Landslides
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Recent debris flows in the Portainé catchment (Eastern Pyrenees, Spain): analysis of monitoring and field data focussing on the 2015 event

Abstract During the night of the 21 August 2015, a debris flow took place in one of the presently most active ravines of the Pyrenees, the Portainé torrent (Eastern Pyrenees, Spain), and caused considerable damage to the road. Detailed information was gathered from the debris flow monitoring system recently installed in the torrent and field surveys. The monitoring system measures ground vibration at geophones and flow height at an ultrasonic sensor. Meteorological data showed that the debris flow was triggered by a convective rainstorm with a total rainfall amount of 29 mm. All these data provide information on the debris flow occurrence and dynamics. The analysis of the data showed that the debris flow had three different surges and mobilised a total volume of about 2130 m^3. The front velocity in the monitoring reach was somewhat small (about 2 m/s) and the peak flow discharge comparatively low (about 13 m^3/s). In addition, the debris flow was back-analysed by a numerical model calibrated by the observed event. The results of the simulation showed that a Voellmy fluid rheological model can represent considerably well the recorded and observed measurements, and the best-fit values were μ = 0.28 and C = 8 $m^{0.5}$/s.

Keywords Debris flows · Monitoring · Rainfall · Portainé catchment · Pyrenees

Introduction

Debris flows represent a significant geomorphological hazard in mountainous regions (Hungr et al. 2014). Their capability to move downhill at very high velocities and their huge mass results in high impact forces which have the potential of damaging elements at risk.

In the Pyrenees, debris flows and shallow landslides are not as widely reported as in other mountainous areas, but still represent an important hazard (Lorente et al. 2003; Portilla et al. 2010). Rainfall-triggered landslides that have occurred in the Eastern Pyrenees have usually been analysed on a regional scale (Gallart and Clotet 1988; Santacana et al. 2003). The majority of these regional studies focus on the catastrophic 1982 rainstorms (Corominas and Alonso 1990), neglecting a detailed analysis of individual events. In conclusion, there is still a lack of information regarding debris flow initiation, flow behaviour and hazard analysis in the Eastern Pyrenees.

In the last years, important efforts have been carried out to study the debris flow hazards in the Central-Eastern Pyrenees. Field observations (Portilla et al. 2010; Abancó and Hürlimann 2014), the installation of monitoring systems (Hürlimann et al. 2014), the analysis of historic MORLEs (Portilla 2014) or susceptibility assessment (Chevalier et al. 2013) have strongly improved the understanding of debris flow process in the cordillera. Especially the Rebaixader monitoring system revealed important information on the initiation and flow dynamics of torrential flows (Hürlimann et al. 2014). The trigger of most events was associated with short, high-intensity rainstorms in summer, but some were also generated in spring associated with snowmelt.

The Portainé basin is of special interest, since debris flow activity has considerably and abruptly increased during the last 10 years, though details on the reasons for the changes are still unclear. An important fact, which may be related to this increase in torrential activity, may be the existence of a ski resort located in the upper part of the catchment and affecting the natural geosystems in different ways (Furdada et al. 2016). As a consequence of the damages caused by the recent frequent debris flows, 11 flexible ring nets have been installed during the last 6 years (Raïmat et al. 2010; Luis-Fonseca et al. 2011).

The major goal of the present paper is to present and analyse the monitoring data and field observations of the recent Portainé debris flows focussing on the 21 August 2015 event. This information not only improves the understanding of the Portainé torrential dynamics but also increases general knowledge on debris flow characteristics.

Description of the study site

The Portainé torrent (ETRS89 42.4372°N, 1.2093°E) is located in the Eastern Pyrenees at the north side of the Orri massif (Pallars Sobirà County, Spain; Fig. 1). A ski resort is situated in the headwaters of the Portainé basin, which was constructed and enlarged between 1970 and 1986. Its access road ascends to an elevation of 2000 m asl and crosses the torrent at various points. A hydropower power station retention dam is located downstream, where the torrent reaches the Santa Magdalena River.

Morphology, geology and climate

The Portainé basin covers a total drainage area of 5.72 km^2, and its altitude ranges from 950 to 2439 m asl. The basin drains towards the north and Portaine torrent is confluent with the Santa Magdalena River. The Melton ratio is 0.62 and the relief ratio is 0.3. The analysis of the morphometric parameters of the catchment indicates that the Portainé basin is susceptible of generating hyperconcentrated flows (Wilford et al. 2004).

From a geological point of view, the Portainé stream is located in the Pyrenean Axial Zone, and is part of the Orri Dome, a Hercynian WNW-ESE oriented antiform thrust fault structure. It consists of metamorphic Paleozoic materials (ICGC 2015). The Portainé area bedrock is exclusively formed by folded and largely fractured Cambro-Ordovician metapelite, sandstone and greywackes. The bedrock is in a great part covered by unindurated Quaternary detrital deposits of variable width (more than 10 m in

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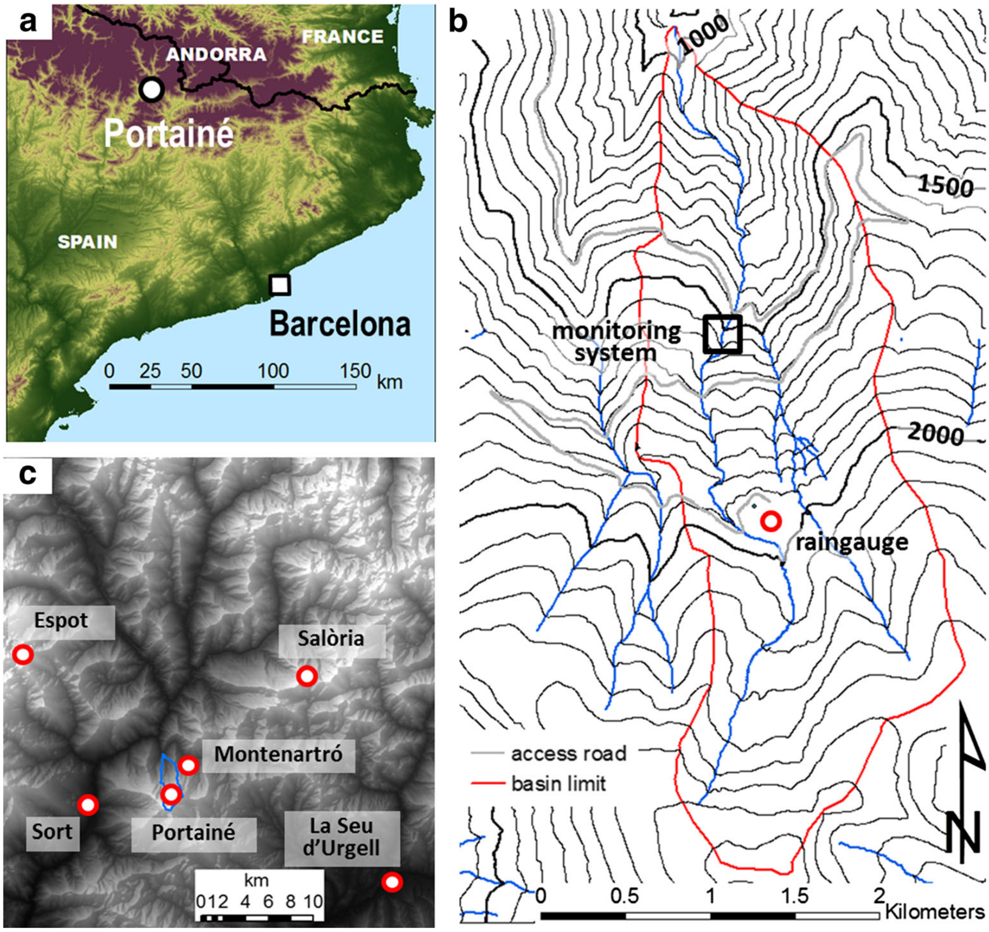

Fig. 1 The Portainé basin. **a** Situation of the basin in the Eastern Pyrenees. **b** Topographic map. The *red* point indicates the location of the Portainé rain gauge inside the basin. The area of Fig. 3 is given by the *rectangular*. **c** Shaded relief with regional extension indicating the locations of the rain gauges used in this study

some road cuts) rich in clasts of metapelites and sandstones. These unconsolidated surficial deposits are very erodible. Furthermore, the highly fractured and surficially weathered Paleozoic bedrock can also be easily mobilised and eroded. These conditions let assume that the sediment availability for the Portainé torrent can be considered to be almost infinite and the basin can be classified as "transport-limited" after Bovis and Jakob (1999).

In the Portainé area, the climate is oceanic with an annual average rainfall of 900 mm, with maxima during spring and summer. The mean annual air temperature is of 5 to 7 °C, and the thermal amplitude of 14 to 16 °C (Martín Vide and Olcina Cantos 2001). Regional weather is influenced by three major factors: the vicinity of the Mediterranean Sea, the influence of the North Atlantic west winds and the orographic effects of the Pyrenean mountain range. Two general types of precipitation patterns that trigger rainfall-induced slides and flows can be distinguished: (1) long duration and moderate-intensity precipitation in autumn, winter and spring and (2) convective, short and high-intensity rainstorms in summer.

Monitoring system

The monitoring site is located upstream from the point at 1450 m asl, where the Portainé torrent crosses for the second time (Road 2 in Fig. 4) the ski area access road (see Figs. 1c and 2). The monitoring program was installed in July 2015.

The Portainé monitoring station is similar to the one used in the FLOW-WR station of Rebaixader monitoring site, located in the Central Pyrenees (Hürlimann et al. 2014). The station consists of four unidirectional geophones (Geospace 20 DX), measuring vertical ground velocity, and an ultrasonic device (Pepperl + Fuchs 30GM), which measures flow depth. All devices are connected by wires to a datalogger (Campbell Scientific CR1000). Geophones are mounted inside a metal box installed on bedrock, within 3 m of the right (downstream) channel bank. The location of each device is illustrated in Fig. 3. Data are transmitted to the server at the University in Barcelona via a GSM modem. Power is supplied to the station by means of a 12 V-22 A battery, powered by a solar cell.

Ground vibration detected by the geophones is directly transformed by an electronic signal conditioner into a number of impulses per second (IMP/s). The datalogger scans the number of impulses at the geophones each second (IMP/s) and checks if a given threshold is exceeded in any of the geophones (Hürlimann et al. 2014). In which case, the station switches to a high-frequency recording mode ("event" mode) with a sampling frequency of 1 s, for the geophones and the ultrasonic sensor. Otherwise, data is cumulated and recorded every 60 min. The threshold was set to 20

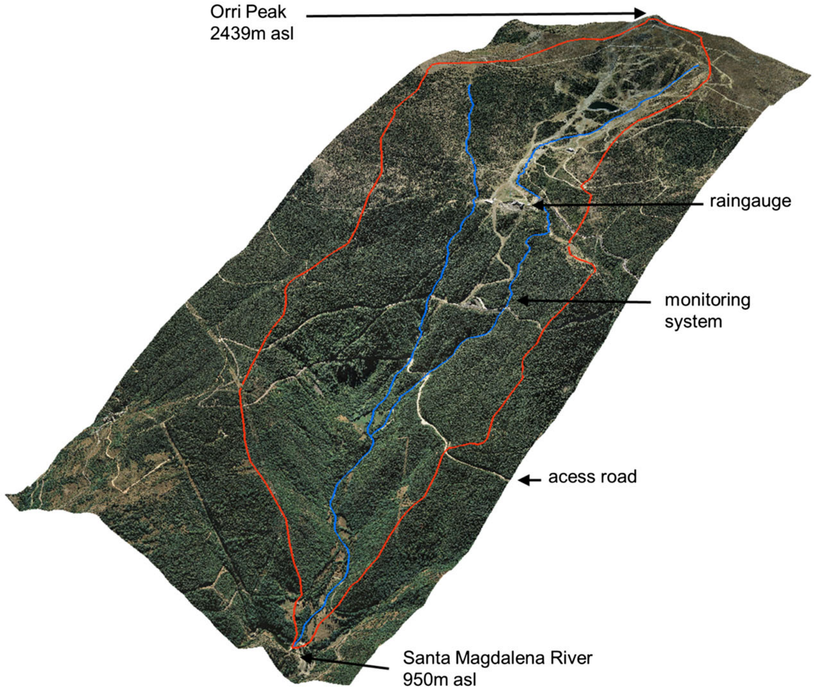

Fig. 2 Aerial photographs draped over the digital elevation model

IMP/s during three consecutive seconds based on the experience obtained in the Rebaixader test site. The use of a recording threshold allows reducing the amount of data to be processed and to minimise false positives (i.e. false alarms in a warning system). Further details on the technical aspects of the monitoring system can be found in Hürlimann et al. (2014).

Recent and historic debris-flow activity

Torrential events in the Portainé basin produce significant economic damage, especially at points where the road crosses the torrent. Some information of important historic events is available, but none prior to 2006 (except for 1982).

The interpretation of aerial photographs back to 1946 did not reveal major visible morphologic changes in the torrents during the twentieth century, and the riverbed seems to be stable without intense erosive processes. The destruction of a road bridge in the 60s was historically reported, but there is no information that allows a correct interpretation of the trigger. In 1982, a catastrophic rainfall event provoked thousands of landslides and some debris flows in the Pyrenees (e.g. accumulation of sediments at the confluence of the Santa Magdalena River with the Noguera Pallaresa River; Balasch et al. 2008). Fañanás et al. (2009) elucidate the possible occurrence of a debris flow in the Portainé torrent. However, since 2006, 10 documented debris flood and debris flow events have occurred in this basin (Table 1), showing an annual recurrence.

In order to better characterise the torrential dynamics of the study area, dendrogeomorphological techniques have been carried out in the downstream part of the Portainé torrent, near the confluence with the Santa Magdalena River (García-Oteyza et al. 2015; Furdada et al. 2016). These ongoing studies revealed that there were multiple indicators (scars, anomalous tree ring growth and other evidences) of intense torrential processes corresponding, at least, to 10 well-determined events that occurred in the periods of 1969–1970, 1973–1974, 1976–1977, 1982–1983, 1992–1993, 1997–1998, 1999–2000, 2005–2006, 2007–2008 and 2009–2010, and five other events with less reliability and evidence. Therefore, dendrogeomorphology allowed us to clearly detect a recurrence interval of about 4 years between 1970 and 2006 (Furdada et al. 2016). Moreover, comparing the occurrence of the torrential flows until 2006 and since that year (recurrence of 1 year), it can be suggested that their frequency has greatly increased in the last 10 years.

Regarding the very active period between 2006 and 2015, debris floods and debris flows were detected in the trees located near the confluence of the Portainé torrent and the Santa Magdalena River. Dendrogeomorphological techniques allowed us to affirm that 2008 debris flow is one of the largest events. We identified 20 injuries in different tree species, many tree growth reductions (suppressions) and the most numerous quantity of growth asymmetries amongst all the detected events in the confluence area. Events that occurred in 2010 were also clearly detected in trees by means of six dated injuries and subsequent suppressions. The last 2015 event could not be analysed using dendrogeomorphology as it did not reach the area where dendrogeomorphologic techniques were applied. According to Furdada et al. (2016) and Victoriano et al. (2016) from 2006 and especially in 2008 and 2010, and due to the coincidence of intense rainfalls with earthworks in the ski resort for the construction of an artificial water pond for snowmaking, the stable equilibrium of the Portainé basin changed. As a result of several factors such as the loss of vegetation cover, there has been a drop-off in the infiltration capability. Therefore, discharges at the initial part of the torrent increase in response of intense storms (Furdada et al. 2017), leading downstream to high sediment load flows. In order to solve this

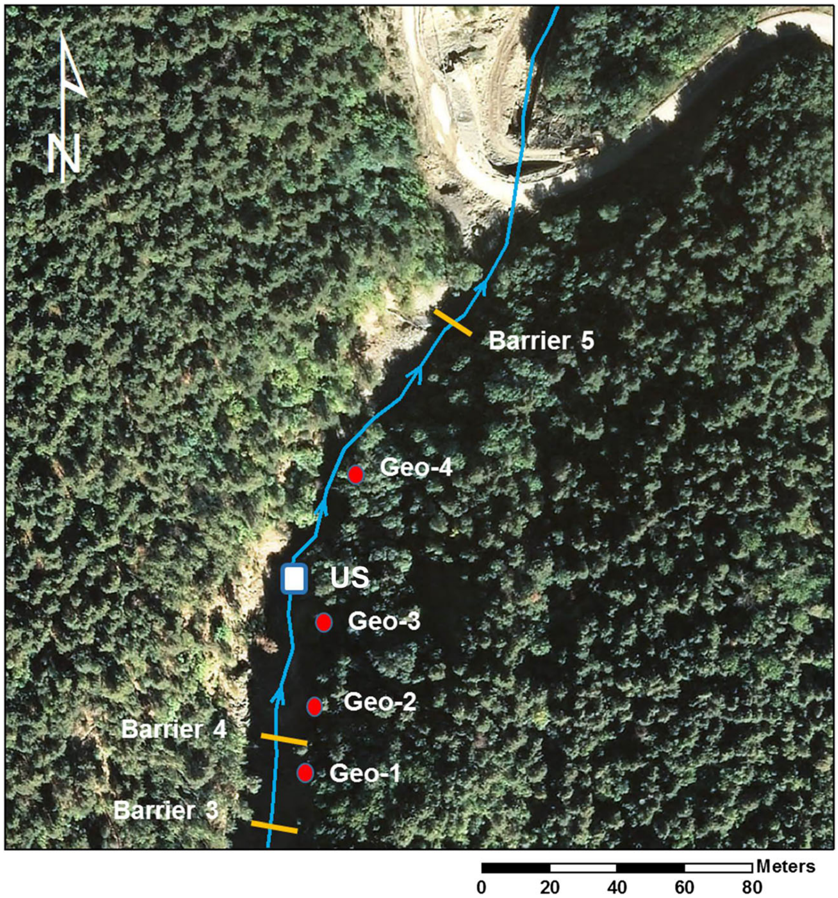

Fig. 3 The Portainé monitoring station. Locations of the four geophones and the ultrasonic device (US). In addition, the three flexible barriers installed in this torrent reach are shown

problem that produces economic damages where the flow crosses the road, several measures have been carried out along the Portainé torrent.

Since 2009, in the upstream part of the Portainé torrent, woods are placed transversally to create a stepped channel. However, the most effective measures are the flexible ring-net barriers. In 2010, seven

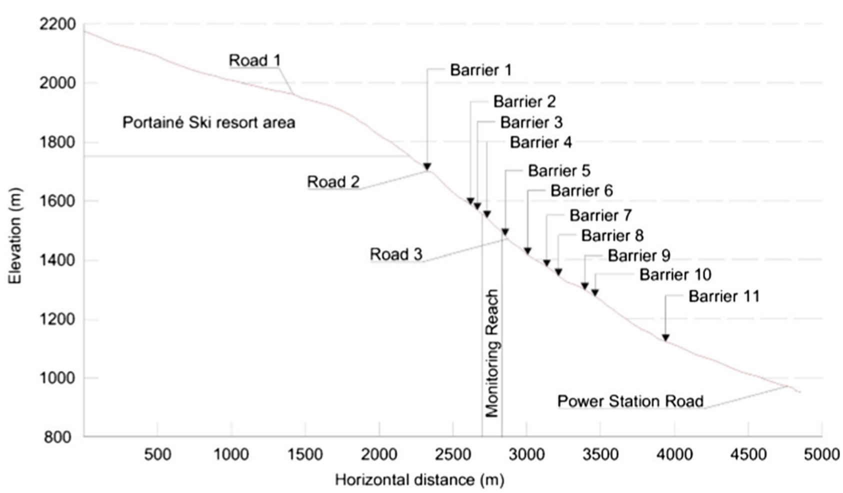

Fig. 4 Topographic profile of the Portainé torrent indicating the location of the ski resort, debris flow barriers, road crosses and the channel reach, where the monitoring system is installed

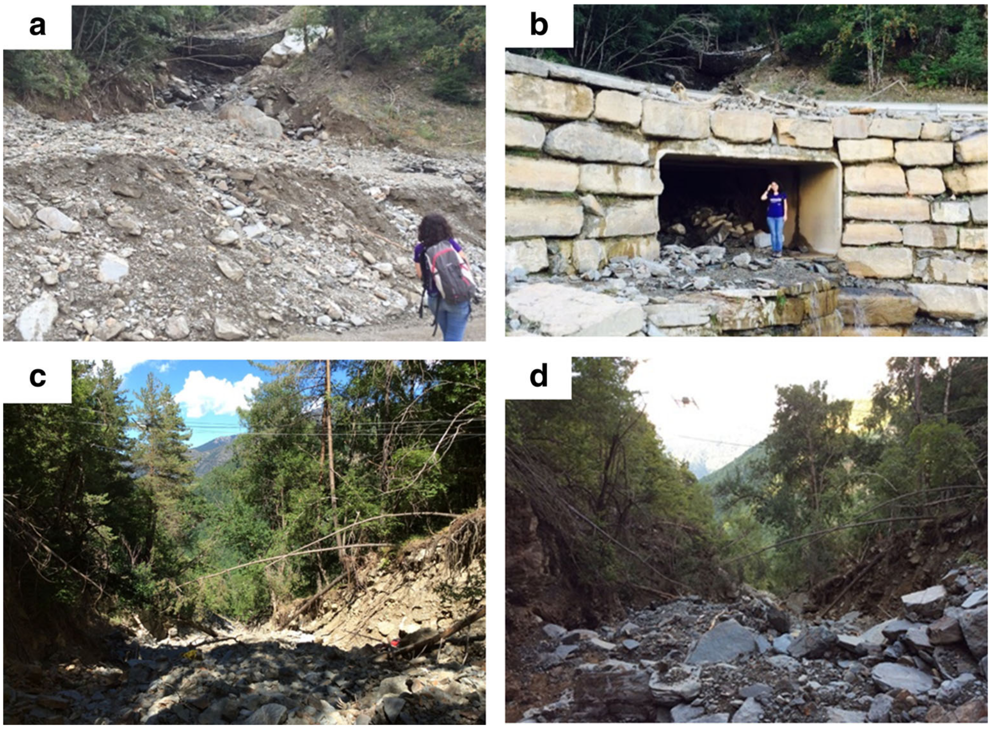

Fig. 5 Field observations of the 2015 debris flow. **a** Sediment deposited on the road cross after the 2015 even. Barrier 5 can be observed in the *upper part* of this photo. **b** Obstructed road culvert. **c** Section of ultrasonic device before the 2015 debris flow. **d** Section of ultrasonic device after the 2015 debris flow

barriers were installed along the torrent. Each of these barriers are 4–6 m high and 12–24 m wide, and their design loads correspond to a retention volume of 15,000–20,000 m^3 (Fañanás et al. 2009). Three months after their installation, a debris flow was triggered during the 22–23 July rainstorm (Table 1) and accumulated a total volume of 25,000 m^3 in these structures (Raïmat et al. 2010; Luis-Fonseca et al. 2011). The barriers prevented the road and the electric plant located at the confluence with the Santa Magdalena River from damage. However, on 12 August 2010, another event took place damaging some of the recently installed barriers, depositing material and damaging the road to the ski resort (IGC 2010). In 2012, four new barriers of same characteristics were installed in reaches of the Portainé torrent where erosive processes were most active. All these measures have not prevented the occurrence of flows and the torrent is still very active.

This high frequency of events in the Portainé torrent during the last 10 years is the reason for installing the monitoring system described in this article. The factors that made Portainé torrential dynamics change, from little debris flow activity to the present occurrence of one or two events per year, are still unknown and generate controversy.

The 2015 debris flow

Three types of data were used for the analysis of the 2015 debris flow: (1) geomorphological field observations, (2) data recorded by the sensors of the monitoring system and (3) precipitation records form meteorological stations.

Field and monitoring data

Regarding the monitoring data that focus on the debris flow dynamics, flow depth measurements and ground vibration from two of the four installed geophones are available. Data from the other two geophones could not be included, because of system malfunctioning.

Ground vibration measurements as well as information recorded by the ultrasonic device can be used to determine the exact time of the debris flow. In addition, an estimate of the mean flow velocity between each sensor can be obtained. Finally, field and monitoring data were used to estimate the debris flow discharge and an approximated volume.

During the night of the 21 August 2015, a convective storm took place in the Noguera Pallaresa River valley. Most probably, this intense rainstorm led to a runoff peak in the Portainé torrent, which caused sediment entrainment in the steep channel bed, in very erodible materials (see Figs. 3, 4, and 5). Since the road culvert at 1700 m asl was not blocked, most volume was incorporated along the channel reach between that culvert and the monitoring system. A debris flow with three surges passed the monitoring reach at about 1500 m asl and finally, stopped at the road cross at 1450 m asl. Almost the total amount of mobilised sediment accumulated at the road or just upstream of the blocked culvert (Fig. 5). The maximum deposition height was about 2.5 m, and a rough estimate of the accumulated volume in this area is of about 2000 m^3.

During the post-event field surveys, mud and erosion marks were observed along the debris flow trajectory. Thus, flow cross sections were measured. Boulders up to 1 m were transported during the event.

The ground vibration, which was provoked by the moving debris flow, triggered the monitoring systems at 21:52. The flow lasted for about 20 min and was composed by three different

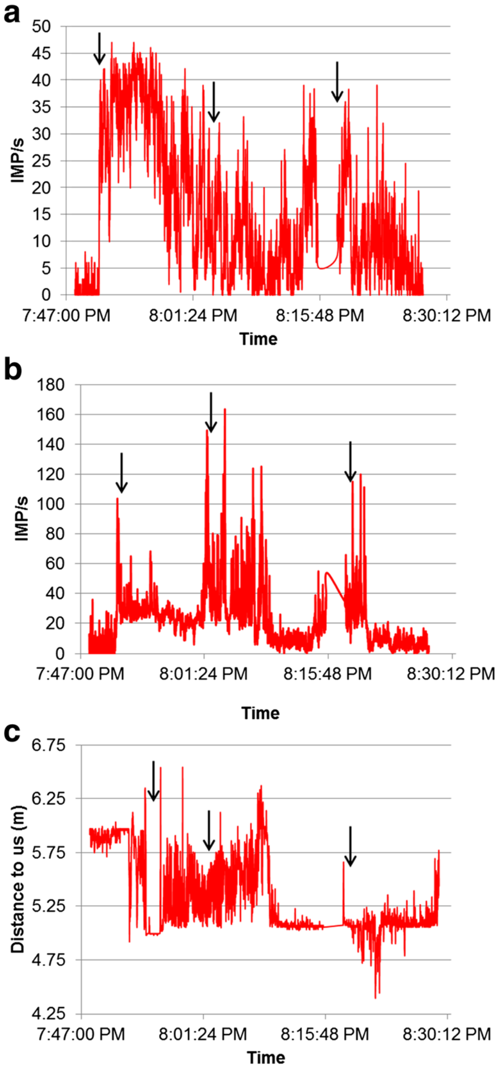

Fig. 6 Monitoring data registered during the 2015 debris flow. **a** Data recorded by Geo-3. **b** Data recorded by Geo-4. **c** Data recorded by the ultrasound (US) sensor. The *black arrows* indicate the beginning of the first, second and third surges

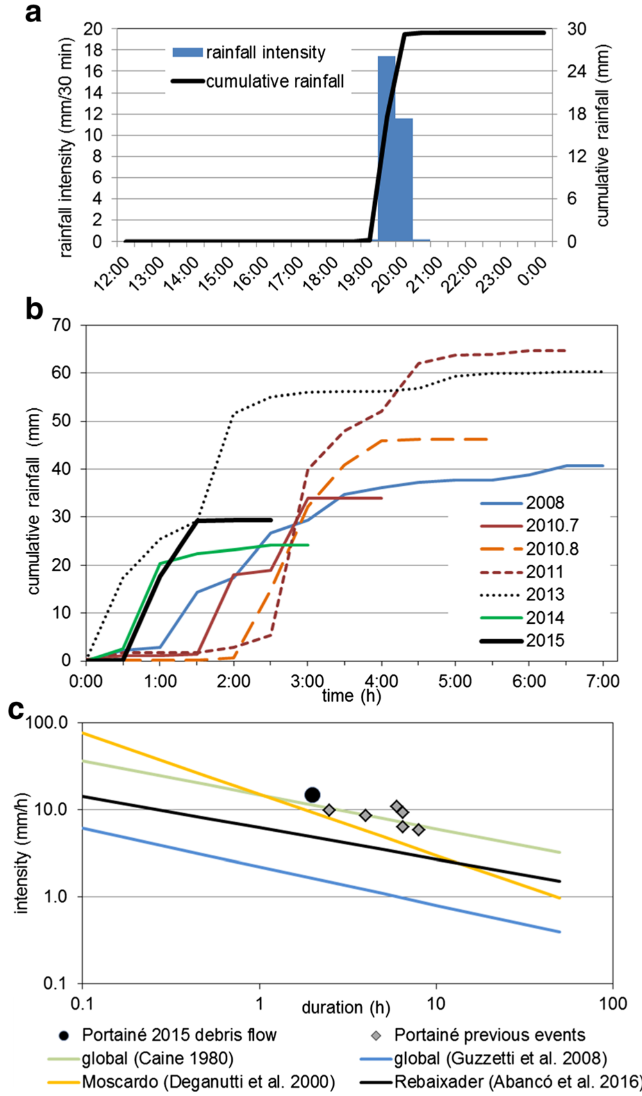

Fig. 7 Analysis of the triggering rainfalls. **a** Data of the 2015 debris flow. **b** Rainfall hyetographs of the recent debris flows. **c** Intensity–duration relationships of the recent debris flows and comparison with existing thresholds

surges (Fig. 6). The data registered at the two undamaged geophones (Geo-3 and Geo-4) and at the ultrasonic device revealed typical debris-flow characteristics (important ground vibration, the existence of three different surges and sharp increase of ground vibration at the front of each surge). At these sensors, three surges can be detected: the first surge lasting the longer, 11 min; the second surge lasting 8 min; and the third lasting only 2 min.

Velocity estimates were obtained from the measurements recorded at the geophones and the ultrasonic device. The distances between the sensors and the time intervals between the recorded peaks revealed mean velocities of about 1.7 m/s for the first surge, 1.9 m/s for the second surge and 2.1 m/s for the third surge. These values are rather low in comparison to other debris-flow velocities published in literature (Rickenmann 1999), but can be supported by the low channel bed slope (16–17°), the high roughness and the small discharge in the monitoring reach.

The ultrasonic device measurements provide values on the maximum flow depth at that section: 1 m for the first surge, 0.75 m for the second surge and 1.5 m for the third surge. The combination of these values, an assumed flow width of 4 m (measured during the post-event survey), the estimated flow velocity and the registered duration reveal an estimate of the total mobilised sediment volume of about 2130 m^3. This volume is similar to the estimated volume of sediment accumulated upstream the road which has been estimated to be of about 2000 m^3.

Triggering rainfalls

In the following, the rainfall data of the 2015 debris flow are presented and subsequently compared with the triggering conditions of all the recent events observed in the catchment. Rainfall data from the meteorological station in the Portainé basin is only available since 2011, whilst complementary measurements from surrounding meteorological stations are included for the previous

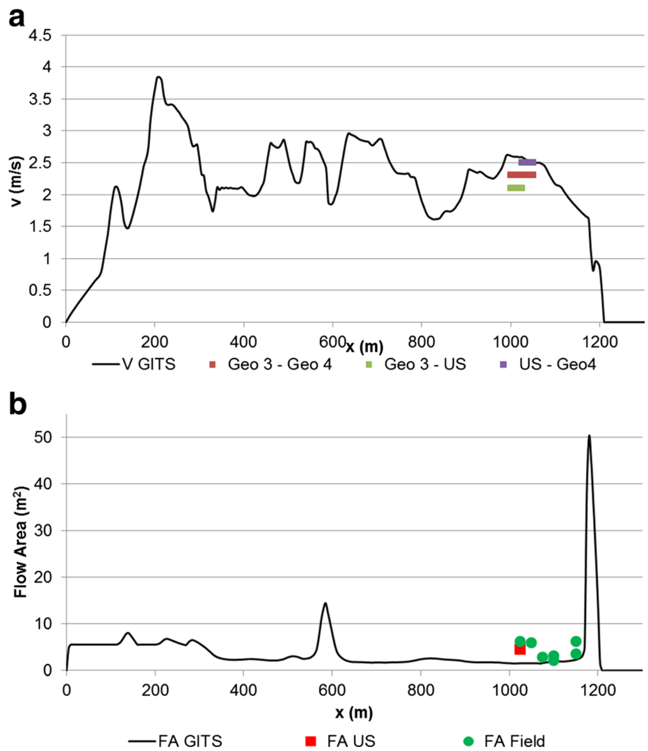

Fig. 8 Back-analysis of the 2015 debris flow by the numerical model. **a** Comparison of the simulated front velocity with the monitoring data: Geo-3–Geo-4, Geo-3-US and US-Geo-4 are mean front velocities obtained with the monitoring system. **b** Comparison of the flow area simulated and measured in the field or by the monitoring system. FA-US is the flow area obtained from the ultrasound flow height measurements. FA field are the flow areas obtained from field observations

events (Fig. 1c). It has to be stated that only the triggering rainfalls were analysed in the present work and the effect of antecedent rainfall was neglected.

The 2015 debris flow was triggered by a very short and intense convective storm, which only lasted 2 h and included a clear peak between 19:30 and 20:30, when peak intensities of more than 34 mm/h were measured (Fig. 7a). The cumulative rainfall measured at the Portainé rain gauge was almost 30 mm.

The triggering rainfall of the 2015 debris flow was compared with the ones observed during the other recent events that occurred in the Portainé catchment (Table 2). Apart from the exceptionally large 2008 debris flow, all other events are characterised by triggering rainfalls of short duration and high intensity (Fig. 7b). It must be mentioned that only the last three events were analysed by the rain gauge located inside the catchment, whilst the ones previous to 2012 were included using the nearby meteorological stations (2008 Salòria, 2010 and 2011 Sort; see Fig. 1c for locations). In spite of the fact that different meteorological stations were used, a good correlation was obtained, when comparing the triggering rainfalls in the intensity-duration plot and also when comparing these data with published threshold lines (Fig. 7c).

Table 1 Recent events and anthropic actions on the Portainé basin since 2006

Year	Torrential process (relative magnitude, date and main damages)	Anthropic actions and correction measures
2006	Medium event, May: partial road obstruction.	
2008	Most significant event, September 11: road obliteration at two points.	Earthworks in the ski resort
	Minor event, November 2: road obstruction.	
2009		Initiation of the construction of 7 flexible barriers
2010	Major event, July 22: obstruction of the road at two points.	Earthworks in the ski resort: construction of water reservoir for artificial snow. June: installation of 7 flexible barriers.
	Major event, August 12: road obstruction at two points.	
2011	Minor event, August 5: road obstruction at two points.	Construction of melt water drainage channels in the ski domain.
2012		Installation of 4 flexible barriers.
2013	Major event, July 23: road obstruction at two points.	
2014	Medium event, August 2: not damages on infrastructures.	
	Medium event, August 30: road obstruction at one point.	
2015	Medium event, August 21: road obstruction at one point.	

Kinematic analysis

The 2015 debris flow was back-analysed by the GITS-1D model, which was developed by the Sediment Transport Research Group of the Technical University of Catalonia. The model is based on the numerical model DAN (Hungr 1995) and the BING code (Imran et al. 2001), and has been thoroughly validated by various real cases and benchmark exercises. The inputs of the GITS-1D model contain a longitudinal profile, the cross-section shape, the input volume and the Voellmy rheological parameters.

The Voellmy model has revealed best-fit results in many debris-flow back analyses (e.g. Ayotte and Hungr 2000; Rickenmann et al. 2006), and it is one of the most widely used rheology to simulate granular flows like the one corresponding to our test site. Moreover, previous studies in the Pyrenees have shown that the Voellmy model gives the most adequate results for debris flow simulations (e.g. Hürlimann et al. 2003; Medina et al. 2008).

In this model, the original debris flow mixture is replaced by a homogeneous Voellmy fluid. The basal shear stress, mainly controlling the flow resistance and the depositional behaviour of the flow, consists of two terms, the turbulent Chezy-like frictional term

Table 2 Rainfall data concerning the recent events. See Fig. 1c for the situation of the rain gauges

Date (dd/mm/yyyy)	Station (m asl)	Daily rainfall (mm)
11/09/2008	Salòria (2451)	40.7
	Sort (679)	17.6
22/07/2010	Sort (679)	35.9
	La Seu d'Urgell (849)	19.5
12/08/2010	Salòria (2451)	2.4
	Sort (679)	46.3
	La Seu d'Urgell (849)	8.8
5/08/2011	Sort (679)	64.7
	Espot (2519)	40.4
23/07/2013	Portainé (1985)	60.2
	Montenartró (1322)	52.6
30/08/2014	Portainé (1985)	26.8
	Sort (679)	36.7
21/08/2015	Portainé (1985)	29.4
	Sort (679)	0.2
	La Seu d'Urgell (849)	0.1

and the dry Coulomb-like friction, and the total friction slope is given by the following relationship:

$$S_f = \mu\cos\delta + \frac{v^2}{C^2 R} \tag{1}$$

where μ is the dry friction coefficient, C is the turbulent friction term, v is the velocity, δ is the slope angle of the channel bed, and R is the hydraulic radius. Equation (1) is part of the shallow water equations which control the unsteady motion of the flow. The Voellmy parameters control flow depth, flow velocity and runout. The Chezy coefficient represents the fluid-like behaviour, and the friction coefficient represents the solid-like behaviour. The GITS-1D model accounts for active and passive earth pressure. For the Portainé simulations, the earth pressure coefficient at rest was set to be 1, the active earth pressure coefficient 0.7 and the passive earth coefficient 1.2.

To simulate the behaviour of 2015 debris flow in the Portainé torrent, a total volume of 2130 m^3 was released from rest at an elevation of 1900 m asl, and a trapezoidal channel of 4 m width was used. This value corresponds to the averaged top width measured in field surveys. The road at 1450 m asl was represented by an increase in width from 4 to 40 m to represent the area where the sediment was deposited, downstream the channel also measured 4 m. The flexible barriers were not included in the topographic input file to overcome problems with resulting numerical instabilities.

Whilst the debris flow volume was defined using the results of the field and monitoring data, modelling focused on the calibration of the Voellmy parameters using, on one side, the maximum runout observed in the field and, on the other side, the velocity and flow area estimates obtained from monitoring data.

The calibration of the two rheological parameters showed that the best-fit values of the dry friction coefficient, μ, and the turbulent friction term, C, are $\mu = 0.29$ and $C = 8$ m$^{0.5}$/s. The simulated runout distance, velocity and flow area of the debris flow coincide rather well with the data gathered in the field and recorded by the monitoring system (Fig. 8). The flow area sharply increases in the last portion of the flow trajectory, where most accumulation occurred. This strong augmentation of flow area represents the debris fan, which was deposited just upstream the road. The value of μ is relatively high compared with values published in the literature (e.g. Rickenmann and Koch 1997; Jakob et al. 2000; Hürlimann et al. 2003), but is supported by the very coarse granulometry of the channel sediment. In contrast, the value of the turbulent friction term is at the lower end of the range regarding other published values. This fact can be explained by the low velocity observed in the monitoring reach and possible stop-and-go mechanisms of the flow. In spite of that, only small differences between the model results and monitoring or field estimates were observed, which may be attributed to model simplifications and uncertainties in the rheology parameters. Future works on these drawbacks are foreseen, which also include the analysis of the effect of the flexible barriers.

Concluding remarks

The present study exhibited monitoring and field data of debris flow that occurred in one of the most active torrents in the Pyrenees. The study focused on the 2015 debris flow, but also presented data of the historic and recent activity.

The analysis of the monitoring data field observations showed that the 2015 debris flow was triggered by short and intense rainfall, which caused in-channel mobilisation of sediment and transported a total volume of about 2100 m^3. Comparing this volume with the estimates for the 2008 event, the volume of the studied event was an order of magnitude smaller, but still enough to block the road culvert and cause important economic damages. The ultrasonic and geophone sensors provide reliable estimates for mean velocity and debris flow volume. The 2015 event consisted of three surges, the third one being the faster with a velocity of 2.1 m/s. Its total volume was of about 2130 m^3.

Regarding the numerical modelling, both velocities and flow areas obtained using the GITS-1D model are very similar to those obtained by field and monitoring data. The calibration of model parameters is of key importance to predict the behaviour of future debris flows, and is a task that should be continued to better understand the dynamic behaviour of the torrential processes in the Portainé torrent and to improve the design of most adequate mitigation measures. Finally, the obtained results show the increase in the occurrence of debris flows in the last decade. This change in the torrential activity may be related to the presence of the ski resort in the headwaters. Changes in vegetation cover and anthropic actions, such as impermeable drainage channels, decrease in the infiltration capability, increasing surficial runoff, may involve a change in the hydrological response of the basin. Future studies should analyse if the observed increase of activity during the last decade can be physically related to the presence of ski resort.

Acknowledgements

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