HIGH-FREQUENCY MONITORING OF DEBRIS FLOWS IN THE FRENCH ALPS

PRELIMINARY RESULTS OF A STARTING PROGRAM

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ABSTRACT

Debris-flows mobilize high sediment loads and are often responsible for most of the sediment yield from upland headwaters and may endanger the safety of life and infrastructure in the vicinity of torrent channels. Two very active debris-flow torrents with different physiographic settings have been equipped in the French Alps, the Manival Torrent (3.6 km²) and the Réal Torrent (2.3 km²). At these two sites, debris-flow monitoring systems are based on a combination of different techniques involving rain gauges, soil vibrations and flow elevation measurements and high-resolution/frequency imagery acquisition. Only flash floods with bed load transport have been observed on the Manival Torrent. Conversely, in spring/summer 2011 four meteorological events triggered debris flows on the Réal Torrent. Most of the debris fronts deposited immediately in the upstream part of the channel. Only one debris-flow propagated from the sediment source area to the basin's outlet. A 1.8 m high debris front propagated with a mean velocity of about 3 m s^{-1}. Its volume was 4,400 m^3 upstream and it increased because of bed erosion. The debris flow reached 6,100 m^3 in the middle part of the basin and then decreased slightly further downstream (8,600 m^3). These measurements highlight the interaction between the debris flow and the torrent channel in the first part of the basin. These results are in accordance with previous sediment budgets estimated for the debris flows which occurred in 2009 and 2010.

Keywords: field monitoring, geophones, video-camera imagery, sediment recharge, channel erosion and deposition.

INTRODUCTION

Small upland catchments in severely eroded areas are prone to debris flows which may endanger the safety of life and infrastructure in the vicinity of torrent channels. In France, about 4,500 municipalities are concerned with flash floods and debris flows (Bourrelier, 1997). These flows mobilize high sediment loads and they are often responsible for most of the sediment yield from upland headwaters (Bardou, 2002). Despite their importance in terms of natural hazard prevention and sediment management in upland catchments, our understanding of the mechanisms that control debris-flow initiation, propagation and deposition is still largely insufficient. This is partly explained by the paucity of field observation programs dedicated to channelized debris flows. Such programs need to

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overcome several difficulties related to the nature of the phenomena: debris flows are rapid, short-lasting, rare and destructive events that need a sophisticated and robust monitoring strategy to guarantee a performing reconstitution of natural processes (Itakura et al., 2005). Over the last 20 years, increasing efforts have been undertaken in Europe, United States and Asia to develop high-frequency debris-flow monitoring stations (e.g. Marchi et al., 2002 ; Hürlimann et al., 2003 ; Arattano and Marchi, 2008; Badoux et al., 2008; McCoy et al., 2010 ; Takahashi, 2009). In France, despite the presence of very active debris-flow torrents and a long historical legacy of torrent-control works, there are not any instrumented torrents dedicated to the study of debris flows. Furthermore, monitoring programs generally focus on flow properties at one location (velocity, stage, shear strength) mainly located in the vicinity of hillslope sources; but they rarely emphasized the downstream changing nature of a debris-flow and its interactions with the torrent channel morphology. To address this issue, two very active debris-flow torrents with different physiographic settings have been equipped in the French Alps: the Manival Torrent (3.6 km²) and the Réal Torrent (2.3 km²).

This paper presents the research aims, the main characteristics and the first results of these two debris-flow torrents equipped in late 2010 in the French Alps by the Cemagref Grenoble, in collaboration with the RTM service (*Restauration des Terrains en Montagne*) of the National Forest Office (*ONF*) and the *Conseil Général des Alpes-Maritimes*. A detailed presentation of the deployed equipments and monitoring system is proposed. At these two sites, debris-flow monitoring systems are based on a combination of different techniques involving rain gauges, soil vibrations and flow elevation measurements and high-resolution/frequency imagery acquisition. Intensive field surveys were also implemented to capture the morphological responses of headwater channels and to study channel erosion by debris flows (Theule et al., 2011). Next, we present our first monitoring results obtained during spring/summer 2011. We finally discuss these results regarding the high-resolution topographic surveys led after the largest flood events in order to provide valuable information about debris-flow processes, and notably their interactions with channels (erosion and deposition).

STUDY SITES

The Manival Torrent is a very active debris-flow torrent located near Grenoble in the Northern French Prealps (Chartreuse Mountains; Fig. 1 and Tab. 1). The close proximity to Grenoble, easy access throughout the main channel and the presence of a large sediment retention basin (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 retention basin, the mean channel slope is 16% with a drainage area of 3.6 km^2. Approximately 180 check-dams (first constructions in the 1890s) throughout the main channel and small gullies, are managed by the RTM service. An archive analysis of the Manival flood history

Tab. 1 Study sites characteristics

Torrent's Name	**Total Drainage Area (km²)**	**Elevation min-max (a.s.l. m)**	**Station Id.**	**Drainage Area (km²)**	**Altitude (m)**	**Melton Indice**	**Eroded Area (%)[1]**	**Channel Slope (m m^{-1})**
Réal	2.3	1218-2069	Réal_S1	1.3	1450	0.52	30	0.195
			Réal_S2	1.7	1340	0.54	20	0.123
			Réal_S3	2.0	1254	0.56	18	0.095
Manival	3.6	570-1738	Manival_S1	1.0	850	0.88	45	0.218

[1] unvegetated area that are potentially sediment sources; the remaining % corresponds to vegetated area

during the last two centuries showed that the torrent can produce large debris flows with volumes ranging from 10,000 to 60,000 m^3. Since 2008, the Manival has produced one debris-flow each year. A high frequency monitoring station was placed in the upper part of the catchment (referred to as Manival_S1) in order to record the initiation of debris flows near the hillslope sources (Fig. 1c and 2b).

The second monitoring site, the Réal Torrent, is located in the Southern French Prealps in the Upper Var River basin (Fig. 1; Tab.1). The 2.3 km² catchment is entrenched into thick fluvio-glacial deposits affected by intense gullying and landsliding. The torrent is known for its dramatic debris-flow activity related to very high sediment supply from hillslopes. At least one debris-flow is produced each year, generally during intense convective storms in late spring or in summer. The main channel is controlled by several check-dams which are regularly buried by channel aggradation. Three high frequency monitoring stations were installed along the torrent with a distance interval of approximately 800 m (Fig. 1). Erosion processes from hillslope sources and the debris-flow initiation area are monitored at the upstream station (also referred to as Real_S1, Tab. 1; Fig. 2a). The second station is located in the middle of the basin (referred to as Real_S2); it was installed to monitor the sediment transfer and the initiation of the debris flows originated from the remobilization of sediment deposited during past floods (Theule et al., 2011). The downstream station (referred to as Real_S3) is located near the catchment outlet in order to study the downstream transfer of the largest debris flows and the deposition of the smallest ones. Such monitoring strategy is expected to provide relevant estimations of the (1) flood and debris-flow volumes and (2) their dynamics along the torrent, i.e. their propagation across the torrent catchment in order to highlight the dynamics of sediment deposition and recharge in the channel during the floods.

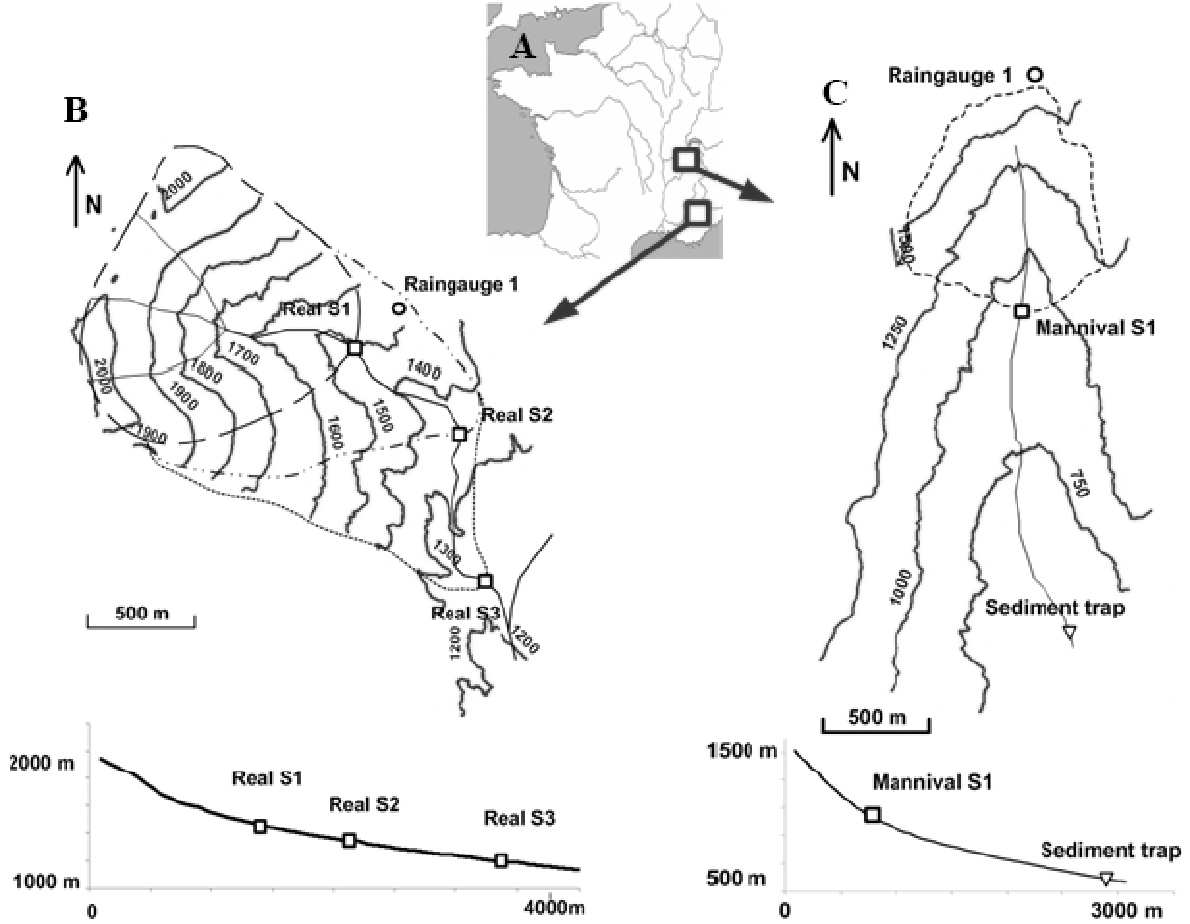

Fig. 1 Location of the study sites in France (Fig. A) with the presentation of the drainage area and the monitoring stations for the Réal torrent (Fig. B) and the Manival torrent (Fig. C). The torrent long profile is also shown for each site with the location of the stations

Fig. 2 Examples of two debris-flow monitoring stations deployed in 2010 at the Réal (Réal_S1; Fig. A) and Manival torrents (Manival_S1; Fig. B)

MATERIALS AND METHOD

All sites are located in mountainous environments with no available current power supply. An environmental datalogger CR1000 (Campbell®) was therefore chosen because of its very low energy consumption. The stations are powered by a battery (100 Ah) and a solar panel (55 Wc) providing their complete autonomy. The datalogger is constrained by its low recording frequency. In this study, we used a 5Hz recording frequency. Rainfalls were recorded with a 5 min. time step. An additional memory was used (2 Go; CFM100 Campbell®) that provides a data storage autonomy of about 80 days. The four monitoring stations have been designed in the same way (Fig. 2). Details of the installation are described below (Fig. 3).

Ultrasonic sensors and radar sensors (Paratronic®) provide the water/sediment level at the monitoring cross-section with high-frequency recordings (200 ms recording time-step) and good resolution (at least 50 cm s^{-1}). These elevations were used to compute the wetted surface area at each gauging cross-section. At the Real_S1 and Manival_S1, the gauging cross-sections are located in sections controlled by a check-dam to guarantee morphological stability of the flow section. At the two remaining sites, no check-dams were available; so flow section topography was regularly surveyed by the RTM service after each cross-section change.

The passage of the front of the debris-flow generates significant soil vibrations at the vicinity of the torrent which can be recorded with geophones (e.g. Marchi et al., 2002; Hürlimann et al., 2003; Itakura et al., 2005). In this study, at each site, we deployed sequentially three vertical geophones GS20DX0 Geospace® (natural frequency, 8Hz) near the flow section to record the front velocity of debris flows (distance interval of approximately 100 m; Fig. 3). The vibration frequency associated with debris flows generally span the range of 50 – 300 Hz (Fuang et al., 2007 ; Huang et al., 2007). A 5Hz sampling frequency attributed to the technical limitation of the datalogger is thus insufficient to directly record the signal output of the geophone, i.e. a voltage proportional to the soil vibration velocity. Therefore, an electronic interface was built to redress, filtrate (Fc=2.5 Hz) and amplify the signal output. The offset and gain of this interface can be calibrated for each geophone individually in order to take into account the soil properties of the river banks and the specific location of each geophone (as for instance, the distance from the main channel or the lithology).

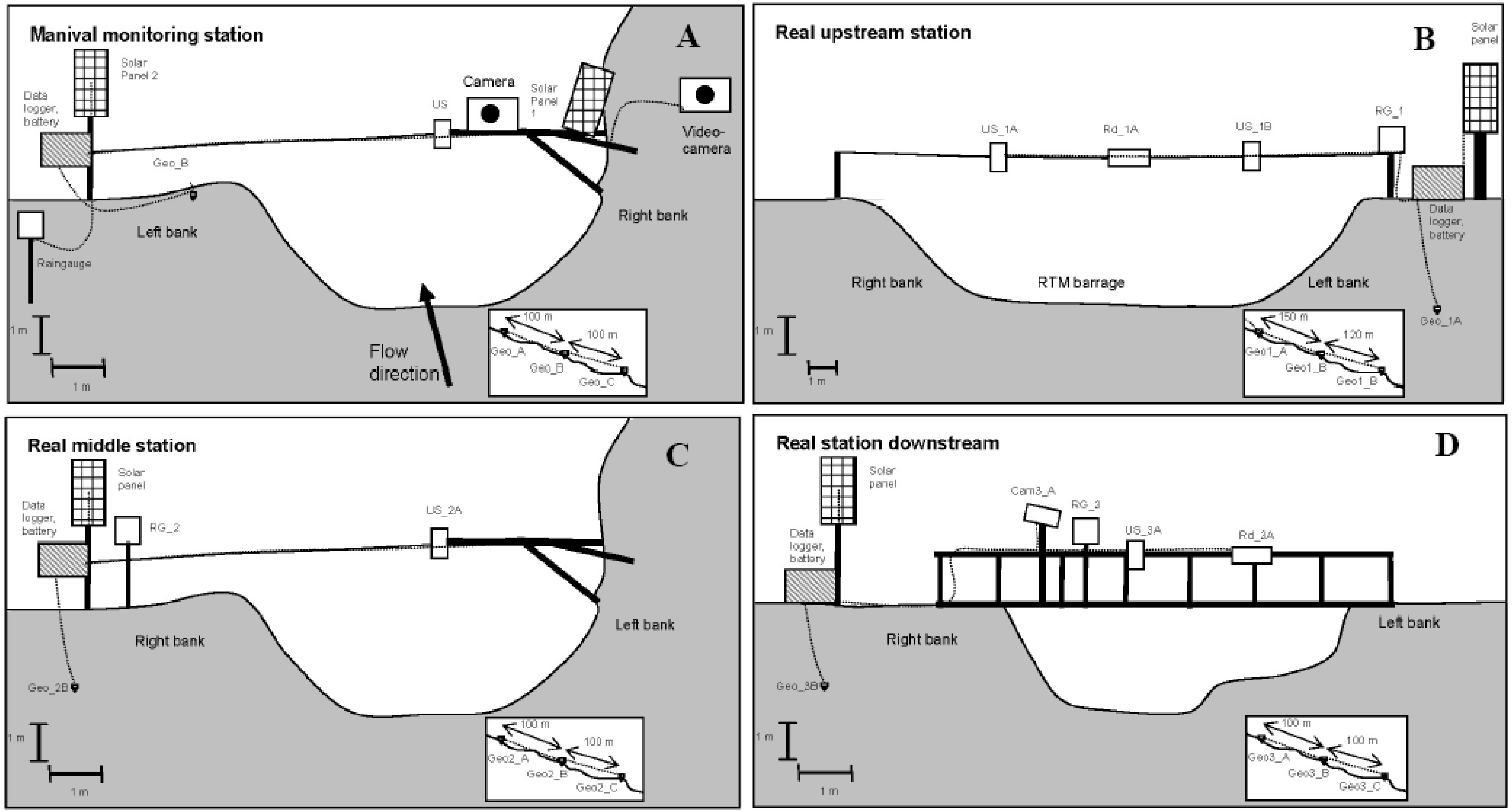

Fig. 3 Monitoring stations installed since October 2010 at the two studied torrents: the Manival Torrent station Manival_S1 (Fig. A), the Real Torrent upstream station Real_S1 (Fig. B), the middle station Real_S2 (Fig. C) and the downstream station Real_S3 (Fig. D). US, Rd, RG, Geo, Cam referred respectively to as the ultrasonic sensors, the radar sensors, the raingauges, the geophones and the camera.

Preliminary tests have been led with heavy boulders (ca. 10 kg) that were manually thrown into the torrent channel (3-4 m high) and bank falling within cross-section of a geophone (for further details see Navratil et al., in press). These tests have shown that (1) our system can record low-magnitude soil vibrations, and (2) the recordings are coherent with the excitation patterns (nature, distance from the geophone). We also found that the magnitude of the signal mainly depends on the location of the geophone (on a bank, a boulder placed on a bank, a check-dam), and also on the soil composition between the vibrating source and the geophone. The best response of the geophone was found when the sensor was fixed on big boulders inserted in a gravelly bank. Each geophone was protected with a metal plate to reduce the direct impacts of rain, hail falls and runoff; the wires were fixed to reduce the noise induced by the wind.

At two stations (Manival_S1, Réal_S3), video and video-camera systems were installed with the aims to define the nature of the flow (bed load, hyper-concentrated, muddy or granular debris-flow), and if possible, to estimate the main physical properties of the flow (water level, front velocity, surface velocity, sediment size; Genevois et al., 2001). Pictures and video imageries are triggered above fixed thresholds (in terms of water-level, geophone and rainfalls). At Manival_S1, a camera (Canon 550D, 5,200*3,500 pixels) was installed in order to take pictures of the torrent every second during the largest events. An infra-red video-camera (Sony, 680*540 pixels, 25 frame.s^{-1}) was also installed at the same location. At the Real_S3, a camera (Campbell® CC640) was installed to take a picture every 10 seconds during the flood events. The monitoring stations are visited at least every 3 weeks and systematically after large flood events. A GSM communication was installed at each station in order to send a SMS alert when a heavy rainfall occurs, and to collect data samples each day to the office (5 min. time step recordings). This procedure allows for checking regularly the status of the monitoring stations from the laboratory to avoid missing data.

To estimate the discharge and flood volumes during flash flood events, a rating curve was built at each station. Discharge measurements at low-flows, surface velocity measurements at higher flows and a hydraulic model (HEC-RAS; USACE) were used at the stations located near a check-dam (Réal-S1, Manival_S1). At the two remaining sites, the critical water depth was used to estimate the flow discharge. During debris-flow, the mean front velocity was estimated by considering the time shifting between the signals of the three geophones and the distance between geophones. Variations of velocity with time were then estimated by the identification of similar patterns between geophone signals – e.g. peak vibration that can be clearly identified for each geophone.

RESULTS AND DISCUSSION

Respectively ten and six flash floods with bed load transport were observed in spring/summer 2011 at Réal and Manival torrents. Peak discharges were found less than 1.5 m^3 s^{-1}. These flood events were associated with moderate rainfall volumes (on mean, 20 mm on the Manival and 9 mm on the Réal) and low maximum rainfall intensities (on mean, 10 mm h^{-1} on the Manival and 15 mm h^{-1} on the Réal). They were insufficient to trigger a debris-flow. It also corroborates with past field observations of flash floods and debris flows in these two torrents (Fig. 4).

No debris-flows were observed in the Manival Torrent. On 17 July 2011, even with favorable soil moisture conditions (45 mm during the preceding month) and rainfall for triggering a debris-flow (total volume of 38 mm with maximum intensity of 27 mm h^{-1}), only a flash flood occurred with a peak discharge of ~1.5 m^3 s^{-1}. The low sediment recharge observed in the sediment sources area and the headwater channels would explain why a debris flow did not occur. This deficit could be attributed to the low snowfall in winter 2010-2011 (40 cm of cumulated snowfall in winter 2010-2011, against 76 cm and 80 cm in winter 2008-2009 and 2009-2010 respectively) that would have in turn reduced the erosion activity on hillslopes. It could also be attributed to the low rainfalls in spring 2011 (total volume of 70 mm in 2011, against 130 and 240 mm respectively in 2009 and 2010).

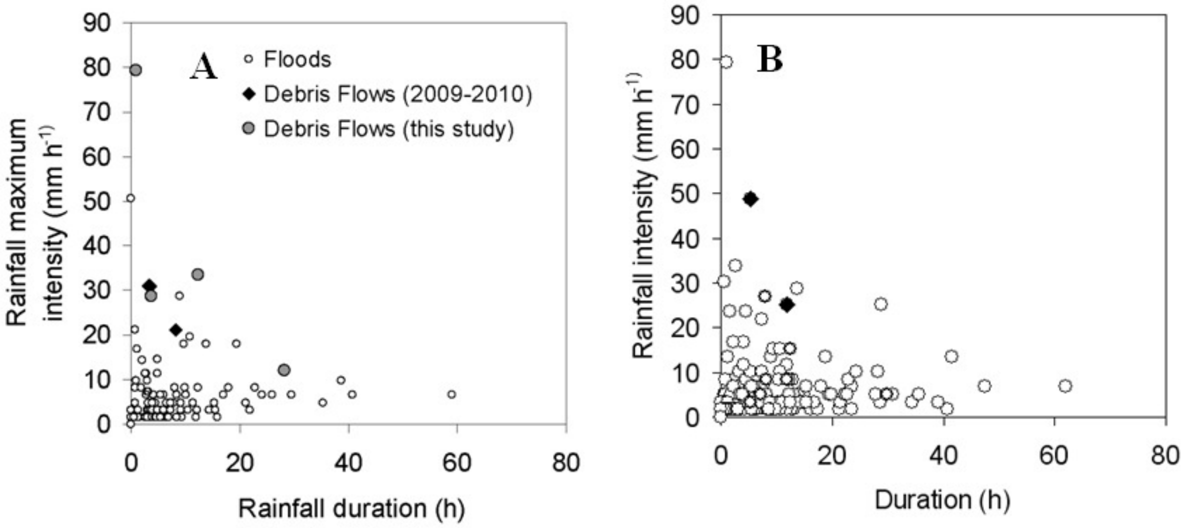

Fig. 4 Rainfall thresholds to trigger debris flows in the Réal Torrent (Fig. A) and in the Manival (Fig. B); for the case of the Manival Torrent, the debris occurred before the monitoring period.

Conversely, freeze-thaw cycles were not significantly different from past winters (about 120 days with sub-zero temperatures). These observations outline the need to consider the antecedent conditions, not only in term of soil moisture but also in term of eroded sediment availability in the source areas.

In the Réal Torrent, four meteorological events have triggered debris flows between April and July 2011. The first three events occurred between the end of April 2011 to the beginning of June 2011. Their rainfall volumes are less than 47 mm, with maximum intensities less than 34 mm h^{-1}. Debris-flows with multiple surges (2-3) were measured at the upstream station (Real_S1), i.e. the closest station from the sediment sources area (Fig. 1). The debris flows were about 0.3 m high with velocities generally lower than 1.5 m s^{-1}. The volumes of each of these debris flows did not exceed 300 m^3. Most of them deposited rapidly in the main channel between Réal_S1 and Réal_S2. Among these three events, only one debris-flow which occurred on 5 June 2011, has propagated downstream and reached Réal_S2. However the surge stopped just downstream from this monitoring station.

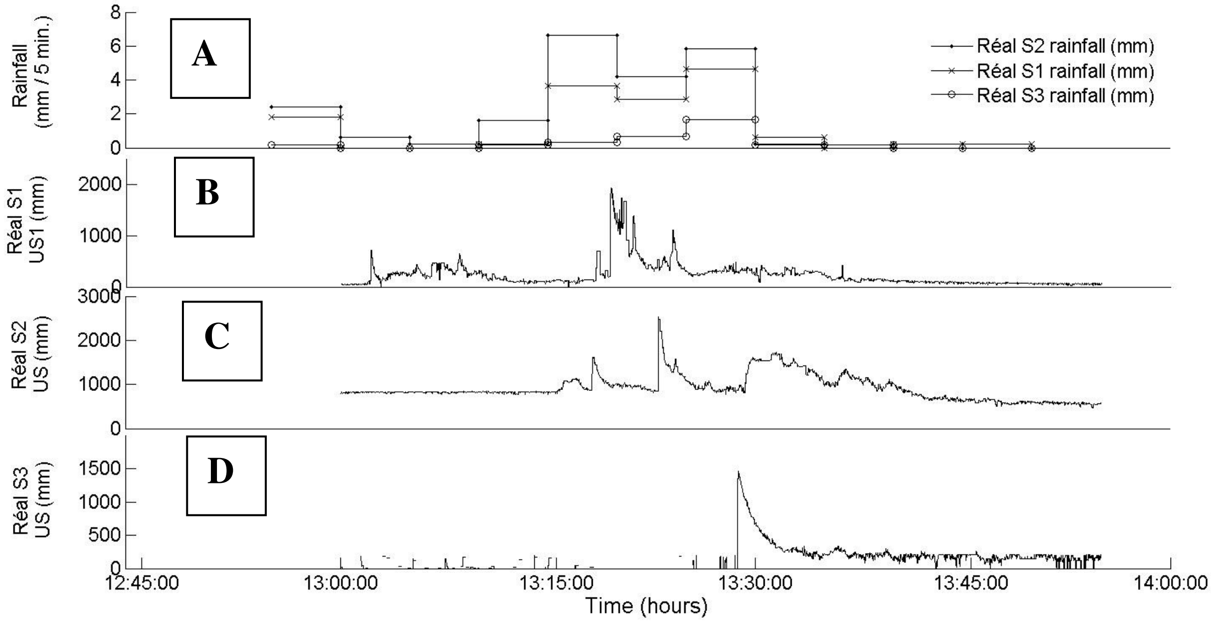

Fig. 5 The 29 June 2011 debris-flow observed in the Réal Torrent. Rainfalls distribution recorded at the 3 stations (Fig. A). Hydrogram recorded at the 3 stations (in mm; Fig. B, C and D).

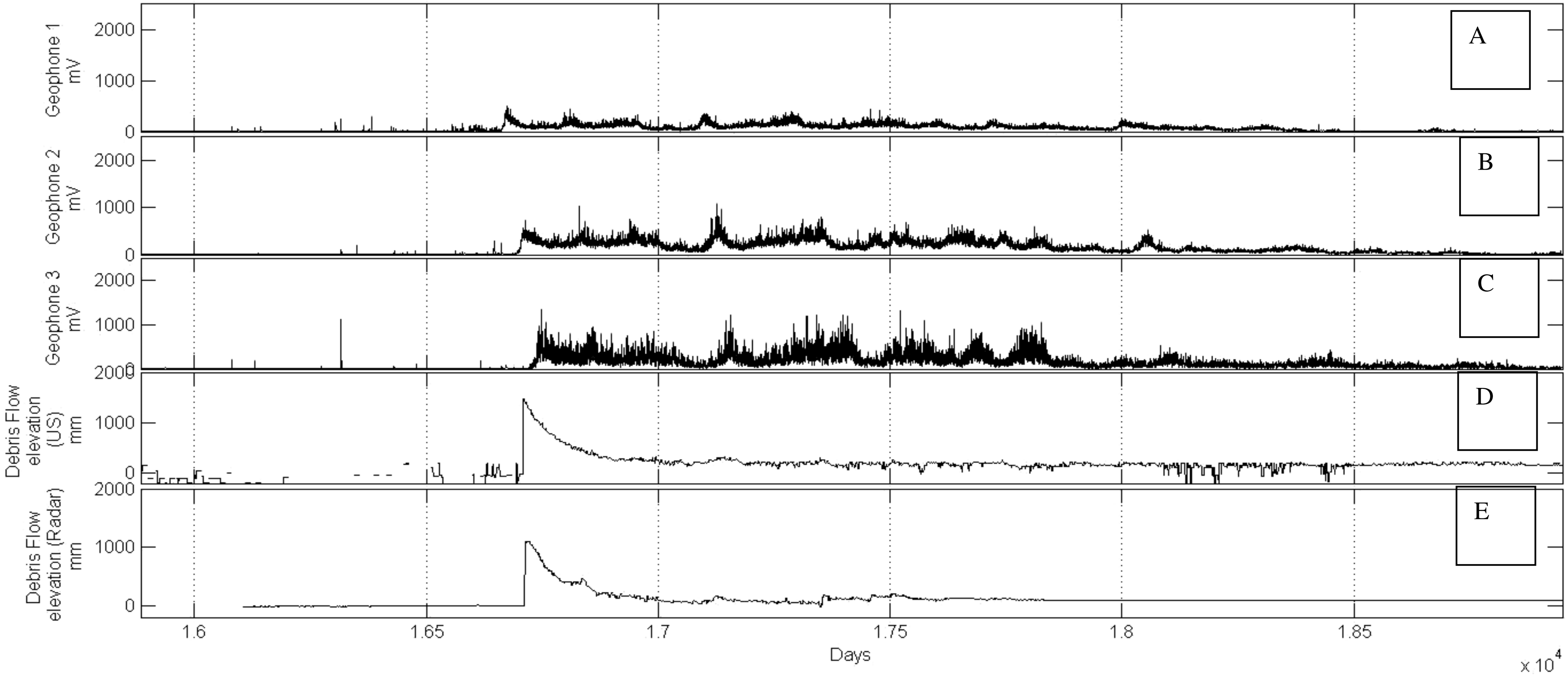

Fig. 6 Recordings at the downstream monitoring station, Réal_S3, the 29 June 2011. Geophones' signals are presented from upstream (Geophone 1; Fig. A) to downstream (Geophone 2 and 3; Fig. B, C), water level measurements are provided for the ultra-sonic (Fig. D) and the radar sensors (Fig. E).

On 29 June 2011, a fourth and larger debris-flow occurred, triggered by a one hour heavy downpour with hail fall. The main surge propagated from the source area downstream all the way out into the Tuébi Torrent (Fig. 1b). Despite the small surface area of the studied catchment (2.3 km²), the precipitation was found heterogeneously distributed. It mainly occurred in the upper part of the catchment, near the source areas and the summit. The precipitation shows a well-marked downstream gradient, i.e. a volume of ~40 mm and a maximum intensity of ~80 mm h^{-1} was recorded at Réal_S1, against a volume of 12 mm and a maximum intensity of ~5 mm h^{-1} at Réal_S3 (Fig. 5a). At Réal_S1, the debris-flow was composed of two debris surges (i.e. defined by well-marked gradient on the hydrograms), and 3 waves that we associate to hyperconcentrated flows (i.e. defined by a smooth shape of their hydrograms; Fig. 5b). The largest debris surge was 1.8 m high and propagated with a mean velocity of 4.2 m s^{-1}. The total volume of the event was ~4,400 m^3, with a maximum discharge of ~32 m^3 s^{-1}. Downstream Réal_S2, the main surge has slowed down and it has propagated along the channel between Réal_S1 and Réal_S2 with a maximum velocity of about 3.4 m s^{-1}. The debris-flow volume slightly increased with sediment erosion along the main channel and reached a total volume of ~6,100 m^3 at the middle station Réal_S2. The debris-flow height did not change significantly (1.7 m), whereas the peak discharge was half (~50 m^3 s^{-1}). At this station, the flow is composed of three debris-flow surges and six hyperconcentrated waves (Fig. 5c).

At station Réal_S3 (Fig. 5d, 6), a more “mature” flow was observed, i.e. a single debris front (1.6 m high; peak discharge of ~33 m^3 s^{-1}) followed by a long (30 minutes) and smooth recession curve (Fig. 6). The different surges identified at the upstream stations can no longer be identified on the downstream hydrogram. The total volume of the debris-flow slightly increased (~8,600 m^3). Thus, the sediment budget of this event gives evidence of a massive transfer of the sediment eroded from the upper part of the catchment to the downstream part of the catchment.

At this station the debris front propagated at 2.7 m s^{-1} (Fig. 7). Many other fluctuations have been identified on the signals of the three geophones. The same shape patterns could have been recognized from one signal to another (Fig. 6), thus each peak of vibration was used to calculate the flow velocity during the debris-flow (Fig. 7). We found that the flow velocity decreased rapidly and reached 0.5 m s^{-1} at the end of the event. This trend however hides important fluctuations (~110% of variation). These fluctuations have a mean period of oscillation of about 5 minutes. They could traduce short-lasting and periodic pulsations in terms of sediment density and/or size.

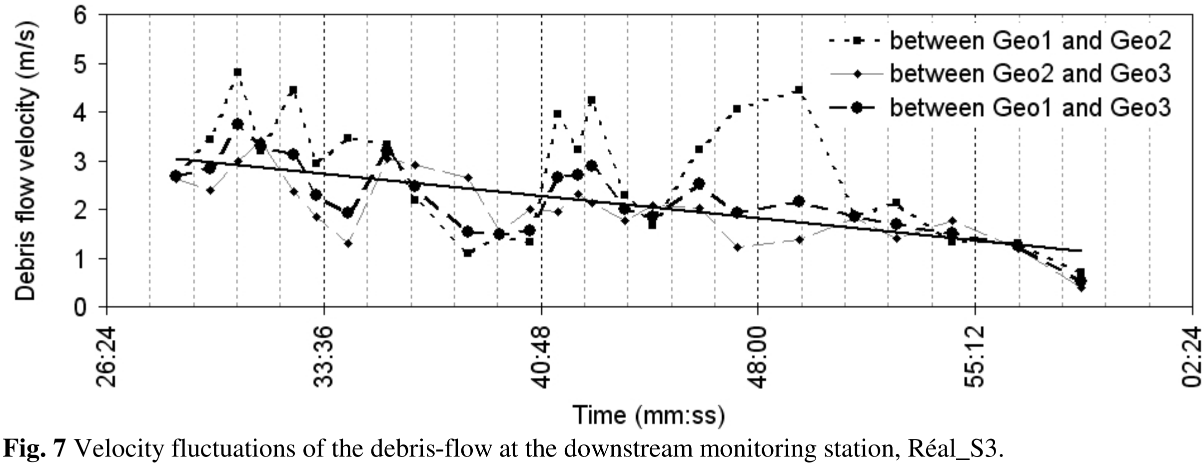

Fig. 7 Velocity fluctuations of the debris-flow at the downstream monitoring station, Réal_S3.

The trend of debris-flow volume derived from the monitoring stations in 2011 is in good agreement with the previous trends of volume change derived from morphologic monitoring of debris-flows in 2010 (Theule et al. 2011; Fig. 8). In 2010, fifteen cross-sections were surveyed before and after every event with the cumulative sediment budget deriving the total debris-flow volume at each point (debris flows presented at Fig. 4a). Even with the 2011 event being quite larger than 2010 events, there is a spatial consistency of growth and depletion of volumes (Fig.8).

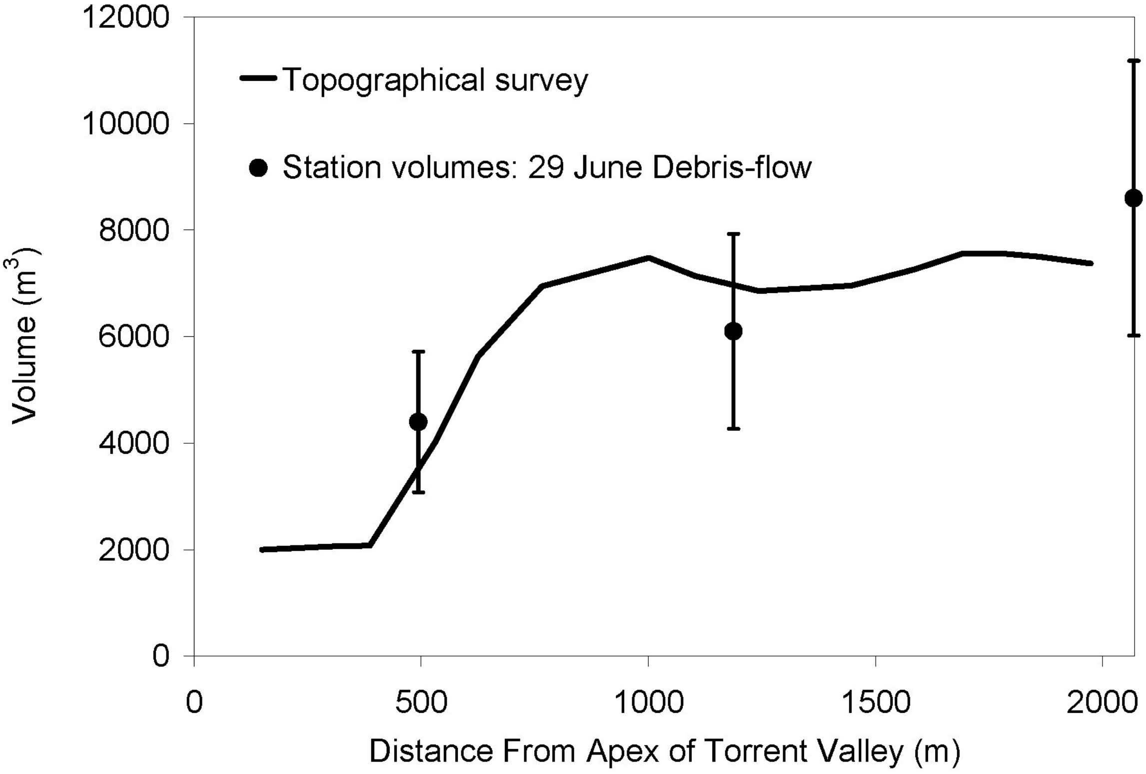

Fig. 8 The progression of debris-flow volumes in the Réal derived from monitoring stations (2011 event) and event-based cross-section surveying (2010 events).

CONCLUSION AND PERSPECTIVES

Four debris-flow monitoring stations have been installed in two French Alps torrents. These torrents show very active production of sediment with about 2-3 debris-flow observed each year. For the moment, four debris-flow events have been monitored at the Réal Torrent. The first recordings obtained are encouraging. On one hand they validate the design of the monitoring station and their robustness. On the other hand, good quality recordings were obtained during the firsts debris flows observed. We are now waiting for debris-flow at the Manival Torrent to test the fourth monitoring station and the imagery system.

We will carry on with these analyses and will focus on the geophone/water level signals processing (e.g. cross-correlation, energetic analysis). These analyses are expected to provide valuable information on debris-flows and its physical properties (e.g., volume variations, rheology). Meteorological radar data and topographical data are also expected to help us to better define the propagation of the debris-flow from sources area up to the basin outlet, and particularly, to obtain information about the seasonality and interaction between flash floods/debris flows and the channel morphology.

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