DOI: 10.4408/IJEGE.2011-03.B-085

SEDIMENT BUDGET MONITORING OF A DEBRIS-FLOW TORRENT (FRENCH PREALPS)

Joshua THEULE(*), Frederic LIEBAULT(*), Alexandre LOYE(**), Dominique LAIGLE(*) & Michel JABOYEDOFF(**)

(*) Unité de Recherche Erosion Torrentielle Neige et Avalanches (ETNA), Cemagref Grenoble, 2 rue de la Papeterie, BP76, 38402 Saint-Martin-d'Hères, France - Email: joshua.theule@cemagref.fr
(**) Institute of Geomatics and Risk Analysis, University of Lausanne, UNIL-Sorge, Amphipôle, CH-1015 Lausanne, Switzerland

ABSTRACT

The Manival near Grenoble (French Prealps) is a very active debris-flow torrent equipped with a large sediment trap (25 000 m^3) protecting an urbanized alluvial fan from debris-flows. We began monitoring the sediment budget of the catchment controlled by the trap in Spring 2009. Terrestrial laser scanner is used for monitoring topographic changes in a small gully, the main channel, and the sediment trap. In the main channel, 39 cross-sections are surveyed after every event. Three periods of intense geomorphic activity are documented here. The first was induced by a convective storm in August 2009 which triggered a debris-flow that deposited ~1,800 m^3 of sediment in the trap. The debris-flow originated in the upper reach of the main channel and our observations showed that sediment outputs were entirely supplied by channel scouring. Hillslope debris-flows were initiated on talus slopes, as revealed by terrestrial LiDAR resurveys; however they were disconnected to the main channel. The second and third periods of geomorphic activity were induced by long duration and low intensity rainfall events in September and October 2009 which generate small flow events with intense bedload transport. These events contribute to recharge the debris-flow channel with sediments by depositing important gravel dunes propagating from headwaters. The total recharge in the torrent subsequent to bedload transport events was estimated at 34% of the sediment erosion induced by the August debris-flow.

***Key words**: debris-flow, bedload transport, sediment budget, terrestrial LiDAR, Manival, French Prealps*

INTRODUCTION

Volumes of debris-flows are highly influenced by channel scouring making sediment availability in talwegs a critical factor for predicting debris-flow magnitude (Hungr *et alii,* 1984; Marchi & D'Agostino, 2004; Hungr *et alii,* 2005; Remaitre *et alii,* 2005; Coe *et alii,* 2008). Therefore, the recharge rate, defined as the rate at which sediments accumulate in the channel during time intervals between debris-flows, controls the frequency of debrisflows and has been used to differentiate supply and transport-limited debris-flow basins (Bovis & Jakob, 1999; Jakob *et alii,* 2005). Although erosion and deposition in steep channels have been recognized as key factors for understanding debris-flow dynamics, few studies have tried to measure it in the field. Another problem is the coexistence of various sediment transport mechanisms in torrent channels. These are induced by both bedload transport and debrisflow and there is a paucity of work trying to compare the geomorphic impacts of both (Mao *et alii,* 2009).

Catchment-scale sediment budgeting can be used to identify main sediment sources, to evaluate the respective contribution of these sources in the sediment yield of the catchment and to better understand sediment transfers in complex geomorphic systems (Dietrich & Dunne, 1978; Johnson & Warburton, 2002; Gomez *et alii,* 2003; Schuerch *et alii,* 2006).

The monitoring of channel morphology with cross-sections resurveys have shown to be very effective for assessing bedload transport in gravel-bed rivers (Martin & Church, 1995; Reid *et alii,* 2007). This morphological approach has rarely been applied on steep headwaters for characterizing the volume of debris-flows (Veyratcharvillon & Memier, 2006). With the recent development of airborne and terrestrial LiDAR, it is now possible to implement topographic surveys with very high resolution and frequency. This technology has been increasingly used for capturing morphological changes in rugged terrain (Milan *et alii,* 2007; Scheidl *et alii,* 2008; Conway *et alii,* 2010).

This paper presents results from a sediment budget monitoring program of a very active debris-flow torrent located near Grenoble (Manival Torrent) combining cross-section and terrestrial LiDAR resurveys. The reconstruction of event-based sediment budgets by integrating monitoring techniques gave interesting observations of erosion and deposition patterns along the torrent channel and allowed us to compare morphological and sedimentary responses associated with debris-flow and bedload transport processes.

Fig. 1 - View of the Manival Torrent channel and production zone of the upper catchment (photo: Joshua Theule)

STUDY AREA

The Manival is a very active debris-flow torrent located near Grenoble in the Northern French Prealps (Fig. 1). The catchment is located in the Chartreuse Mountains where the torrent flows into the Isère River. The close proximity to Grenoble, easy access throughout the main channel and presence of a large sediment trap (25 000 m^3) in the channel to protect the urbanized fan against debris-flows make the Manival a practical site for implementing a monitoring program of sediment transfer in steep slope torrents.

Above the sediment trap, the mean channel slope is 16% with a drainage area of 3.6 km^2 for a total relief of 1 200 m. Approximately 180 check-dams constructed since the 1890s throughout the main channel and small gullies are managed by the French Forest and Torrent-Control Service (ONF-RTM service).

The geology of the catchment is typical of the sedimentary prealpine ranges. Bedrock is composed of highly fractured, alternating sequences of Jurassic marls and limestones. A long reverse fault runs through the axis of the catchment with secondary faults found regularly on the head and east side of the catchment. The bedrock is covered by thick colluvial deposits which are mobilized by shallow landslides, hillslope debris-flows and snow avalanches. Limestone rock faces are prone to active rockfalls which supplies debris to talus slopes. During the snowmelt season, gullies located under rock faces can experience one rockfall every 5 to 10 minutes (according to the authors' field experiences). Debris-flows and colluvial slope failures are often initiated in the talus slopes influenced by a "firehose effect" (Godt & Coe, 2007).

Archive analysis of the Manival flood history during the last two centuries showed that the torrent can produce large debris-flows ranging from 10 000 to 60 000 m^3 (Peteuil *et alii,* 2008). Since 2008, the Manival has produced one debris-flow each year.

METHODS

In Spring 2009, we started to monitor the sediment budget of the catchment above the sediment trap by implementing a detailed topographic survey of the channels and hillslopes. Two different techniques are used: cross-section resurveys along the main channel and terrestrial LiDAR resurveys of representative hillslopes and gullies (Tab. 1). The sediment trap is used to characterize sediment outputs by measuring sediment deposition from terrestrial laser scanning.

Date	Measurements	Measurement Locations		
		Sediment Trap	Main channel	Production Zone*
01/06/2009	Airborne LiDAR	x	x	x
03/06/2009 - 06/07/2009	Cross section survey		x	
29/07/2009 - 01/08/2009	Terrestrial LiDAR			x
25/08/2009	Debris-Flow			
28/08/2009 - 30/08/2009	Cross section survey		x	
29/08/2009 - 30/08/2009	Terrestrial LiDAR	x		x
26/09/2009	Flow event			
07/10/2009 - 08/10/2009	Cross section survey		x	
10/2009	Flow events			
29/10/2009 - 16/11/2009	Terrestrial LiDAR	x		x
12/11/2009 - 13/11/2009	Cross section survey		x	

* Gully and main channel (see Fig. 2)

Tab. 1 - Field measurements performed between events are listed with their dates and locations

The rainfall has been measured since October 2008 using a tipping bucket rain gauge installed in the upper basin (resolution of 0,14 mm).

CROSS-SECTION SURVEYING

Thirty-nine monumented cross-sections were deployed along the main channel between the sediment trap and the confluence of the two largest gullies of the production zone (Fig. 2). Cross-sections are surveyed before and after flow events with a total station (Leica FlexLine TS02, electronic distance measurement precision of 1,5 mm +2ppm, angular resolution of 7'' or 0,34 cm of precision at a distance of 100 m) for quantifying erosion and deposition volumes in the channel and back-calculating sediment transport using the morphological method (Martin & Church, 1995; Reid *et alii,* 2007; Raven *et alii,* 2009).

Volumes of deposition V_D and erosion V_E between crosssections are obtained by the following:

$$V_E = \frac{A_{E(n)} + A_{E(n+1)}}{2} L_{(n,n+1)} \quad (1)$$

$$V_D = \frac{A_{D(n)} + A_{D(n+1)}}{2} L_{(n,n+1)} \quad (2)$$

The estimated volumes of V_D and V_E cover the length *L* between the two cross-sections *n* and *n+1* with their mean cross-sectional area of erosion A_E and deposition A_D. The sediment balance δ_V for the channel reach between two cross-sections is determined by the difference of the two volumes V_D and V_E. The principle of mass conservation is used to determine the coarse sediment transport for each reach with following equation:

$$V_{out} = V_{in} - \delta V \quad (3)$$

with V_{out} the sediment output and V_{in} the sediment input. Through monitoring sediment outputs with the sediment trap and the sediment balance within the channel, the sediment supply from the production zone can be determined.

Fig. 2 - Shaded relief map of the Manival catchment derived from airborne LiDAR survey; main features of the monitoring program are indicated in the map

Uncertainties of volume estimates for each sub-reach between two cross-sections, $\sigma_{\delta V}$, were calculated according to the propagation of uncertainty's law of Taylor (Reid *et alii,* 2007):

$$\sigma_{\delta V} = \sqrt{\left(\sigma_L\left[\frac{\delta V}{\delta L}\right]\right)^2 + \left(\sigma_z\left[\frac{\delta V}{\delta z}\right]\right)^2 + \left(\sigma_d\left[\frac{\delta V}{\delta l}\right]\right)^2} \quad (4)$$

The terms σ_d and σ_z s refers respectively to errors associated with distances and elevations of cross-sections points. We attributed to both a value of 5 cm, corresponding to the D_{84} of the bed surface grain size distribution, representing the roughness of the channel. The term σ_L , defined as the error in distance between two crosssections, is dependant on the interpretation of flow path distances, and has been calculated as the mean variation of determined distances by two experts for all reaches equaling 97 cm.

LASER SCANNING

Laser scanning is a more precise technique for quantifying erosion and deposition and is ideal for surveying inaccessible slopes. The Manival catchment provides ideal view points for maximum coverage limiting shadows for terrestrial scans. However, there are still incised areas that or not feasible for scanning as well as areas of very dense vegetation providing limited ground points.

A terrestrial laser scanner (Optech Inc.) was used for resurveying the sediment trap providing detailed volumes of sediment outputs for the catchment. Resurveys were also performed on an active gully which experiences frequent rockfalls. The gully is accessible on a trail and can be seen from a view point with optimal angle and coverage. The majority of the torrent channel in the production zone could also be monitored providing information of sediment transport upstream from the monitored cross-sections. The coverage of this area was limited and difficult to monitor which depended on high resolution airborne LiDAR as its preliminary surface.

Resolution of terrestrial laser scans range from 2 to 10 cm which is highly dependant on the distance from the scanning position (maximum ~800 m). Scans were merged on Polyworks and georeferenced to the airborne LiDAR scan creating regular maximum standard deviation of ± 0,08 m. Elevation models were developed through ordinary kriging which gives the best interpretation for channel morphologic features with terrestrial laser scans (Heritage *et alii*, 2009). The digital terrain models are developed on a 0,1 m grid where differences are used for calculating volumes of erosion and deposition.

The airborne LiDAR survey of the whole catchment was flown in June 2009. The filtered point cloud has a mean density of 6.9 points/m². A 0.1 m grid was derived from raw LiDAR data for the active channel by cleaning manually the sparse vegetation cover. The digital terrain model was created with a linear drift kriging for smoothing high density linear swaths of points in the airborne scans which is required for using a 0,1 m grid resolution.

RESULTS

Three periods of intense geomorphic activity in the channel occurred in 2009. The first was induced by a high intensity convective storm in August which initiates a debris-flow. The two others were associated with long duration and low intensity rainfalls which generate bedload transport flow events in September and October.

AUGUST 2009 DEBRIS-FLOW

The storm causing the debris-flow had a maximum rainfall intensity of 48,9 mm h^{-1} (Fig. 3a). The difference of the two LiDAR-derived DEM before and after

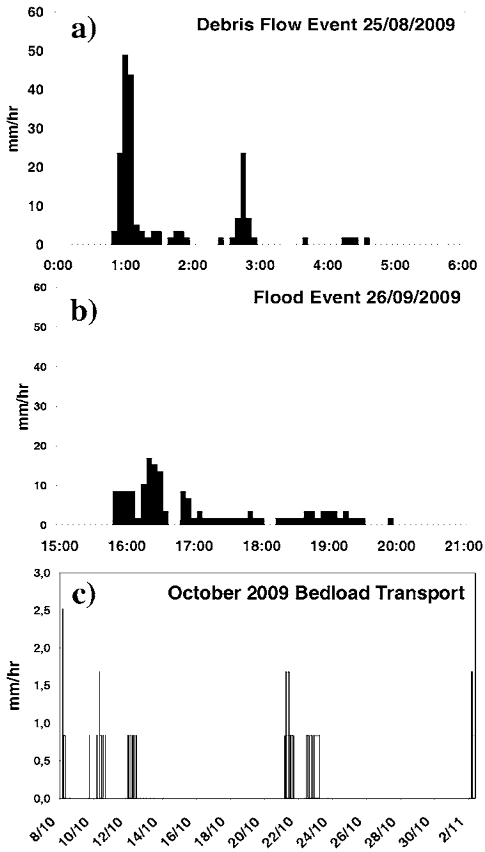

Fig. 3 - Rainfall intensities (5 minutes interval) associated with (a) the August debris-flow, (b) the September and (c) October flow events

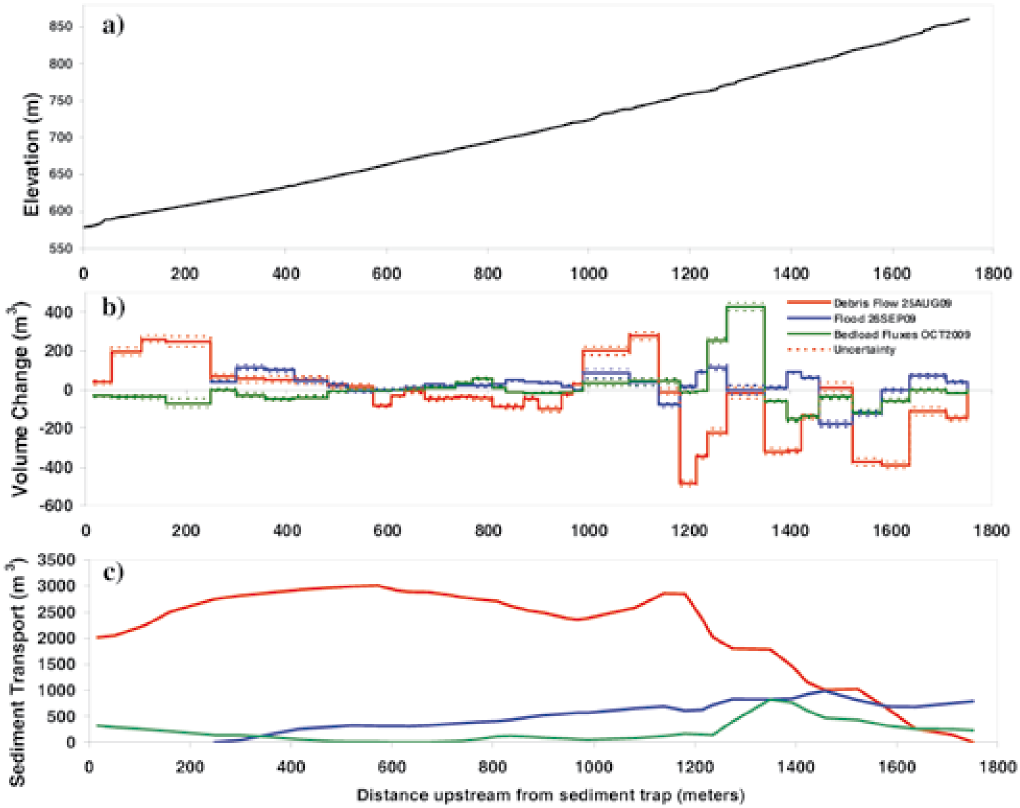

Fig. 4 - Long profile (a), volume changes (b) and sediment transport (c) along the main channel for the 3 investigated periods of geomorphic activity; data derived from cross-sections resurveys

the event in the sediment trap gives a sediment accumulation of 1 873 ±62 m³. Topographic monitoring of cross-sections along the main channel showed a net loss of 2 034 ±559m³ (deposition: 3 200 m³, erosion: 5 215 m³) (Fig. 4b). These results show that sediment outputs from the production zone (upstream from the surveyed reach) were insignificant despite the intensity of the storm and that the volume of the debris-flow was entirely supplied by channel scouring. This is confirmed by laser scans made in the production zone. The upper channel experienced sediment deposition (Fig. 5a). It trapped sediments coming from two active gullies which are identified as active during the storm and generated a sediment discontinuity between the production zone and the main channel. These observations show that confined reaches with very steep channel slope (32%) can store sediments during convective storms.

LiDAR resurvey of the gully showed that a talus slope failure occurred at the upper end of the gully (Fig. 5c). Erosion of 237 m³ took place at the talus slope with 274 m³ deposited 40-80 m down the gully. The gain of 38 m³ of material most likely originated above the immediate cliff. There was no change in topography further then the extent of the deposition.

All of these observations show that the initiation of the debrisflow occurred in the upper reach, just downstream from the confluence between the two main gullies of the production zone. The channel slope here is 18% with a drainage area of 0,87 km². Upstream from the confluence, high water marks could be recognized however no signs of debris-flow features were visible. Levees begin to form ~100 m downstream from the confluence. The debris-flow grew in volume along a reach of 600 m length contributing 3 000 m³ (mean slope: 18%). This gives a yield rate of about 5 m³/m. Most of these sediments were transported without significant interactions with the channel along a 730 m reach with a mean slope of 15% (Fig. 4c). Deposition starts at a slope of 14% and terminates at the sediment trap.

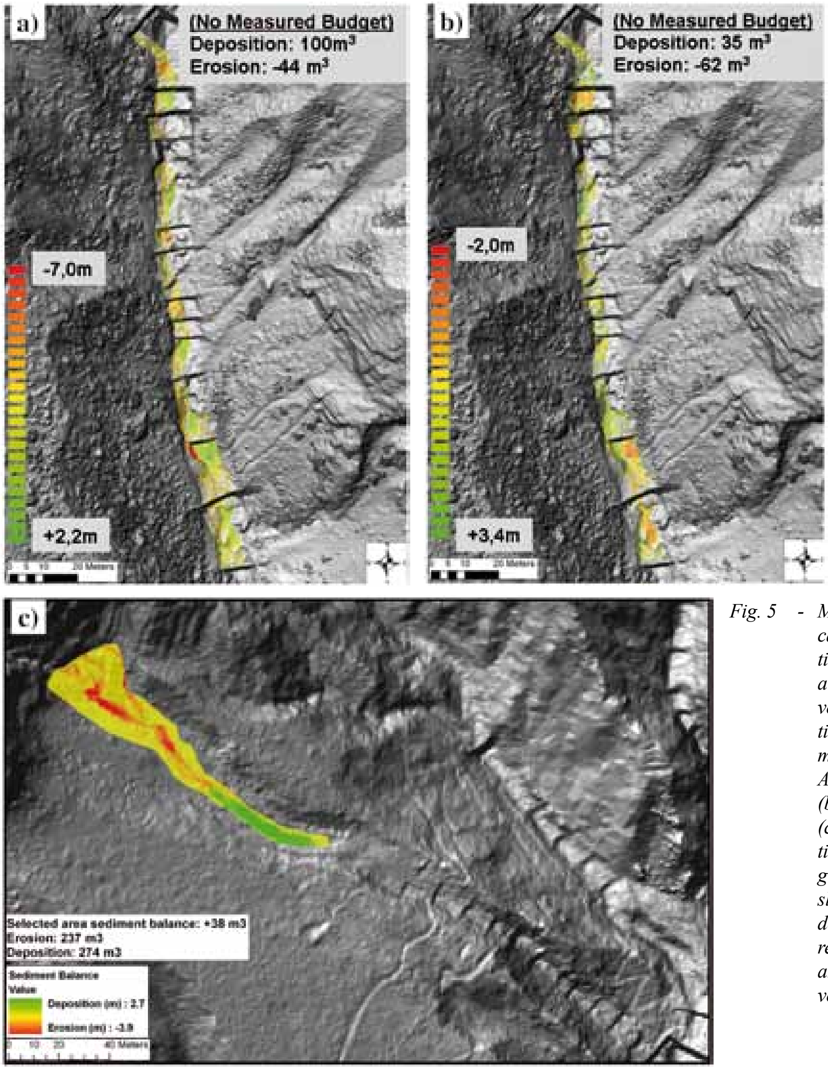

Fig. 5 - Morphological changes captured in the production zone with terrestrial/airborne LiDAR resurveys: erosion and deposition patterns of the upper main channel (a) after the August debris-flow and (b) autumn flow events; (c) erosion and deposition pattern of a small gully incised in talus slope after the August debris-flow; the shaded relief map derived from an airborne LiDAR survey is used in background

Fig. 6 - Morphological changes associated with the deposition of gravel dunes transported as bedload during autumn flow events (photos: JOSHUA THEULE)

	August debris-flow	September flow event	October flow events
Input from the production zone	~0 m^3	789 ±392m^3	? m^3
Storage change in the main channel	-2034 ±559m^3	+789 ±392m^3	-89 ±322m^3
Output (sediment trap)	1873 ±62m^3	~0 m^3	Disturbed

Tab. 2 - Sediment budget of the Manival catchment for 2009 events

SEPTEMBER AND OCTOBER 2009 EVENTS

The September event occurred after a long duration rainy period of moderate intensity (maximum intensity of 16,9 mm h^{-1}) (Fig. 3b). No traces of debris-flows have been detected in the main channel and no sediment deposition was observed in the sediment trap. However, the cross-sections resurvey showed substantial morphological changes in the main channel, reflecting a relatively large volume of sediment transport by bedload, despite the moderate flows. The sediment budget shows a net storage gain of 789 ±392 m^3 (deposit: 2 195 m^3 erosion: 1 410 m^3) (Fig. 4b). We also observed that deposition occurred preferentially in subreaches that were scoured during the August debris-flow (Fig. 6). We calculated that 39% of the channel storage loss from the August debris-flow was recharged by bedload transport of the September event.

Rainfalls in October have endured entire days with maximum intensities of 1,6 mm hr^{-1} (Fig. 3c). Flow in the channel becomes more regular disappearing and reappearing through the gravel/cobble storages. During peak intensities of some of these flows bedload transport has been observed which constantly changes the surficial flow direction in the channel. The sediment budget of the main channel showed a loss of 89 ±322 m^3; however deposition of at least 233 m^3 in the upper part of the channel reveals more recharge from the production zone (Fig. 6). The lower half of the torrent towards the sediment trap experienced incision of at least 321 m^3 due to the constant flow channelizing through remnant deposits of the debris-flow and flood. The sediment trap was disturbed by operators extracting the material; therefore the budget for this event could not be determined. Further recharge however is being taken place in the upper half of the monitored torrent.

During September and October events the channel storage in the production zone experienced erosion (limited LiDAR coverage does not allow a full estimate of volume). Figure 5b shows that the production zone deposition during the debris-flow event was removed by autumn flow events.

CONCLUDING REMARKS

Recent studies reveal the significance of sediment availability, channel recharge, and hillslope-channel coupling for debris-flow occurrence (Coe *et alii,* 2008; Schlunegger *et alii,* 2009). Our observations indicate that debris-flow is a scouring process for the channel whereas bedload transport is a process that replenishes the scoured reaches by deposition of gravel dunes (Tab. 2). Despite erosion activity in the production zone during high intensity convective rainfall, sediment was stored in the gullies and upper channel and the sediment yield of the production zone was low. Volumes entrained in gullies were small and travel distances were short, creating a delay of delivery into the main torrent channel. These sediments produced during convective storm were delivered to the main channel during autumn rainfall by bedload transport. The sediment yield of the production zone was much more important (3 orders of magnitude more), despite rainfall of less intensity. This sequence of events is a typical annual observation for the Manival catchment, the controlling conditions for travel distances and connections of sediment transport still needs to be fully understood.

The first results for this project are very encouraging which motivates us to continue the monitoring program on the Manival. Supplementary efforts are also made to (1) quantify the contributions from the catchment source with terrestrial laser scanning and to (2) instrument the main channel for real time monitoring of flow events. These elements will allow us to obtain necessary data for interpreting and predicting responses of sediment transport in steep channels and establishing comprehensive sediment budgets for studying the hillslope-channel coupling.

ACKNOWLEDGEMENTS

This research was supported by the Interreg Alpine Space Paramount Project and by the “Pôle Grenoblois d’étude et de recherche pour la prevention des Risques Naturels” (PGRN). Michael Deschatres, Hugo Jantzi, Mathieu Cassel, Emilien Parisot, and Nicolas Talaska are acknowledged for their assistance during field works.

REFERENCES

Bovis M. J. & Jakob M. (1999) - *The role of debris supply conditions in predicting debris flow activity*. Earth Surface Processes and Landforms, **24**: 1039-1054.

Coe J. A., Kinner D. A., & Godt J. W. (2008) - *Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado.* Geomorphology, **96** (3-4): 270-297.

Conway S.J., Decaulne A., Balme M.R., Murray J.B. & Towner M.C. (2010) - *A new approach to estimating hazard posed by debris flows in the Westfjords of Iceland*. Geomorphology, **114** (4): 556-572.

Dietrich W.E. & Dunne T. (1978) - *Sediment budget for a small catchment in mountainous terrain.* Zeitschrift für Geomorphologie, Suppl. Bd., **29**: 191-206.

Godt J.W. & Coe J.A. (2007) - *Alpine debris flows triggered by a 28 July 1999 thunderstorm in the Central Front Range, Colorado*. Geomorphology, **84**: 80-97.

Gomez B., Banbury K., Marden M., Trustrum N.A., Peacock, D.H. & Hoskin, P.J. (2003) - *Gully erosion and sediment production: Te Weraroa Stream, New Zealand*. Water Resources Research, **39** (7).

Heritage G.L., Milan D.J., Large A.R.G. & Fuller I.C. (2009) - *Influence of survey strategy and interpolation model on DEM quality.* Geomorphology, **112** (3-4): 334-344.

Hungr, O., Mcdougall, S., & Bovis, M. (2005) - *Entrainment of material by debris flows*. In: Jakob, M. & Hungr, O. (2005, eds.) - Debris-Flow Hazards and Related Phenomena. 135-158 Springer, Berlin Heidelberg, Germany.

Hungr O., Morgan G.C., & Kellerhals R. (1984) - *Quantitative analysis of debris torrent hazards for design of remedial measures.* Canadian Geotechnical Journal, **21**: 663-677.

Jakob M., Bovis M., & Oden M. (2005) - *The significance of channel recharge rates for estimating debris-flow magnitude and frequency*. Earth Surface Processes and Landforms, **30** (6): 755-766.

Johnson R.M. & Warburton, J. (2002) - *Annual sediment budget of a UK mountain torrent*. Geografiska Annaler, **84A** (2): 73-88.

Mao L., Cavalli M., Comiti F., Marchi L., Lenzi M.A. & Arattano M. (2009) - *Sediment transfer processes in two Alpine catchments of contrasting morphological settings*. Journal of Hydrology, **364** (1-2): 88-98.

Marchi L. & D'agostino V. (2004) - *Estimation of debris-flow magnitude in the Eastern Italian Alps*. Earth Surface Processes and Landforms, **29**: 207-220.

Martin Y. & Church M. (1995) - *Bed-material transport estimated from channel surveys: Vedder River, British Columbia*. Earth Surface Processes and Landforms, **25**: 1011-1024.

Milan D.J., Heritage G.L. & Hetherington D. (2007) - *Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river*. Earth Surface Processes and Landforms, **32** (11): 1657-1674.

Peteuil C., Maraval C., Bertrand C. & Monier G. (2008) - *Torrent du Manival: Schéma d'aménagement et de gestion du bassin versant contre les crues.* Unpublished technical report; Office National des Forêts, Service de Restauration des Terrains en Montagne de l'Isère, Grenoble,107 pp., Grenoble, France.

Raven E.K., Lane, S. N., Ferguson, R. I., & Bracken, L. J. (2009) - *The spatial and temporal patterns of aggradation in a temperate, upland, gravel-bed river*. Earth Surface Processes and Landforms, **34** (9): 1181-1197.

Reid S.C., Lane S.N., Berney J.M. & Holden J. (2007) - *The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river*. Geomorphology, **83** (1-2): 152-182.

Remaitre A., Malet J.P. & Maquaire O. (2005) - *Morphology and sedimentology of a complex debris flow in a clay-shale basin*. Earth Surface Processes and Landforms, **30** (3): 339-348.

Scheidl C., Rickenmann D. & Chiari M. (2008) - *The use of airborne LiDAR data for the analysis of debris flow events in Switzerland.* Natural Hazards and Earth System Science, **8** (5): 1113-1127.

Schlunegger F., Badoux A., McArdell B.W., Gwerder C., Schnydrig D., Rieke-Zapp D. & Molnar P. (2009) - *Limits of sediment transfer in an alpine debris-flow catchment, Illgraben, Switzerland.* Quaternary Science Reviews, **28** (11-12): 1097-1105.

Schuerch P., Densmore A.L., McArdell B.W. & Molnar P. (2006) - *The influence of landsliding on sediment supply and channel change in a steep mountain catchment*. Geomorphology, **78** (3-4): 222-235.

Veyrat-Charvillon S. & Memier M. (2006) - *Stereophotogrammetry of archive data and topographic approaches to debris-flow torrent measurements: Calculation of channel-sediment states and a partial sediment budget for Manival torrent (Isère, France).* Earth Surface Processes and Landforms, **31** (2): 201-219.