et al., 2003). Hence, the uncertainty related to both scans registration and point cloud georeferencing, the instrumental error included, was defined by the standard deviation of the distance (σ_d) between the points (Fig. 6). The LoD was therefore set at 2σ of the co-georeferencing and corresponds to the 95 % confidence limit (Table 3). Comparison with the approach considering the error propagation for all uncertainties associated with each point cloud, and assuming a normal distribution of the error in distance (Taylor, 1997), shows that the uncertainties considered here are reliable.

In the case of volume computation, information on elevation uncertainty associated with each point cloud survey needs to be extended on a DEM cell by cell basis. For any grid cell (i,j) generated by the interpolation of adjacent points *p* with independent elevation, the uncertainty of a cell elevation can be considered as the standard deviation (σ_e) of the data points elevation, where $\sigma_{\bar{e}_{i,j}} = \sigma_{e_p} / \sqrt{n}$ according to the equation of standard error of the mean, *n* being the number of points to define the cell elevation. The elevation uncertainty for each cell in a DEM of difference is then expressed by:

$$\sigma_{\Delta\bar{e}_{i,j}} = \sqrt{\left(\sigma_{1\bar{e}_{i,j}}\right)^2 + \left(\sigma_{2\bar{e}_{i,j}}\right)^2} \ . \tag{1}$$

The volume uncertainty is then calculated by summing up the derived volume uncertainty of each cell of the feature as follow:

$$\Delta\bar{v}_{feature} = a\left[\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\sigma_{\Delta\bar{e}_{i,j}}\right)^2}\right], \text{ with } a = \text{cell area.} \tag{2}$$

The smallest detectable volume is about 10^{-3} m^3 (10 x 10 x 10 cm) (Table 3), but can reach up to 0.006 m^3 (25 x 25 x 10 cm) depending on the point spacing at maximum range. Topographic change detection and volume computation depend not only on the quality of TLS data, such as point density and post-processing related inaccuracy. It also depends on the complexity of the surface geometry, like in our case, by integrating the range in position of all data points defining each grid cell value of a feature. Monitoring the hillslope activity is also limited by the ability of the process to create a distinct topographic change. Consequently, the deposition of individual small rockfall was not always detected, as detached rock masses fragment into smaller pieces that are below the LoD. A similar issue was observed for erosion processes on debris. Nevertheless, most of the material accumulation could be related to landslides or scouring. The sediment budgets were therefore kept in volumetric units, as they are commensurate for a consistent analysis. They were not converted to mass, although this would make more sense for comparing hillslope processes and rock slope yields. Such conversion requires an accurate density value of each surface process, whose approximations would bring unknown inaccuracies. Deposition related to rock failures may be slightly overvalued in the sediment balance, although parts of the volumetric amplification are compensated by a limited detection of small features.

3.5 Sediment budgets of the Manival torrent

The monitoring of the coarse sediment transfer was performed all along the main torrent channel to the sediment trap located downstream on the alluvial fan. The in-storage change was established after every noticeable flow event, using the morphological approach based on cross-section survey techniques (Ashore and Church, 1998), and the volume of sediment deposited in the sediment trap was measured by TLS survey differencing. Sequential volumes of recharge enable to study the influence of debris supply from the production zone through the seasons. The characteristics and observational analysis of this event-based monitoring was documented in details in Theule et al. (2012, 2015) and is therefore only shortly reported here.

3.6 Estimation of debris production rate

A rate of debris production for the study period is obtained from the total volume of rock slope erosion. A more objective estimation can be deduced by characterising the cumulative distribution of rockfall volumes with a power law as follows (Gardner, 1970):

$$N(v > V) = aV^{-b}. \qquad (3)$$

N is the rockfall frequency for a volume v greater than V, a and b are constants. a depends on the study size and on rock slope properties, whereas b tends to be rather site independent (Dussauge-Peisser et al., 2002; Dewez et al., 2011). Considering that rock slope process activity causing rockfall does not fluctuate much over time, the inventory analysis can be used to infer the frequency of occurrence of larger events. This is done by integrating the rockfall frequency derivative $n(v)=\frac{dN}{dV}$ over the range of potential volumes. Estimation of the total volume V_t per unit time that can be expected in average over a longer period of observation is therefore expressed by (modified from Hantz et al. (2002)):

$$V_t = \int_{n(V_{\min})}^{n(V_{\max})} V dn = -ab \int_{V_{\min}}^{V_{\max}} V \times V^{-b-1} dV = -ab \int_{V_{\min}}^{V_{\max}} V^{-b} dV = \frac{-ab}{(1-b)} V^{1-b} \Big|_{V_{\max}}^{V_{\min}} . \quad (4)$$

The goodness of fit of the power law was evaluated with the χ^2 test (Taylor, 1997) and the standard deviation of value a and b were determined with the maximum likelihood estimate (Aki, 1965). The erosion rates are assessed by dividing V_t with the surface prone to rockfall.

4 Results: Hillslope process activity monitoring

4.1 1st monitoring period (April 2009 – August 2009)

The topographic changes recorded from July to August 2009 did not show any relevant geomorphic activity (only few small rockfalls). The results were therefore merged with the preceding monitoring period.

Rock slope activity is dominated by individual small rockfalls disseminated throughout the upper catchment. Only few events exceed 1 m^3, such that contributions in terms of debris production are marginal in most parts of the catchment (Fig. 7). The significant geomorphic activity was located almost exclusively in the major gullies of Baure and Grosse Pierre ravines, and consists essentially of debris scouring of a few 100 m^3 re-deposited further down. Material re-entrainment was also observed in several other smaller gullies, but their volumes are not relevant. The rock couloirs of the Genievre subcatchment and the scar of the old rock deposit barely showed any geomorphic activity. The channels displayed a net incision (-636 m^3 ± 43) in the upper reaches. Bedload aggradation remains very low (+90 m^3 ± 6). Below the upper confluence, the channel trunk exhibits a mixed pattern of zones of erosion (-60 m^3 ± 2) and deposition (+80 m^3 ± 4) induced by bedload transport. The flow path scours in-channel gravel-wedges and creates new depositions further.

4.2 2nd monitoring period (September 2009 – November 2009)

Rock slope activity remains similar in spatial extent and volumes to the previous survey period, but rockfall frequency is higher (Fig. 8). Hillslope process activity was more widespread on the east side, but still particularly local on the western valley walls, while the rock couloirs showed no geomorphic activity. In the upper headwater, material reworking concentrated almost exclusively in the steep tributary gullies. They displayed scouring of significant volume (-357 m^3 ± 12). Deposition features along the thalweg were quasi inexistent (+18 m^3 ± 1.3). In the south-east, not only the Baure Ravine (net erosion: -61 m^3 ± 8), but the whole series of hillside gullies exhibited signs of activity, such as erosional segments alternate with deposition. On scree slopes, several minor rilling areas and their associated debris deposits were observed, some of them reached the channel trunk (+42 m^3 ± 2). Such small hillside debris flows were probably triggered by sediment entrainments in rills themselves, as no evidence of sliding at their head was observed. The channels show a net erosional character upstream (-482 m^3 ± 18), whereas continuous incisions were more pronounced in the Manival channel (-443 m^3 ± 16) as in the Roche Ravine (-40 m^3 ± 3). Deposition zones were almost completely absent (15 m^3 ± 1.3). Towards the upper confluence, the lower segments of Manival channel exhibited continuous zones of aggradation (97 m^3 ± 6) that were scoured on one side. This morphology is characteristic of close-process debris flow levees and run-up zones beside the incised channel bed. Below the upper confluence, channel bed cut (-40 m^3 ± 2) and fill (+16 m^3 ± 1) was sparse and concentrated at the junction with hillside gullies. Such pattern of bed reworking evidences the connectivity of the Baure gully series with the channel trunk.

4.3 3rd monitoring period (November 2009 – July 2010)

This period showed an important increase of rock slope erosion, both in frequency and magnitude, resulting from the occurrence of large slope failures and enhanced rockfall activity locally, for instance in rock walls made of calcareous marl situated directly above the Manival (2035 m^3 ± 39) and the Roche Ravine (256 m^3 ± 17) channels (Fig. 9). Most of debris collapses supplied the channel directly; the rest was temporary deposited in breaks of slopes. The lower headwater part showed a great fluctuation as well (Genievre: 116 m^3; Grosse Pierre: 145 m^3). At the top of the Baure Ravine, 816 m^3 ± 25 of rock fragments contributed substantially to recharge the gully head. Below, debris infilling was continuously scoured. A 1170 m^3 ± 18 rockslide is responsible for the large channel infilling of the Manival subcatchment. Several other smaller rockfalls contributed to the recharge of tributary gullies and scree hollows. In the Roche Ravine, debris deposits were sparse, because rockfall remained of low magnitude in average (571 events < 1 m^3), although frequency was high (578 events). The large debris infilling of the channel head was caused by two erosion scars in the gullies (270 m^3 ± 14 and 65 m^3 ± 4). In the rock couloirs of the Genièvre subcatchment, a significant accumulation of material from landslides and rockfalls was observed (remnant volume: 204 m^3 ± 13), regarding that hillslope erosion represents 450 m^3 (± 14). In the Grosse Pierre Ravine, 343 m^3 ± 17 of debris were accumulated at the rock couloir outlet, recharging the scree slope above the channel head. In the Col du Baure, an important aggradation of the lower part of tributary gullies was observed (remnant volume: +142 m^3 ± 2), resulting from material entrainment. Several debris slides were also detected on scree slopes, without any contact with the channel trunk.

The upper channel-reaches were clearly depositional, in consequence of large slope failures. The Manival channel showed a continuous zone of remnant accumulation of 948 m^3 (± 18) in which a portion was carried along downstream as bedload. Towards the confluence, erosion dominated clearly (-487 m^3 ± 19) against deposition (+25 m^3 ± 3). In the Roche Ravine, a sustained erosion in the scar of the old rock deposit produced debris accumulation mostly on the slope. But a landslide of 190 m^3 ± 9 reached the channel. Globally, aggradation was observed all along the channel head (+148 m^3 ± 18) and scouring was sparse (-65 m^3 ± 4). From the confluence downstream, the channel behaviour is dominantly erosional (-97 m^3 ± 4) almost without any aggradation (+3 ± 0.3 m^3).

4.4 Rock slope production inventory

Over the 16 months, 1’866 rockfalls with volumes ranging from 10^{-4} to 10^3 were recorded. This yields a total of 3’575 m^3 ± 30 and an erosion rate of 3.1 mm/yr, given the topographic surface area of rock faces. The inventory follows a power law (Fig. 10) with a 99 % confidence level for events larger than 3 m^3 (χ^2 value = 17.3). For events larger than 1 m^3, the power law is accepted at the 95 % confidence level (χ^2 value = 5.89). Both threshold volumes provide a b-value close to 0.81 ± 0.06. Considering only the volumes above 10 m^3 (25 events) gives a b-value of 0.76. Below 0.1 m^3, the observed frequency deviated clearly from power law regime until the roll-over reaches a quasi-constant rate for the smallest volumes. According to the inventory, rockfall of more than 1 m^3 are expected 153 ± 11 times per year in average. The largest event (1’170 m^3) occurs every two years, and the one year return period rockfall is about 465 m^3. Considering only class of volumes of the inventory, the rock slope production reaches a rate of 3’678 m^3/yr ± 210 (4 mm/yr ± 0.3).

4.5 Torrent in-channel storage changes

Two debris flows with multiple surges and several remarkable bedload transport events were observed in the main torrent during the survey period (Theule et al., 2012). A debris flow occurred on the 25th August 2009, caused by a short duration rainstorm. The volume of sediment eroded in the torrent (5232 m^3 ± 136) coincides with what was re-deposited in both the torrent itself and the sediment trap (5072 m^3 ± 125), suggesting that the entrained material was stored in the torrent in great majority (Table 4). Sediment input from the headwater can be considered as marginal. Before that, no significant torrent activity was observed, despite series of rainfall of low to moderate intensity. In September 2009, a long period of moderate rainfall intensity caused material reworking induced by bedload transport all along the torrent. However, no sediment supplied the sediment trap. A net gain of storage supplied by the headwater could be monitored. In October, a succession of low intensity rainfalls induced some major sediment transport in the torrent that aggraded the sediment trap with at least 302 m^3 ± 36. The sediment budget indicates clearly a recharge of 229 m^3 ± 31, a transfer of debris that was stored mostly in the distal part of the torrent. Throughout the winter, a gradual incision was observed all along the torrent resulting from frequent periods of low intensity rainfall conjugated to snowmelt. Due to maintenance (dredging), the sediment trap was disturbed and no reliable data was available. No sign of competent activity was detected anyway. A new debris flow on June 6th deposited 3320 m^3 ± 176 in the sediment trap. This time, a certain supply from the headwater was observed (~ 270 m^3). This event was followed by series of intense rainfall without much reworking in the distal part, suggesting that no competent transfer occurred anymore towards the torrent. The in-torrent storage changes and estimated recharge budgets are shown for each monitoring period in Figure 11.

5 Synthesis

The overall transfer dynamic, from debris source zone to the apex of the fan, is illustrated in Figure 12. The volumes detected during the 16-month study period reveal a net export of 3’378 m^3 ± 361 of sediment from the headwater to the main torrent (Table 5). The overall rock slope yield is 3’575 m^3 ± 30, for a volume of erosion reaching 3’129 m^3 ± 150 on the hillside and 1’809 m^3 ± 92 in the channel complex. Volume of deposition, induced from both debris production and material reworking, yields a total volume of 5’135 m^3 ± 251, of which only 1’382 m^3 ± 56 (27 %) concern the channel complex. In the main torrent, the sediment transfer was important (~20’000 m^3; net storage change -4950 m^3 ± 118) and essentially related to the occurrence of two debris flows (Theule et al., 2012), depleting significantly the in-torrent sediment storage of the distal parts (entrainment zone). Material deposited in the sediment trap for the survey period yields 6075 m^3 ± 45. During the autumn, bedload transport of hundreds of m^3 contributed to sediment recharge throughout the torrent.

In the spring-midsummer period, the hillside sediment budget yields a total rock slope production of 99 m^3 ± 6, for a volume of erosion of -547 m^3 ± 50 and deposition of +408 m^3 ± 35 (Table 5). This suggests that about 238 m^3 ± 61 of material supplied the channel complex, coming almost exclusively from material re-entrainment in gullies (Fig. 13). The sediment budget of the channels indicates a significant degradation in storage (-487 m^3 ± 44), comprising large and continuous incisions (-636 m^3 ± 43) in the upper reaches and material aggradation (+149 m^3 ± 11) in the lower reaches resulting mostly from zones of transient re-deposition. This results a recharge of the torrent of +726 m^3 ± 103 for this survey period.

During the late summer - autumn season, the total volume of hillside erosion is of -640 m^3 ± 27, resulting particularly from a widespread scouring of tributary gullies located east and southeast of the headwater (Fig. 14). The total volume of rock slope production (50 m^3 ± 3) and deposition (+182 m^3 ± 12) remain low. Globally, the sediment budget indicates, that the hillslope contributed at recharging the channel reaches with sediment for about 510 m^3 ± 30 (Table 5). The channels sediment budget yields -522 m^3 ± 20 of erosion for +127 m^3 ± 13 of deposition. This is characterized by bedload reworking in both low-order and trunk channels, and a progressive transfer of +904 m^3 ± 51 of material in the torrent.

During winter - spring 2010, a total deposition volume of +3163 m^3 ± 147 is recorded on the hillside, for an eroded volume of -3129 m^3 ± 150. An important production of debris (3424 m^3 ± 89) is observed (Table 5). The net sediment balance on the hillside yields to a supply of +2203 m^3 ± 187 of sediment in channels, and the one for the channel complex indicates an increase of in-storage sediment of +455 m^3 ± 47, according to a total volume of deposition of 1105 m^3 ± 36 and erosion of 651 m^3 ± 29 due to large portions of bed scouring in the downstream reaches. Sediment transfer to the torrent is 1749 m^3 ± 199 (Fig. 15).

6 Discussion

6.1 Debris supply through rock slope production

Debris production from rock walls shows a strong seasonal pattern. The great majority of recorded rock instabilities in both magnitude (95%) and frequency (75%) occurred during the cold period. Previous studies of the calcareous cliffs near Grenoble, which represent a similar morphotectonic context, revealed that freeze-thaw cycles are the main triggering factor of rockfall (Frayssines et al., 2006). Ice jacking can cause microcracks propagation leading to failure (Matsuoka and Sakai, 1999). Along the eastern ridge, the bedrock surface is often highly fractured, suggesting frost shattering. The spatial pattern of rockfall strongly suggests also a tectonic-lithological influence that can be explained by differential erosion between the successive limestone and marl beds. In the rock wall series on the west side, the monoclinal configuration of the bedding, combined with a strong difference of competency between stratigraphic sequences, give rise to overhanging formation highly susceptible to failure. On the east side, the bedding is mostly cataclinal and approaches dip-slope, depending on the slope. Rock failures initiated by planar sliding on bedding planes were observed.

The observed debris production follows a power law distribution in a range covering at least 3 orders of magnitude [10^0-10^3]. The exponent b is slightly higher than the average value reported for the Grenoble cliffs [0.4-0.7] (Hantz et al., 2011), but is in agreement with short inventories covering a lower range of volume [10^{-2}-10^2] (Hungr et al., 1999; Dussauge et al., 2003). Inventories dominated by small volumes tend to increase the b-value, compared to the ones covering rather large volumes (Stark and Hovius, 2001). Above 100 m^3, the deviation from the power law may be attributed to the short period of sampling for events of such large magnitude. The roll-over encountered towards small volumes results most likely in the under-detection of the number of events. This sampling bias being far above the minimum volume of detection (0.006 m^3), another behaviour characterizing the failure of small volumes cannot be excluded. This may presuppose a physical erosion process that differs from the one influencing larger instabilities, which are controlled primarily by local predisposing factors, such as the geometrical and geomechanical properties of the rock mass (Selby, 1993; Sauchyn et al., 1998), and such as the local conditions of tectonic weakening (Cruden, 2003; Coe and Harp, 2007). As observed here, low magnitude rockfall represent anyway little contribution in terms of debris supply, even though they vary locally from 1 or 2 orders of magnitude in volume over time. The amount of sediment available is only significantly influenced by instabilities of high magnitude (Fig. 16).

Previous sediment budgets derived from topographic measurement using stereophoto-grammetry estimated the highest erosion rates over an average of 40 years to range from 10.8 mm/yr to 17.8 mm/yr in the headwater (Veyrat-Charvillon and Memier, 2006). Although the large uncertainty of the approach, and the fact that they measured the hillslope and thalweg geomorphic activity, these values are compatible with the erosion rate revealed here from the short period rockfall inventory, by supposing the possible occurrence of rockslide magnitudes [10^6-10^7]. Considering that the power law is valid for larger slope failures, a 7'500 m^3 event can be expected every 10 years, respectively 100 years for 120'000 m^3. The average debris production ranges between 5'587 ± 241 to 12'903 ± 305 m^3/yr, according to a maximum potential erosion of 10^5, respectively 10^7 m^3, over several centuries (Table 6). No historical Manival rockslide exists to support this estimation. The large old rock deposit (~6.1 Mm^3) of the upper catchment is the largest detected event, but it may have formed from several rock collapses. Rockfall inventory of the Grenoble cliffs reports volumes smaller than 10^5 m^3 for the last century, respectively 10^7 m^3 since the 17th century (Hantz et al., 2003]. Such a magnitude is also likely at the Manival. A mean rate of rock slope erosion of approximatively 10 mm/yr. (10'000 m^3/yr) can be therefore expected in the upper catchment over the century.

Upstream from the Manival channel, scouring of debris slopes and scree hollows induced from rock slope production contributed for instance for about 40% of the net erosion recorded during the autumn period, respectively 25% in the Baure Ravine over the entire study period. The spatial pattern of geomorphic work showed, that hillslope process activity was observed principally in gullies and scree slopes situated directly below active rock walls. The dominant mode of debris supply in the Manival headwater is therefore highly episodic, implying a great spatial heterogeneity in recharge rates.

6.2 Debris supply through hillslope activity

As rock slope activity was very little from spring to autumn, hillslope geomorphic activity dominated the process of sediment recharge. Until the end of August, hillside gullies and low-order channels remain quasi inactive in terms of sediment delivery. Conversely, the autumn period was characterized by a general increase in intensity of geomorphic activity. Continuous scouring and the quasi inexistence of deposition features from hillside gullies as well as clear incisions and micro debris flows in channel reaches indicate that mobilized material was integrally entrained downstream by runoff. For the entire area, the hillside contribution represents on average a volume 5 times larger than what was observed in spring and summer and channel bed reworking was of much larger magnitude as well.

During winter-spring 2010, the total volume of deposition recorded on the hillside significantly overcomes the rate of deposition recorded so far, resulting from the huge increase of debris production that can be attributed to the winter according to observations carried out in the preceding spring. Hillslope and gully erosion remain on average comparable to the volumetric transfer of sediment observed in the preceding autumn, implying a clear connectivity.

These negative sediment balances in all sediment cascade components suggests a very high degree of connectivity between hillside and channels in autumn, whereas hillside fan deposits observed in early-spring along low-order channel banks reflect thus an effective hillslope-channel coupling. This differs from competent sediment transfer occurring mostly during the summer (e.g. Berger et al, 2011; Cavalli et al, 2013).

6.3 Sediment recharge of the torrent

The sediment input, back-calculated from the in-torrent storage changes, coincides with the net sediment output recorded from the headwater for the first two survey periods. In the torrent, the morphological monitoring that started in July revealed quasi no recharge (< 70 m^3) and is coherent with observations made in the summer in the upper catchment. The headwater sediment output must have accumulated before, probably mobilized as bedload by common runoff events in spring. In autumn, both budgets coincide (1018 ± 84 m^3 against 904 m^3 ± 51), considering that few segments between both entities are missing, and that both budgets were in volumetric units, although different sediment density. The morphological budget indicates that the torrent experienced a net recharge in the distal part, and emphasizes the clear connectivity from the production zones to the torrent, as mentioned before. In the 3rd survey period, the headwater sediment balance indicates a net export of debris (1749 m^3 ± 199), whereas the morphological monitoring detected no significant volumes of debris entering the main torrent. Even the recharge (sediment input, Fig.11) measured during the June debris flow events (< 600 m^3) remains far below the transfer of sediment recorded upstream in the headwater. This discrepancy may result from material deposition right in the non-monitored segments at the headwater outlet. But field studies did not confirm this. The analysis of past series of sediment budgets performed in the upper Manival catchment (Veyrat-Charvillon, 2005) reveals, that the spring-early summer time currently exhibits a period of recharge following a phase of discharge within a short time lapse depending on the hydrometeorological and snow melt conditions. The most reasonable explanation results therefore in the long time interval between measurements, such as the successive reworking of bedload transport must have inhibited the cut and fill pattern, and masked the short term behaviour of sediment transfer operated in the torrent. This is a well-known issue when working with channelized hillslope processes (Fuller et al., 2010). Although this monitoring aspect concerns the topographic changes recorded by TLS in the headwater as well, geomorphic activity, such as micro debris flows and continuous channel bed degradation, strongly suggest a phases of sediment recharge preceding in time the debris flow event, which would be consistent with other studies (e.g. Brayshaw & Hassan, 2009; Marchi et al., 2002, Bennett et al., 2012).

6.4 Possible causes of seasonal fluctuations in debris supply

The Manival headwater experienced low geomorphic activity through the summer, and consequently low recharge of the torrent, even though high intensity rainstorms were competent enough to trigger debris flow of significant magnitude in torrent. Considerations of the temporal pattern of sediment transfer and the analysis of erosion features, like alternating areas of scouring and infilling in gullies, suggest that runoff still exerts an important role on the headwater sediment dynamics. A clear relation between sediment transfer magnitude and precipitation remains complex however (Fig. 3), as being often the case in mountainous catchment (VanSteijn, 1996; Bovis and Jakob, 1999; Pelfini and Santilli, 2008). The enhanced geomorphic activity observed in the hillside of several headwater subsystems, for instance during the autumn period, induced simultaneously a highly heterogeneous response in their channel reaches. A significant increase of bed incision and debris flow similar reworking was observed in the upper reaches of the Manival subcatchment, implying an important sediment transfer. In contrast, the activity of other channel reaches was reduced by half, e.g. in Roche Ravine, or even remained geomorphically much less active with only little sediment recharge.

Considering that meteorological conditions were similar, this opposite behaviour may only be explained by a certain depletion of debris availability. This reduction of sediment yield can come not only within a supply-limited regime of the contributing area (Jakob et al., 2005;

Glade, 2005), but also from the fact that check dams, like bedrock dominated reaches, inhibit channel bed incision. Hence, the sediment storage has to be refilled either from the contributing hillside or from upstream mass movement. A similar observation can be drawn from the Grosse Pierre Ravine sediment budget, whose gully downslope remained completely disconnected from the head over the whole study period at least. Although this ravine is very steep and incises the large old rock deposits, no geomorphic work was observed, resulting most likely from the absence of debris supply from upstream. Hillside sediment delivery seems therefore to be clearly a limiting factor to sediment yield from low to high-order channels, and thus to the recharge rate of the debris flow torrent downstream. As the occurrence of bedload transport and micro debris flows is controlled predominantly by the availability of sediment, even very competent rainstorm derived runoff does not conduct systematically to significant transfer of sediment from the hillside to low-order channels in the case of material depletion.

But still, this behaviour is somehow equivocal, considering the fact that the transport capacity of ephemeral stream runoff and sheetwash related to high intensity rainstorms are larger than the one generated by low intensity long duration rainfall; above all, when gully material (like in the Manival) can be characterized as coarse and poorly sorted rockfall fragment derived debris. Lenzi et al. (2003) interpreted the annual fluctuation in sediment yield as the effect of sediment source destabilization or reactivation following a high-magnitude flow event, which facilitates material entrainment by subsequent runoff. Johnson and Warburton (2006) refer to the influence of sediment source characteristic in the control of hillslope sediment discharge. The explanation may be, that the 25^{th} August rainstorm dramatically altered the debris sources in a way that the autumn rainfalls, although of lower intensity but longer flood time, were able to transfer sediment downslope, for instance by saturating debris deposits in the long term. Excess pore-fluid pressure in debris deposits can persist for days to weeks after sediment emplacement time (Major and Iverson, 1999; Major 2000), making debris deposits geotechnically less stable.

Although depending on the local geomorphological aspect, such as slope gradient, local topographic hollow, degree of convergence (Reneau et al., 1990; Stock & Dietrich, 2006; Mao et al., 2009), these observations tend to show that long lasting rainfall reduces the stability of the coarse surface layer that armours the gullies and scree slopes. This in turn effects the amount of debris supply from the hillside, despite the flow capacity and sediment availability.

7 Conclusions

This investigation of a yearly pattern of sediment dynamic underlines that the seasonal cycle of sediment discharge from the headwater supplying the Manival torrent with debris consisted of two phases of recharge: (1) in early spring, linked to enhanced debris production and runoff conditions; (2) in autumn, during long period of rainfalls. Furthermore, the occurrence of the debris flow events was subordinated to a net sediment delivery toward the torrent.

Globally, the torrent effectiveness seems to be controlled early in the season by sediment production and later in the season by the ability of hydrological effects to weaken the remnant debris sources, depending not only on debris availability as a limiting factor at the Manival. The rate of sediment delivery, directly recharging both hillside and low-order channels, was essentially caused by high magnitude slope failure of moderate frequency and occurred mostly during winter time. Consequently, material re-entrainment concentrates locally in specific tributary gullies. The delivering of sediment to the torrent may be related to the hydrometeorological conditions since the last rainstorm, rather than to flow capacity directly. Low-order reaches contribute significantly to the sediment delivery mechanism of the catchment headwater, by controlling storage and routing processes. Hence, the recharge threshold required for a new debris flow to occur at the Manival depends primarily on the short-term debris supply, partly derived from the rate of rock slope sediment production and partly derived from the destabilizing of mobilizable debris on the hillside. The rate of sediment recharge in the torrent is however greatly inconstant, since production and entrainment are both highly stochastic processes. This regime of headwater sediment delivery may have been identified in other close mountain environments, but very little literature exists (Alvarez and Garcia Ruiz, 2000; Veyrat-Charvillon, 2005; Berger et al., 2011), that has explored in sufficient details the time scale of sediment discharge, e.g. on a seasonal basis.

Debris flow magnitudes have so far been mostly determined based on volume estimates derived from past events, reducing the susceptibility analysis to the known history. A monitoring of the in-storage changes in torrent linked to the debris supply can readily improve knowledge on recharge threshold leading to debris flow activity, and therefore their prediction. According to the rock slope production observed in this study, 10'000 m^3/yr of debris supplying the headwater channels can be expected in Manival over a century. Although the multiplicity of sediment sources and mode of transfer operating at different spatial and temporal scales, the pattern of processes governing the sediment dynamic can be considered precisely on a seasonal basis using TLS techniques. And maximum sediment discharges from the torrent system can be specified. Without direct measurement of the rate of sediment flux and of the coupling between hillslope and channel processes, this cannot be rigorously determined. The timing of sediment budget monitoring is however a crucial aspect for their interpretations.

Acknowledgements

The authors would like to thank their colleagues at IGAR and IRSTEA Grenoble (ex. CEMAGREF), in particular A. Pedrazzini and M.-H. Derron for their valuable comments during the preparation of this publication. This study was funded entirely by the University of Lausanne, except for the event-based cross-section surveys that was funded by the Pôle Grenoblois d'étude et de recherche pour la prévention des risques naturels. The ONF-RTM38 is acknowledged for making the access to the upper Manival Catchment easier.

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Table 1. TLS dates of acquisitions. Note that for the analysis, the 2nd survey was merged with the 1^{st} one (see text for details).

Monitoring period	Starting date of Survey	Period ID
1^{st}	01/04/2009 - 12/07/2009	MP1
2^{nd}	12/07/2009 - 30/08/2009	merged with MP1
3^{rd}	30/08/2009 - 11/11/2009	MP2
4^{th}	11/11/2009 - 08/07/2010	MP3

Table 2. TLS data and surface coverage characteristics of the 5 subcatchments from MP1. As the view points and parameters of acquiring remained similar, the values are essentially the same within all surveys.

Subcatchment name	Surface[1]		Lidar Data Survey				Scanned area[1]	
	Total [km^2]	Vegetated coverage [%]	Numbre of points	Mean spacing [m]	Mean range [m]	Mean density [pts/m^2]	Total [km^2]	non vegetated [%]
Col du Baure	0.29	43.0	37'625’236	0.055	131	340	0.11	84
Roche Ravine	0.30	20.5	43’736’412	0.071	278	251	0.17	79
Manival	0.35	9.1	40’192’976	0.096	349	141	0.28	90
Grosse Pierre	0.08	9.0	9’703’449	0.110	447	145	0.07	97
Genievre	0.35	26.6	19’886’472	0.108	311	109	0.18	79
Production Zone	1.36	22.7	151’144’545	0.081	275	219	0.82	84

[1] topographic surface area

Table 3. Registration and georeferencing standard deviation (in cm) of the position uncertainty on a point to point basis period that was used to derive the LoD at 95% confidence interval and subsequently the detected minimum volume of geomorphic features.

Sub-catchment.	2σ co-registered [cm]				2σ co-georeferencing (LoD) [cm]			2σ Taylor uncertainty[1] [cm] $\left(\sigma_{d_{reg}} = \sqrt{\sigma^2_{d_{PC1}} + \sigma^2_{d_{PC2}}}\right)$		
	Survey				Monitoring period			Monitoring period		
	1st	2nd	3rd	4th	1st	2nd	3rd	1st	2nd	3rd
Col du Baure	1.9	1.7	1.5	1.5	5.9	6.9	6.9	5.1	4.5	4.2
Roche Ravine	3.2	2.9	2.6	2.7	8.4	9.4	9.0	8.6	7.7	7.5
Manival	4.6	4.1	3.0	3.4	9.6	10.2	12.2	12.3	10.2	9.1
Grosse Pierre	4.1	3.0	3.3	3.3	10.6	10.6	12.2	10.2	8.9	9.3
Genièvre	3.7	3.6	3.2	3.6	6.7	7.6	8.3	10.3	9.6	9.6

[1] pc = point cloud used to generate the map (point cloud) of difference in 3D

Table 4. Sediment budget (in m^3) of the Manival torrent established after noticeable events using the morphological approach after Theule et al. (2012). The torrent recharge (sediment input) is estimated from in-storage changes in channels and volumes deposited in the sediment trap (output).

Monitoring Period	Survey dates in the torrent	Sediment Output	Storage Change	Channel Erosion	Channel Deposition	Sediment Input	Total sediment Input
1st	#1 06/07/2009 - 28/08/2009	1873 ±62	-2034 ±559	5232±136	3199±63	0-63	0 - 63
2nd	#2 30 /08/2009 - 07/10/2009	0	789±84	1409±31	2197±53	736-842	934 - 1102
	#3 08/10/2009 - 12/11/2009	302±36	-73±66	1546±36	1473±31	198-260	
3rd	#4 13/11/2009 - 01/06/2010	580±45	-580 ±81	1961±45	1372±36	0-36	174 - 844[(1)]
	#5 02/06/2010 - 08/06/2010	3320±176	-3052 ±272	7658±178	4606±93	0-537	
	#6 09/06/2010 - 08/10/2010	819±46	-608 ±82	2246±46	1637±36	174-246	

[(1)] The TLS survey MP3 lasted until 08/07/2010; #6 were not considered for the analysis of the sediment budgets

Table 5. Overall headwater sediment budget recorded during the three survey periods and net sediment balance of the 16 months of monitoring (Sediment budgets for each catchment subsystem are detailed in the supplement).

1st monitoring period	Volume Total [m^3]					
	Hillside		**Channel**		**Headwater**	
Rockfall	99.4	±5.9			99.4	±5.9
Deposition	408.2	±35.4	149.2	±10.9	557.4	±46.3
Erosion	547.2	±49.5	636.4	±43.3	1183.5	±92.8
Subtotal	-238.3	±61.2	-487.2	±44.7	-725.6	±103.9

2nd monitoring period	Volume Total [m^3]					
	Hillside		**Channel**		**Headwater**	
Rockfall	50.5	±3.0			50.5	±3.0
Deposition	181.8	±12.2	127.2	±8.0	309.0	±20.5
Erosion	639.8	±27.1	522.5	±19.4	1162.3	±46.4
Subtotal	-508.5	±29.9	-395.3	±23.4	-903.7	±50.9

3rd monitoring period	Volume Total [m^3]					
	Hillside		**Channel**		**Headwater**	
Rockfall	3424.9	±89.1			3424.9	±21.4
Deposition	3163.5	±147.9	1105.5	±36.4	4269.0	±175.6
Erosion	1941.6	±72.8	650.8	±28.8	2592.4	±91.6
Subtotal	-2203.0	±187.4	454.7	±46.5	-1748.3	±199.2

Total monitoring	Volume Total [m^3]					
	Hillside		**Channel**		**Total**	
Rockfall	3574.7	±97.9			3574.7	±30.3
Deposition	3753.5	±195.6	1381.9	±55.6	5135.4	±251.3
Erosion	3128.5	±149.4	1809.7	±91.3	4938.2	±240.8
Subtotal	-2949.8	±264.9	-427.8	±106.9	-3377.6	±361.4

Table. 6: Rock slope debris production rate estimated from the inventory analysis using power law distribution of volume for potential rockfall (fig. 10).

Class of volume in m^3	10^{-3} – 10^{-2}	10^{-2} – 10^{-1}	10^{-1}- 1	1- 10	10^{1} - 10^{2}	10^{2} - 10^{3}	10^{3} - 10^{4}	10^{4} - 10^{5}	10^{5} - 10^{6}	10^{6} - 10^{7}
Measured frequency (per year)	143 (112.5)	742 (583.7)	789 (620.7	168 (132.2)	19 (14.95)	3 (2.36)	1 (0.79)			
Calculated frequency	36990 ±4366	5621 ±581	854 ±86	130 ±9.6	19.7 ±1.2	3.0 ±0.14	0.46 ±0.015	0.069 ±0.0013	0.011 $\pm 1 \cdot 10^{-4}$	0.0016 $\pm 1.2 \cdot 10^{-5}$
Cumulative Measured Frequency	1467	1355	772	152	19	3.1	0.79			
Cumulative Calculated Frequency	43619 ±5043	6629 ±677	1007 ±97	153 ±11	23 ±1.58	3.5 ±0.198	0.54 ±0.018	0.08 ±0.0014	0.01 $\pm 1.1 \cdot 10^{-4}$	0.0016 $\pm 1.2 \cdot 10^{-5}$
Fallen volume per year [m^3]	102 ±12	155 ±16	236 ±19	358 ±26	544 ±32	827 ±37	1257 ±39	1911 ±32	2904 ±8	4413 ±51
Total fallen volume per year [m^3]	298 ±43	454 ±59	689 ±79	1047 ±105	1592 ±136	2419 ±172	3676 ±210	5587 ±241	8491 ±249	12903 ±305
Cliff area	826804 m^2 (only the topographic rock slope surface)									
Erosion rate [mm]	0.36 ±0.05	0.54 ±0.07	0.83 ±0.1	1.3 ±0.1	1.9 ±0.2	2.9 ±0.2	4 ±0.3	6.8 ±0.3	10.2 ±0.3	15.6 ±0.4

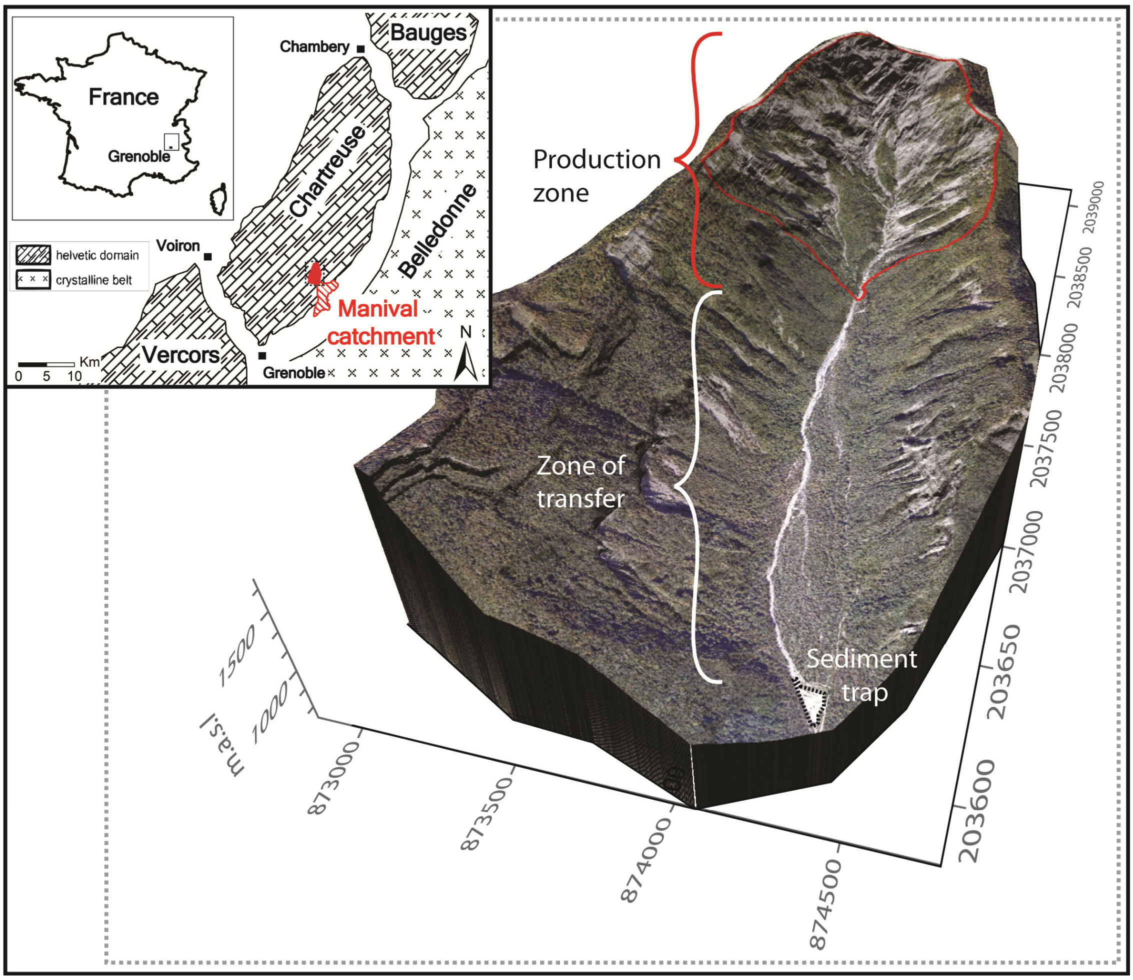

Figure 1. (Inset) Map of the study area; the Manival catchment is displayed in full red and the impressive debris fan is streaked. (Outset) Aerial view of the Manival catchment; sediment supply concentrates exclusively in the headwater (production zone) as erosion activity from the middle and lower catchment is not connected to the torrent (zone of transfer).

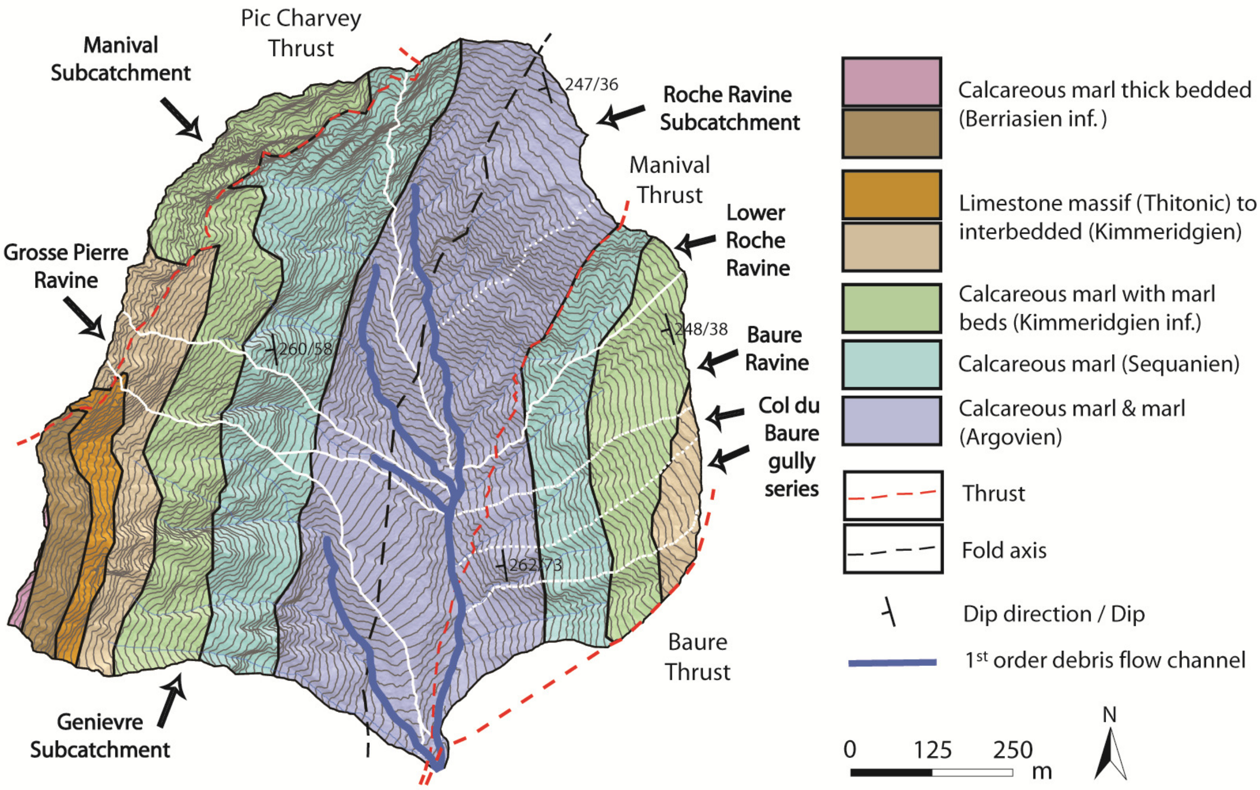

Figure 2. Geological map of the catchment headwater (production zone), after Gidon (1991) and location of first-order debris flow channels (thick blue line) and their respective contributing area (white lines)". For the ease of analysis, the Roche Ravine and Col du Baure subcatchments in the east side were further subdivided according to their gully complex.

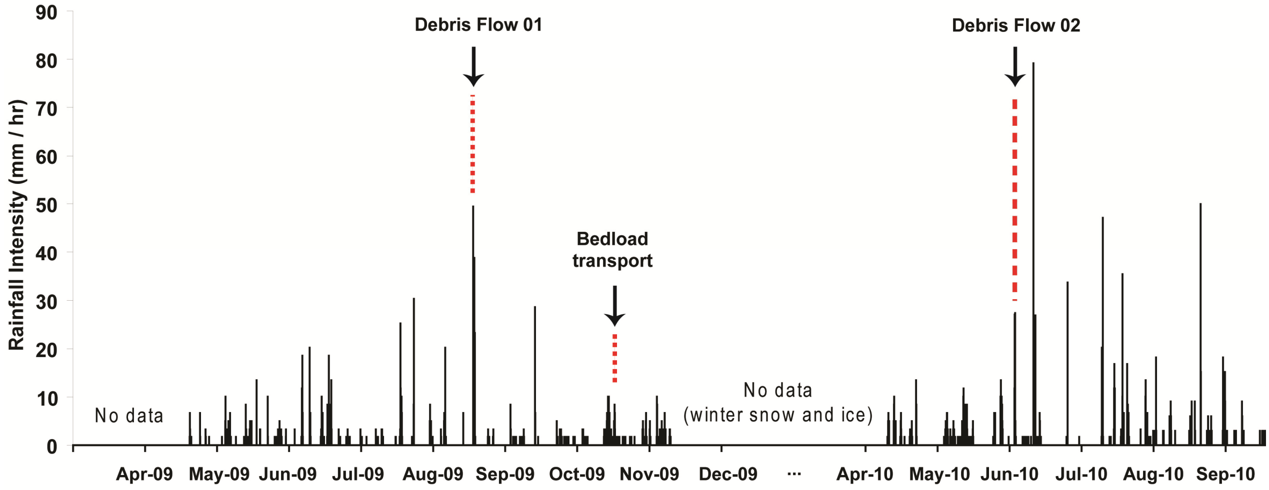

Figure 3. Maximum rainfall intensity over the monitoring period measured by a rain gauge located at the top of the torrent (calculated for a 5 minutes time interval). The mean annual precipitation is about 1500 mm in the headwater of the Manival (modified from Loye, 2013).

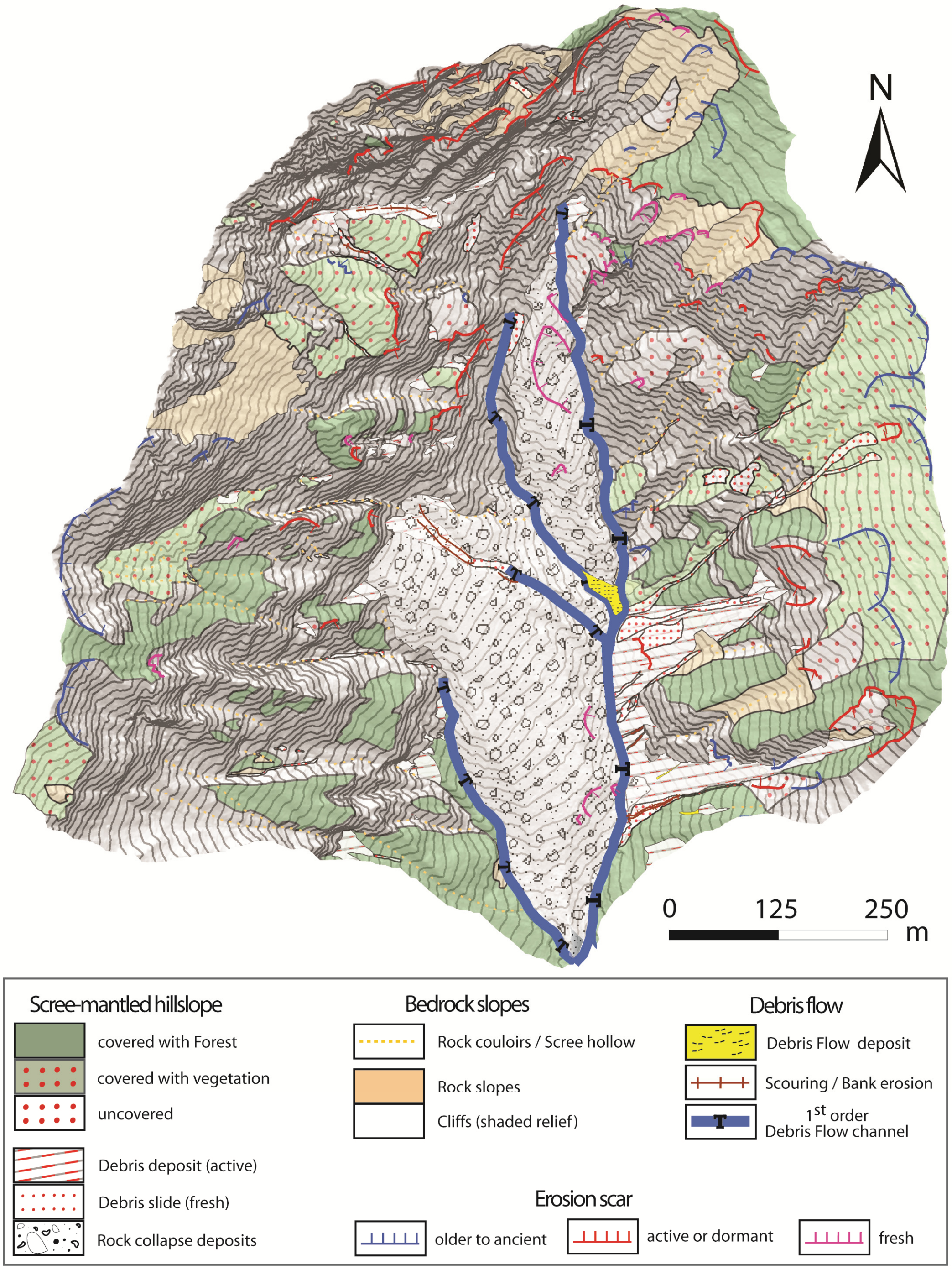

Figure 4. Geomorphic process map (contour interval: 20m) illustrating the spatial pattern of sediment sources and transfer in the first-order channel complex. Note the impressive rock collapse deposits now crossed by four first-order debris channels. Their bed incision is strongly constrained by series of check dams, but erosion scars all along the deposit suggest that the reaches are still subject to lateral erosion.

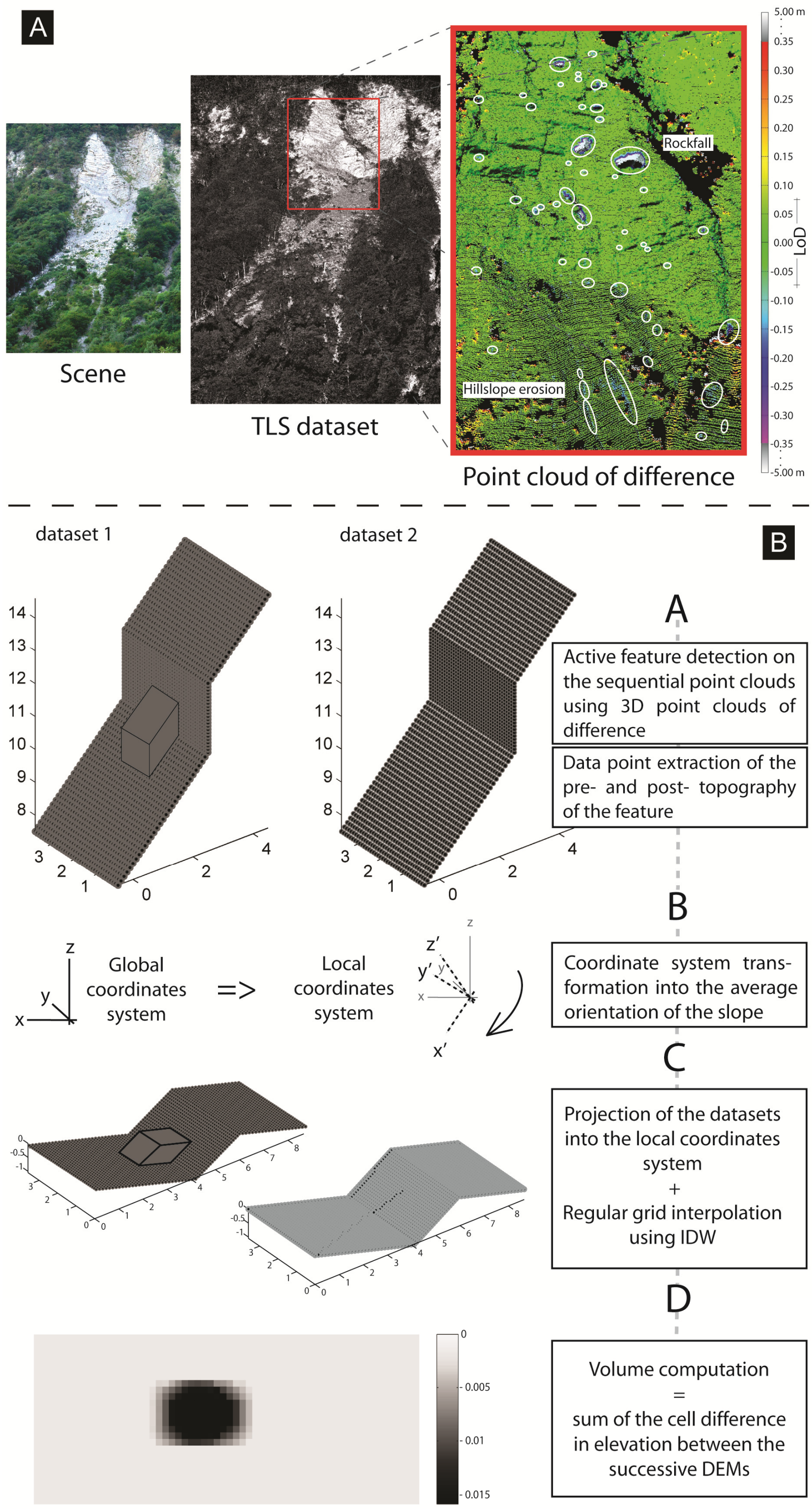

Figure 5. (A) 3-D detection and (B) extraction and volume computation method of an individual active feature provided by two successive point cloud datasets.

Histogram Statistics ICP : Georeferencing Point Cloud April 2009 - July 2010	
Subcatch. name	Manival
Mean (μ)	0.000104
Std Dev. (σ)	0.060718
Minimum (min)	-0.212658
Maximum (max)	0.212658
Peak	48593
Number of Points	3526850

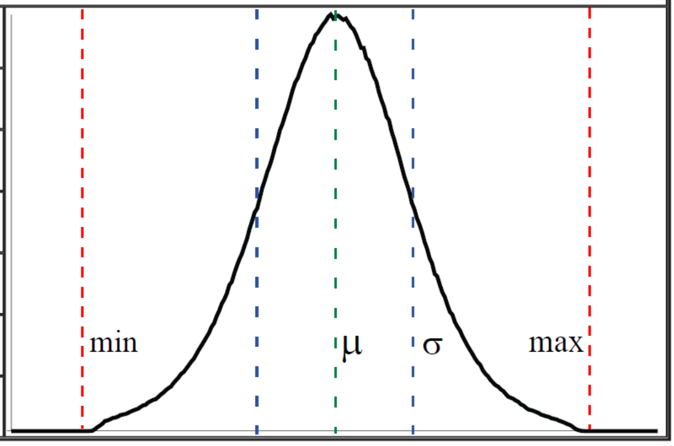

Figure 6. Distribution of the distance between two survey point clouds after the process of georeferencing using ICP procedure. The distance approaches normal distribution with a zero mean, showing that errors generated by multiple scan registration and point cloud survey georeferencing are Gaussian, random and independent. Data are given in meters.

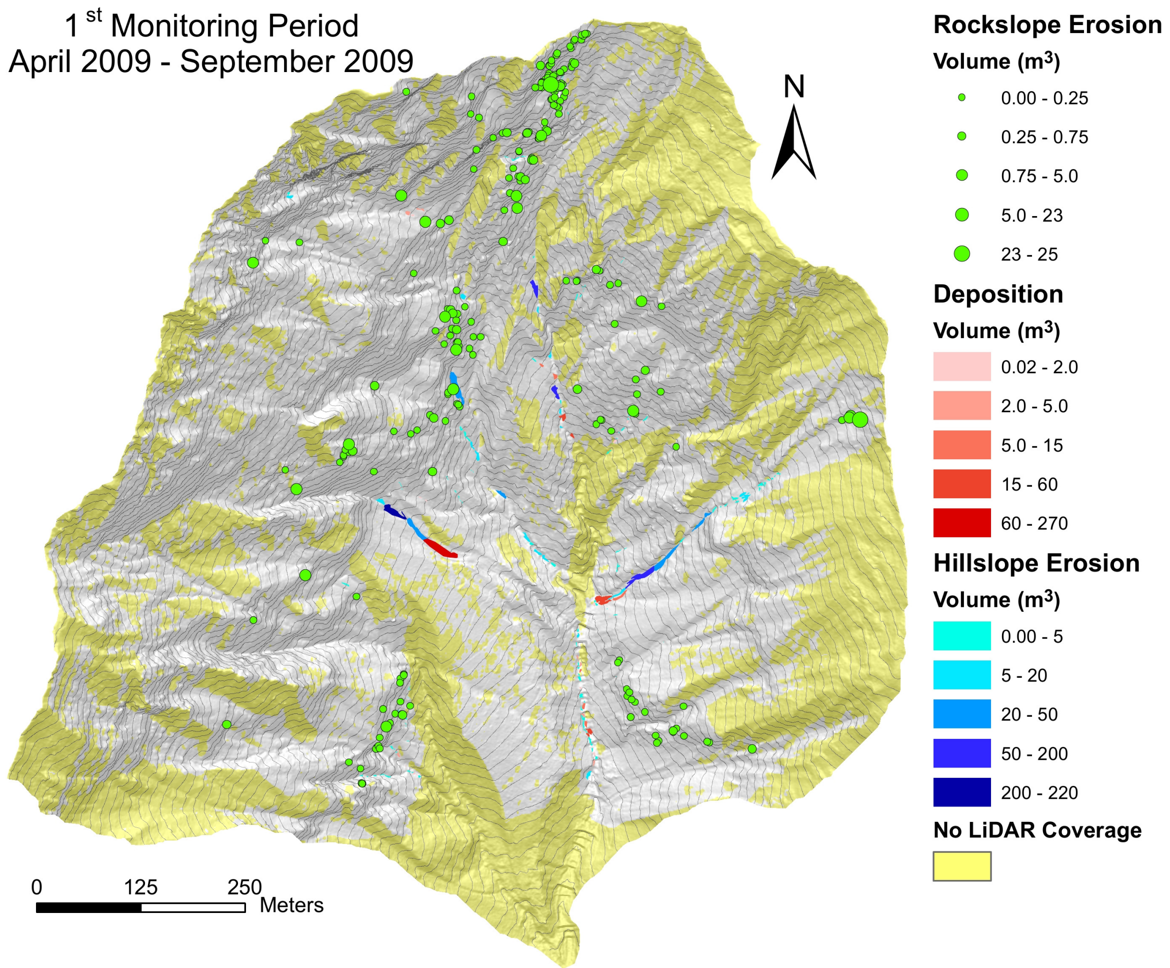

Figure 7. Geomorphic activity revealed by comparing the topographic differences of the two successive TLS surveys operated in April and August 2009. The sediment budgets are detailed for each subcatchment in Fig. 13.

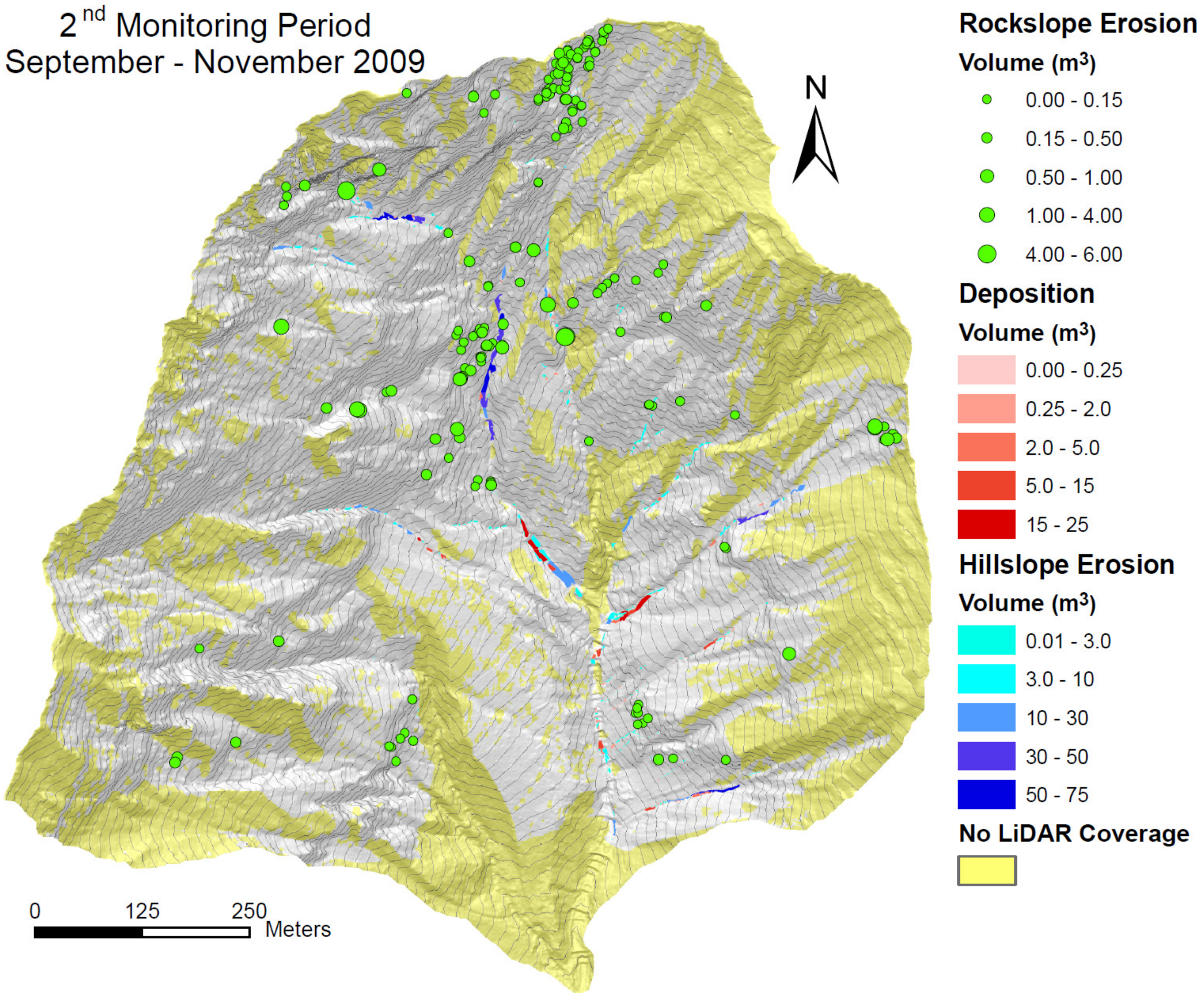

Figure 8. Geomorphic activity revealed by comparing the topographic differences of the two successive TLS surveys operated in August and November 2009. The sediment budgets are detailed for each subcatchment in Fig. 14.

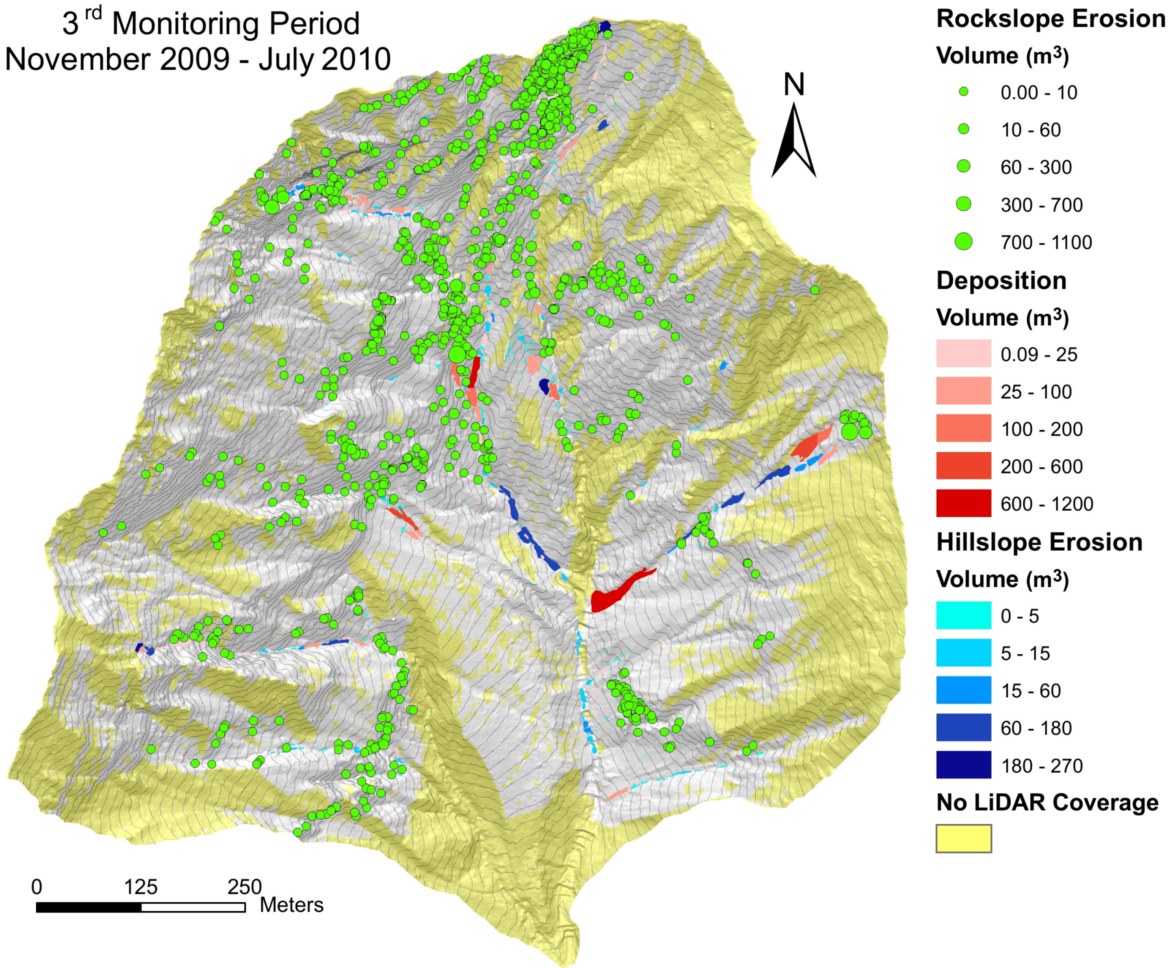

Figure 9. Geomorphic activity revealed by comparing the topographic differences of the two successive TLS surveys operated in November 2009 and July 2010. The sediment budgets are detailed for each subcatchment in Fig. 15.

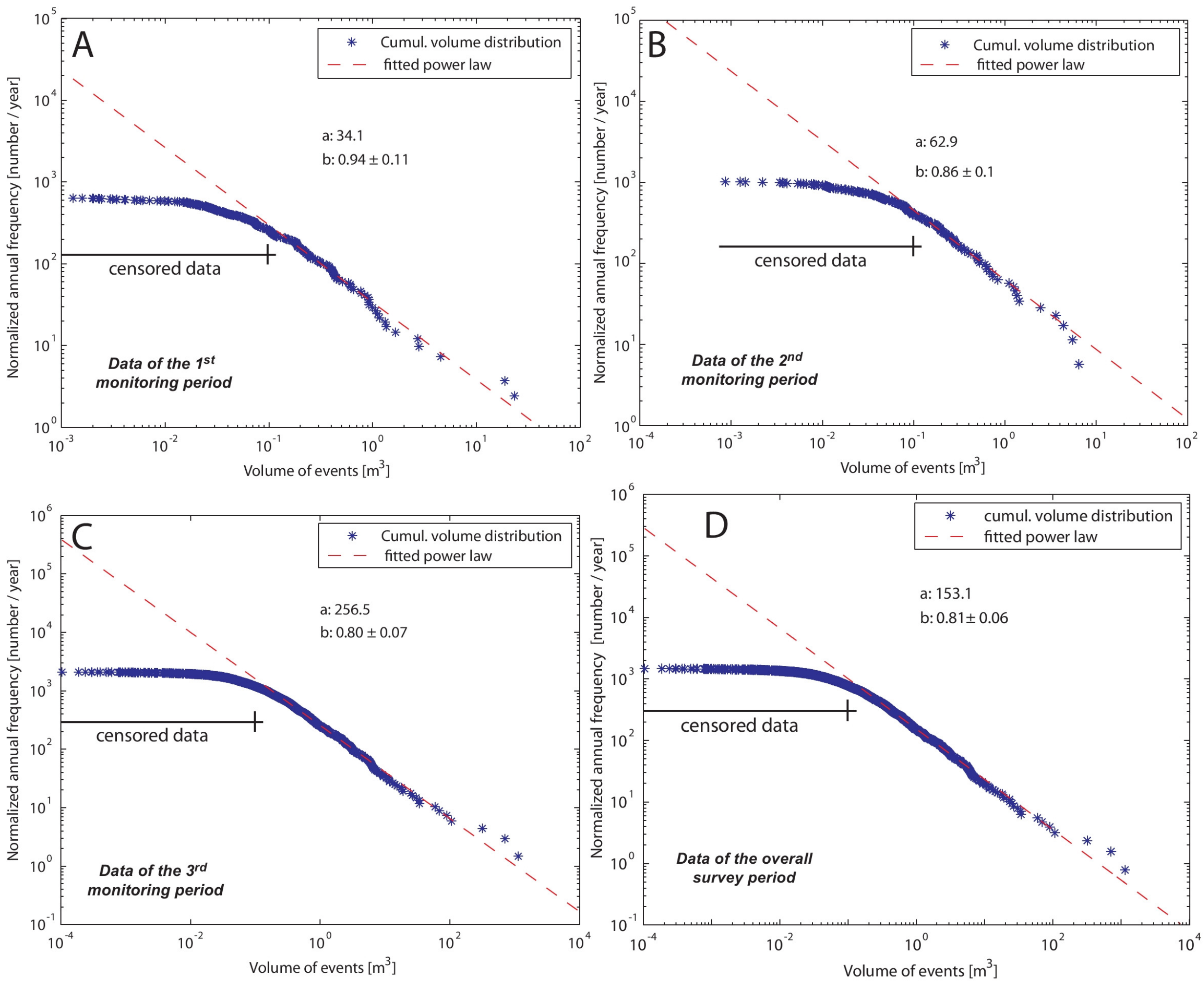

Figure 10. Cumulative volume distribution of the rockfall observed during the first (A), the second (B), the third monitoring period (C) and over the entire study time of 16 months (D). For each dataset, the power law is fitted for volumes larger than 0.1 m^3. Below this threshold volume, the distribution exhibits a roll-over that progressively reaches a quasi-constant frequency for the smallest detected volumes.

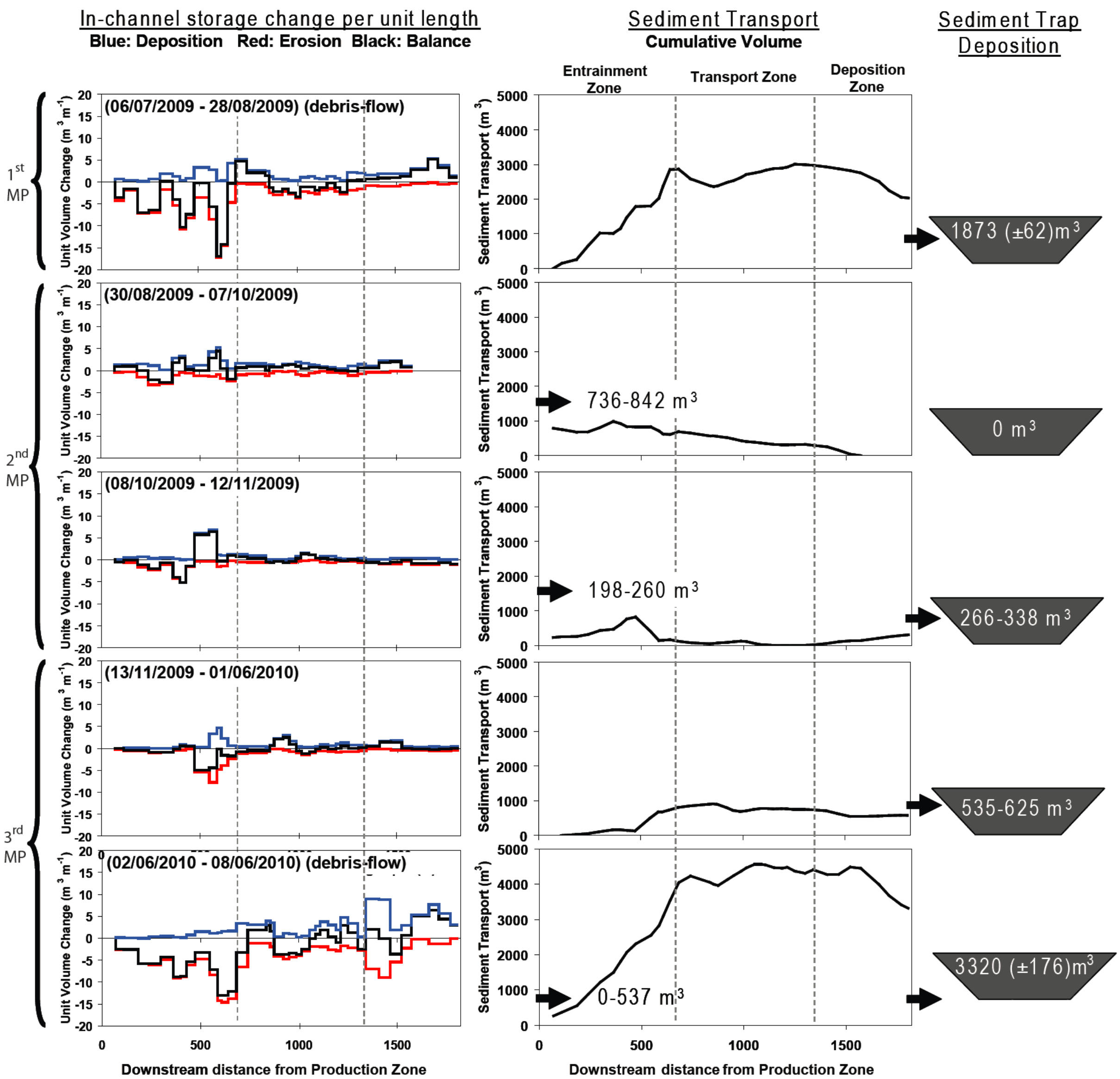

Figure 11. Torrent in-channel storage changes per unit length and sediment budgets of cumulative volumes transported in the torrent from the headwater outlet to the sediment trap downstream for each monitoring period (MP). The torrent recharge (sediment input) was estimated given the in-storage change and the volume deposited in the sediment trap (see Table 4 for details on values) (modified from Theule et al., 2012).

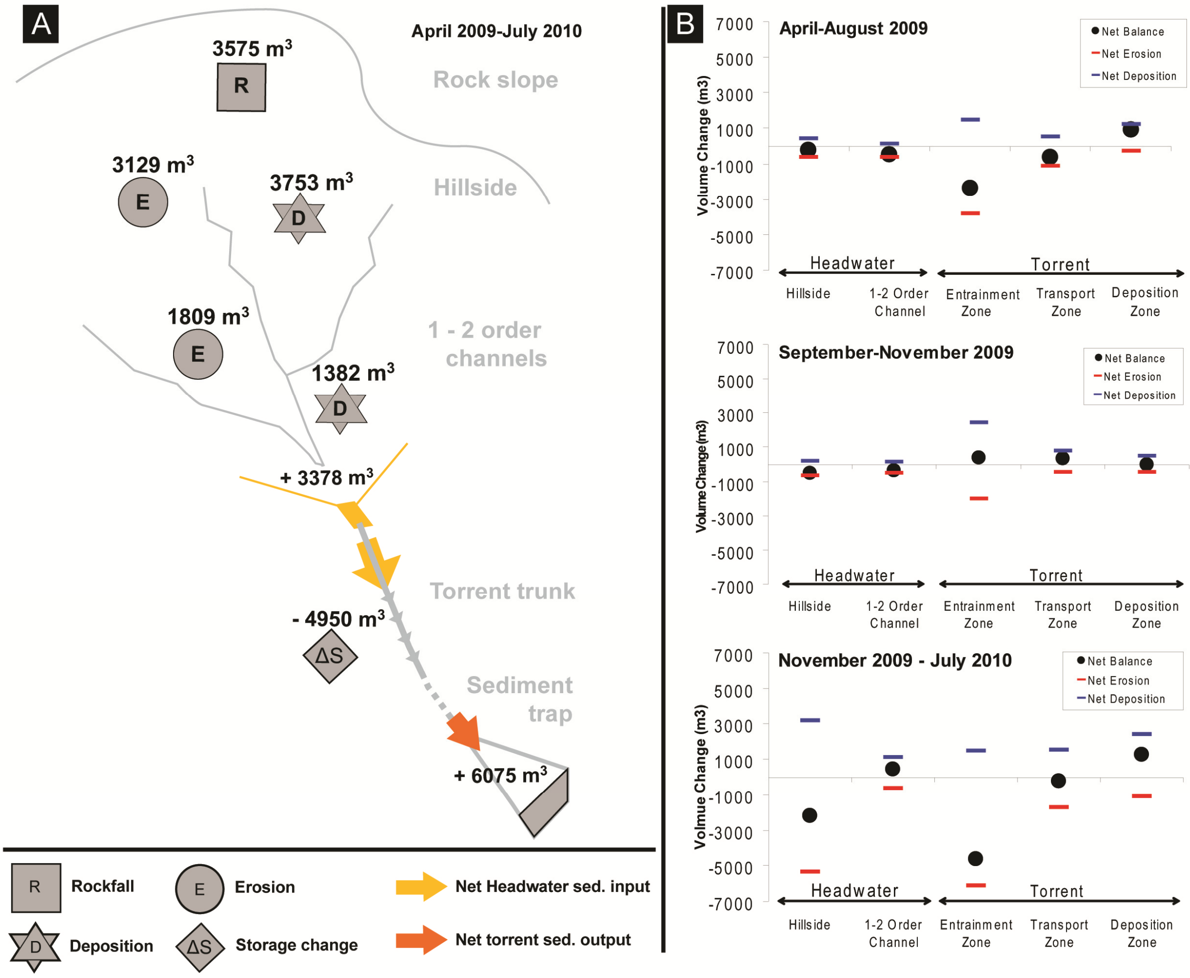

Figure 12. (A) Global sediment budget and (B) net sediment balance for each monitoring period showing the overall transfer dynamic from debris source zone in the headwater to the apex of the fan through the torrent observed during the period of investigation.

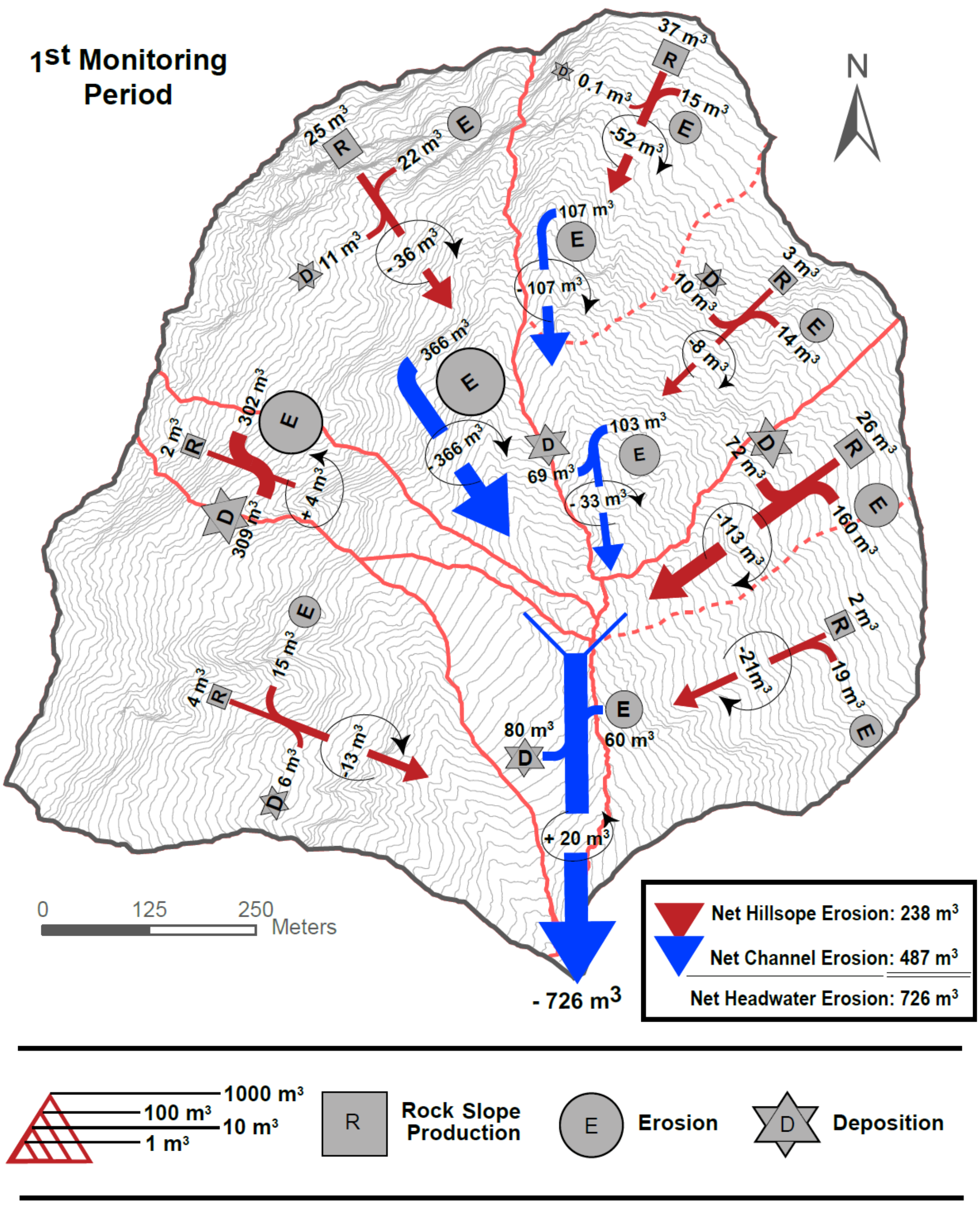

Figure 13. Overall headwater sediment budget observed during the 1st monitoring period revealing the sediment dynamic through the spring-summer season and the net balance of sediment recharge in the downstream torrent for the several months preceding the august 2009 debris flow.

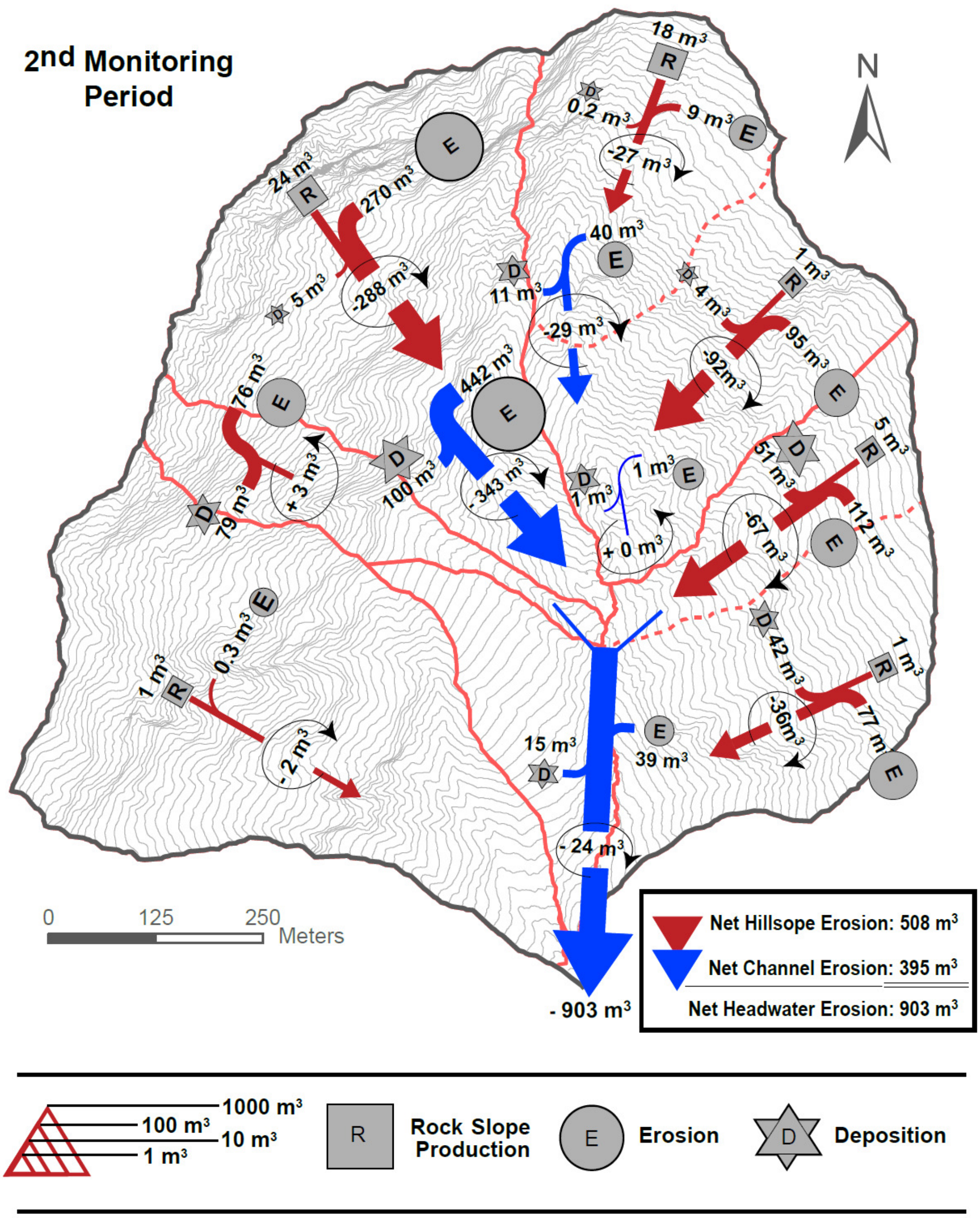

Figure 14. Overall headwater sediment budget observed during the 2nd monitoring period revealing the sediment dynamic and the net balance of sediment recharge in the downstream torrent during the autumn.

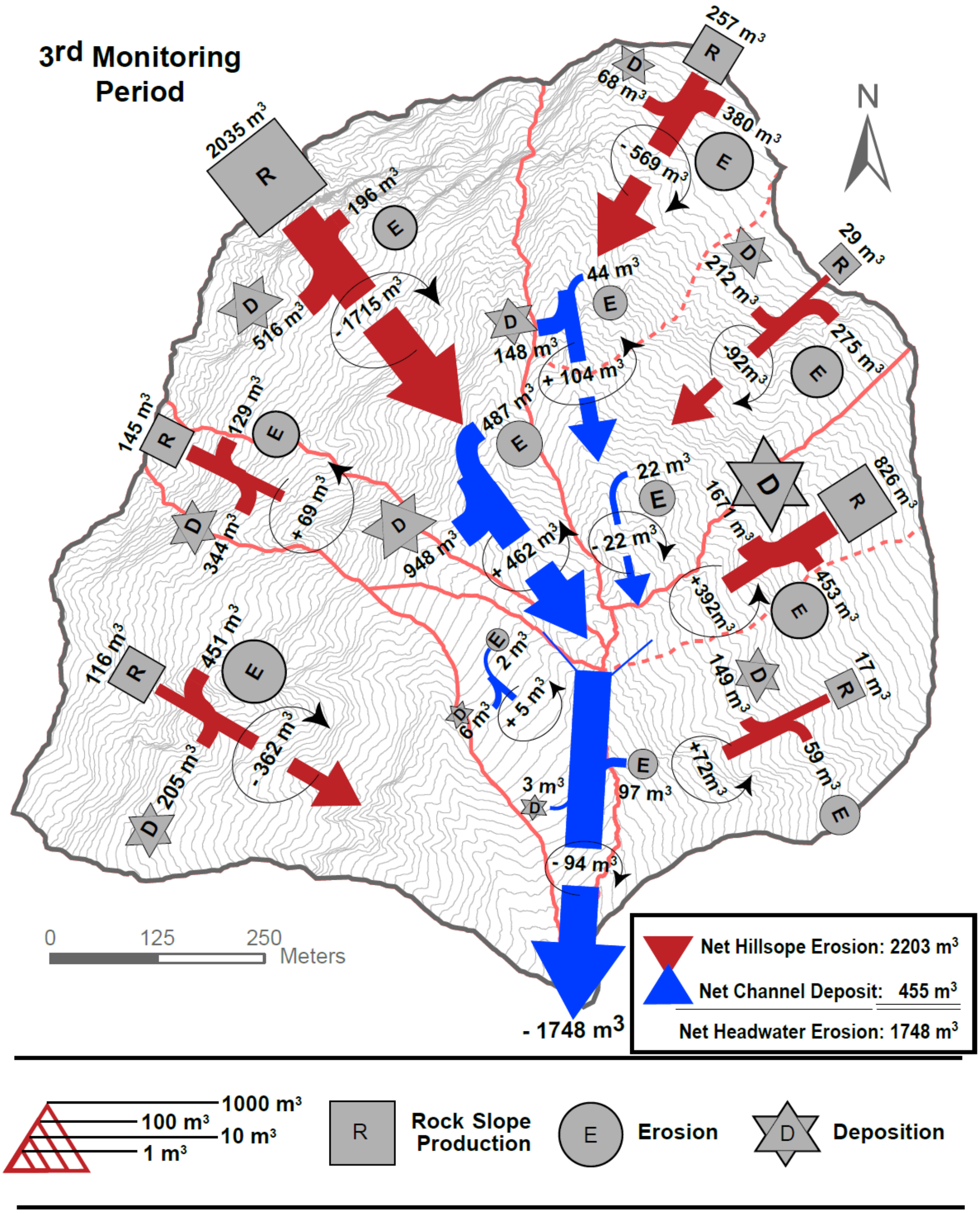

Figure 15. Overall headwater sediment budget observed during the 3rd monitoring period revealing the sediment dynamic through the winter-spring and the net balance of sediment recharge in the downstream torrent for the period preceding the June 2010 debris flow.

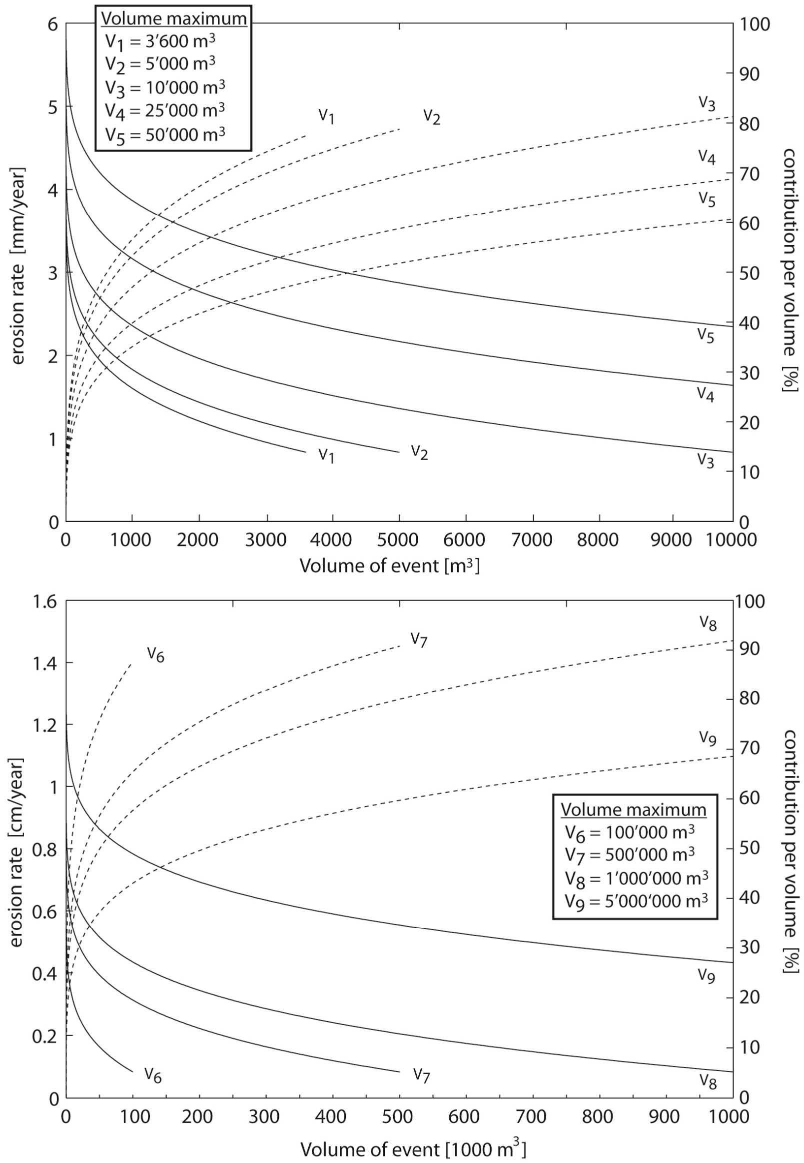

Figure 16. (continuous line) Erosion rate as function of size of events for a certain volume of production (potential maximum volume $V_{1...9}$), considering that rockfall volume distribution observed at Manival follows power law behaviour (Table 6). (dash line) Contribution of each class of volumes to the erosion rate showing the significant effect of large slope failures. For a maximum volume eroded of 3'600 m^3/yr (V_1), the 1'000 m^3 rockfall event contributes for 60%, while events less than 100 m^3 induce less than 20% of erosion, although of much higher frequency; a 100'000 m^3 rockslide would generate 70% of a total of material eroded of 500'000 m^3 (V_7) over a century.