Implementation of an integrated management strategy to deal with landslide triggered debris flows: the Valloire case study (Savoie, France)

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Abstract

The Rieu Benoît is a debris-flow-prone catchment located in Valloire (Savoie, France). In 2011, a lateral landslide was detected about 600 m upstream of the fan apex where houses are present. This landslide has evolved slowly since 2011 but is likely, in case of rapid collapse, to provide up to 150,000 to 200,000 m^3 of material to the channel and generate intense debris flows thus threatening human settlements on the fan and in the Valloire ski resort. This paper presents a contribution to the definition of a protection strategy based on the principle that a catastrophic evolution of the landslide can be detected sufficiently in advance to set up an effective alert procedure. Such early warning system can be designed provided (i) the landslide is instrumented to properly detect its evolution and characterize the volumes likely to mobilize into debris flows, this is carried out using photogrammetric, seismic, and electrical techniques; (ii) the interaction between the landslide and the channel is observed and sufficiently understood, this is carried out using a time-lapse camera taking a picture every two hours and at higher frequency once a flow is detected by a geophone; (iii) subsequent debris flows are observed and characterized in terms of flow thickness and velocity, this is carried out at a monitoring station located at the fan apex and equipped with a radar flow stage sensor and three geophones; (iv) consequences on urbanized areas are evaluated *a priori* on the basis of scenarios, this is carried out by simulating the spreading of debris flows for different volumes and material properties. The final step consists in building alert and evacuation procedures in collaboration with local authorities.

Keywords: debris flow, landslide, monitoring, hazard assessment, risk protection

1. Introduction

The Rieu Benoît is a 6.3 km^2 debris flow-prone catchment located in Valloire (Savoie, France). Elevations range between 1,540 and 3,037 m a.s.l. The Rieu Benoît is a tributary of the Valloirette mountain river which flows across the city and has the capacity to propagate debris flows triggered in its tributaries. Significant events were recorded in 1682, 1934, 1935, 1982, 2006, 2008, 2009 and 2011. In 2011 a lateral landslide (Fig 1.a) was detected about 600 m upstream of the fan apex where houses, buildings and roads are present (Fig 1.b). This landslide has evolved slowly since 2011 but is likely, in case of rapid collapse, to provide up to 150,000 to 200,000 m^3 of material to the channel and generate intense debris flows thus threatening human settlements on the stream fan and in the Valloire ski resort. A scientific study was initiated in the aim of defining a protection strategy based on the concept of integrated management of natural risks. This strategy is based on the principle that a catastrophic evolution of the landslide could be detected sufficiently in advance to set up an effective alert procedure. Before setting such a procedure, we

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need to better understand and quantify all factors potentially contributing to the debris-flow triggering. In particular, in the case of a landslide triggering, it is critical to unravel the various cascading effects that can lead to increased risk to the population. This paper focuses on the methodology and monitoring techniques used to address these questions about the physical processes at work in the considered catchment.

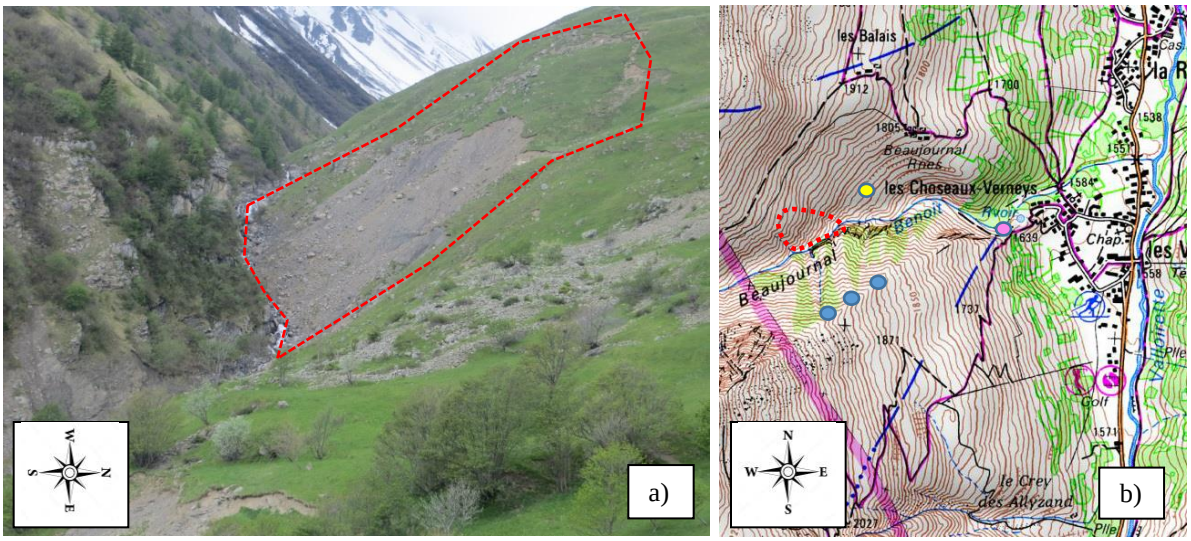

Fig. 1. (a) picture of the stream channel and approximate delineation of the landslide (red dashed line); (b) local topographic map with the downstream part of the Rieu Benoît stream including the alluvial fan and position of human settlements. The position of the lateral landslide is given by the red dotted line. Pictures for the photogrammetry study were taken from the positions marked by the blue dots (see section 3.1.). The yellow dot gives the position of the permanent observation station (see section 4.1.). The pink dot gives the position of the monitoring station (see section 5.).

2. Objectives and methodology

Our main goal is to analyze the possible cascading effects leading to an increase of the debris-flow risk. This can be achieved by considering the following points:

- Debris flows can be initiated in the upper part of the catchment, we must thus consider them independently of the landslide. This study will be mainly based on a Lidar survey covering the whole catchment, which will be used to characterize all the areas of active erosion and to analyze the connectivity of these areas with the hydrographic network. We supplement this analysis with information on past events from historical archives.
- We need to characterize the landslide and, in particular, its volume and conditions of collapse in order to create scenarios of future evolution (see section 3.)
- We need to analyze precisely the processes at the contact between the landslide and the stream channel. This area has already been recognized as a key-point of debris-flow triggering for the reasons developed in section 4.
- Because of the complexity of cascading processes, one can hardly deduce the flow characteristics (depth, velocity, discharge…) immediately upstream of the areas at stake only from consideration of the triggering conditions. Thus, we considered monitoring the flows at the apex of the stream fan. This point will be presented in section 5.
- It is only when we understand the exact impact on urbanized areas that we can set up efficient alert systems and procedures. Our strategy consists in establishing a series of hazard maps based on forecast scenarios of evolution of the landslide. This point will be presented in section 6.

3. Landslide monitoring

Before setting a permanent station to monitor the landslide evolution (Larose et al., 2015; Bottelin et al., 2013; Colombero et al., 2017), we performed preliminary photogrammetric and geophysical studies in order to estimate the landslide activity and the potential unstable volume, respectively.

3.1. Photogrammetric study

We performed two photogrammetric surveys in 2015 and 2018 to estimate the activity of the landslide. Pictures were taken from three sites located in the opposite side of the thalweg and represented by blue dots in Fig 1.b. Each pixel of the photos represents a 3 cm x 3 cm surface of the terrain and the elevation, measured with a RTK GPS, is known with a precision of 4 to 6 cm. On Fig 1.a, we can clearly see the headscarp and the lower gully. The difference between 2015 and 2018 surveys (Fig 2.) reveals maximum motions of 1.5 m, with erosion zones mainly located at the top of the gullied area and, to a lesser extent, at the headscarp. No massive motion is observed and the material moved over three years is estimated at 230 m^3.

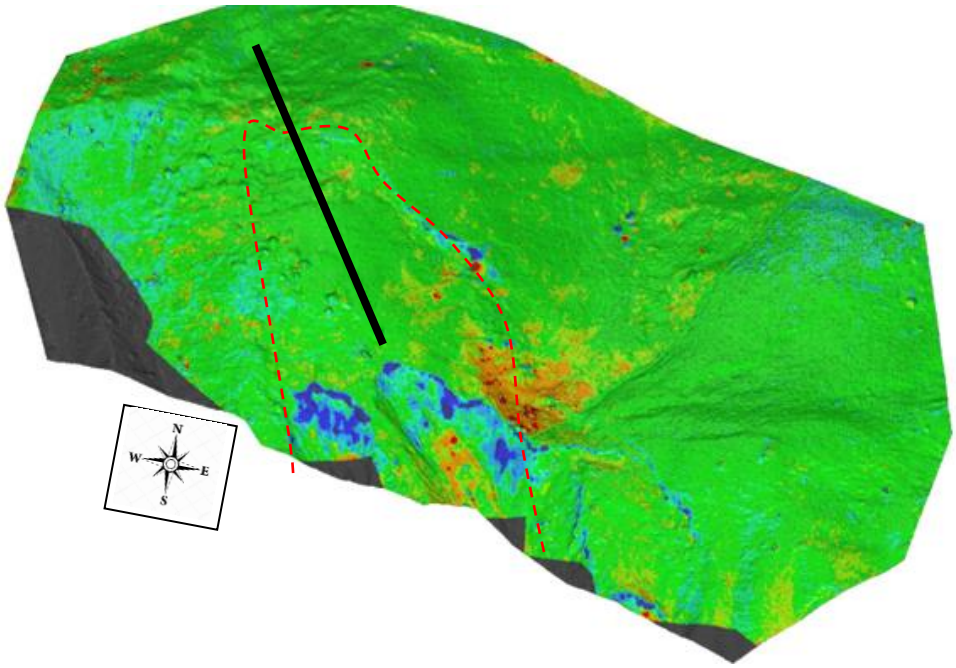

Fig. 2. Difference between the November 2015 and July 2018 photogrammetric surveys. Red: accumulation. Blue: erosion. The maximum motion is 1.5 m and the displaced volume is estimated at 230 m^3. The red dashed line gives an approximate delineation of the landslide. The black line marks the position of the seismic tomography profile (see section 3.2.)

3.2. Geophysical investigation

A geophysical campaign including seismic and electrical tomography profiles was carried out in July 2018 with the aim of determining the geological structure of the slope and the prone-to-move volume. Fig 3. shows the seismic image (P-wave velocity) obtained along the slope (black line in Fig 2.). The analysis of both electrical and seismic results has led to the detection of three layers: (1) a thin, low-velocity (300-600 m/s) layer of grass cover and colluvium, (2) a 20-m-thick till layer with a velocity ranging from 800 m/s to 1,000 m/s, (3) a high-velocity (from 2,000 m/s to 2,800 m/s) layer, probably corresponding to the weathered bedrock. The permeable till layer is drained and the water table is low, probably located close to the interface with the bedrock.

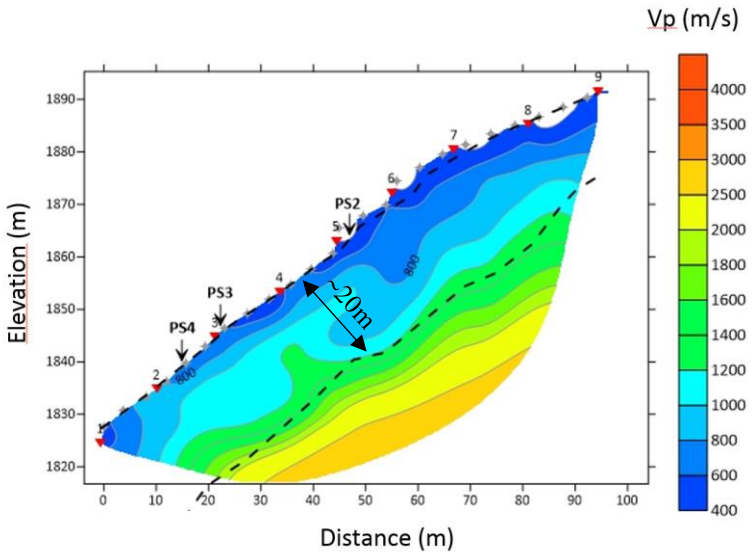

Fig. 3. Seismic tomography profile (P-wave velocity) performed along the slope (black line in Fig 2.) in the upper part of the landslide (over the gullied area).

The landslide develops in the till layer with a rupture surface (bottom of the layer) located at about 20 m below the surface (Fig 3.). From this observation, we estimate that the maximum volume of the prone-to-move material is between 150,000 and 200,000 m^3. By creating different landslide scenarios, we will be able to estimate the soil volume that could reach the thalweg and generate debris flows.

4. Monitoring the landslide – stream channel interaction

The contact zone between the landslide and the stream channel is of particular interest for several reasons. The slope gradient of the stream channel is higher in this area compared to values observed upstream and downstream. The destabilization of this section by erosion could lead to the release of substantial quantities of solid material, independently of the landslide activity. Additionally, it could destabilize the bottom of the landslide and trigger its collapse. In the absence of significant erosive processes of the streambed, the collapse of the landslide would provide large quantities of solid material in this area, which are likely to be remobilized by water or debris flows coming from the upstream part of the catchment. For these reasons, it was decided to specifically monitor this area by combining two techniques: permanent observation using a camera and quantitative evaluation by comparison of DEMs obtained by Lidar surveys before and after some substantial activity is detected by the camera.

4.1. Permanent observation station

The permanent station was installed on the North bank of the stream, about 50 m above the channel. Its position is given by the yellow dot in Fig 1.b. It is mainly composed of a camera (Canon Rebel T6®) aimed upstream toward the base of the landslide, and a time-lapse controller (DigiSnap Pro®) taking a picture every two hours in normal conditions. The camera is installed on a mast, protected by a waterproof box and electric power is supplied by a solar panel (Fig 4.a). The pictures (Fig 4.b) are locally stored in full resolution and some of them are compressed and transferred using the GPRS network. The pictures are regularly visually checked to detect signs of morphological (erosion/deposition) evolution in this area. Additionally, to enhance the temporal resolution during an event, the camera is triggered by an external input based on a geophone sensor. This geophone, installed near the stream on a lateral bank, measures the vertical ground displacement speed. The geophone signal is digitalized and processed by an Arduino Nano® and triggers the camera every 4 seconds if it overcomes a calibrated threshold. More technical information is available in Piton et al. (2018).

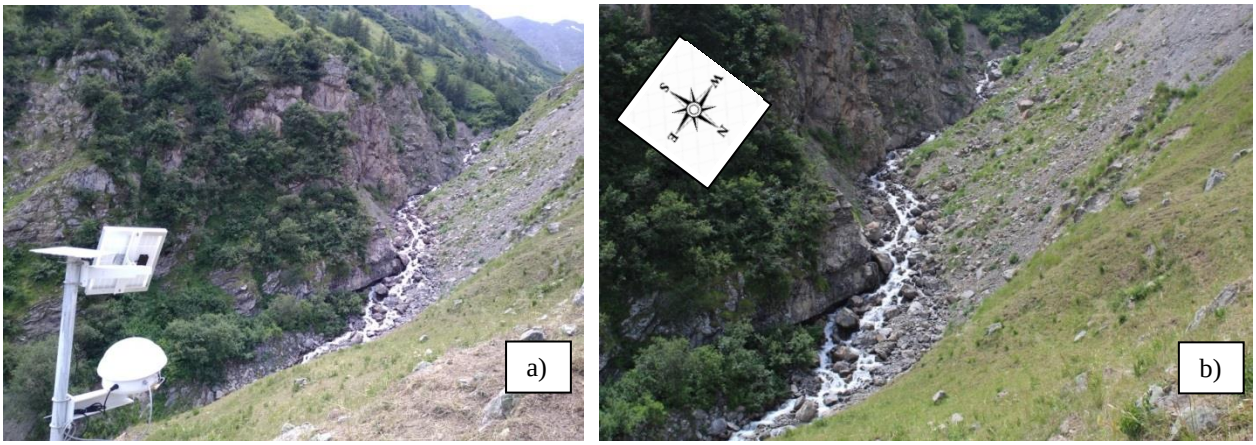

Fig. 4. (a) The permanent observation station installed about 50 m above the stream channel on the left bank and pointing upstream. Its position is given by the yellow dot in Fig. 1.b; (b) Example of a picture shot by the camera, the gullied part of the landslide can be seen on the top right side of the picture

4.2. Lidar survey of the landslide – stream channel interaction area

The direct observation of the landslide – stream channel area helps detecting processes but is not sufficient to quantify them. In that aim, we acquire a series of high-resolution DEMs of the area of interest: one initial DEM acquired in July 2018 used as a reference and one DEM each time movements are detected. Comparison of the DEMs will provide a basis for quantification. Such strategy requires acquisition techniques that can be quickly deployed. For this reason, we have chosen to carry out surveys with the help of a drone (Escadrone SIX 3®, Fig 5.a) equipped with a Lidar (YellowScan Surveyor Ultra®). A 3D representation of the initial DEM, which has a resolution of one point every 0.1 m, is given in Fig 5.b.

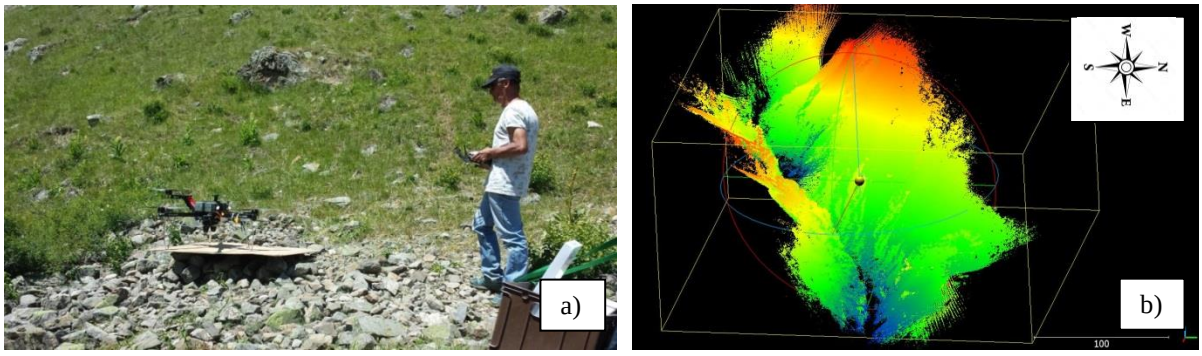

Fig. 5. (a) operating the drone; (b) 3D representation of the initial DEM acquired in July 2018 by the Lidar installed under the drone

5. Monitoring floods and debris flows at the fan apex

The main threat on human settlements comes out of the flows that are likely to reach the Rieu Benoît alluvial fan and the Valloirette downstream. Characteristics of the floods and debris flows in this area can hardly be deduced from the consideration of triggering processes only. That is why we decided to install a monitoring station at the fan apex with the objective to directly measure flow depths and velocities and to discriminate between floods with bedload transport and debris flows (Fontaine et al., 2017). The monitoring station (Fig 6.) is set up at the outlet of the gorge overhanging the fan (pink dot in Fig 1.b). It is equipped with a tipping bucket rain gauge, a radar flow stage sensor and a set of three vertical geophones, about 100 m away. Data are recorded by an environmental datalogger (Campbell Scientific CR1000X®) powered by a solar panel, and are stored in a SD card (Bel et al., 2017). Thanks to

the geophones located along the channel at a known distance, we can assess the velocity of the debris-flow front on the basis of the phase shift between the peak intensities of vibrations detected by each instrument (Arattano & Marchi, 2005). Flow stage and conditioned seismic signal are sampled at a 20-Hz frequency. Rainfall is totalized over a 5-min period.

Fig. 6. Flow monitoring station located at the fan apex (pink dot in Fig 1.b) with: rain gauge, solar panel and flow stage sensor on cables; all devices are connected to a datalogger.

6. Debris-flow event scenarios and associated hazard maps

As the volume of material mobilized during a single event cannot be known long before the debris flow triggers, the adopted strategy consists in building a series of scenarios and analyzing the respective possible consequences on urbanized areas. In practice, the consequences of each scenario, and, in particular, the affected area, are assessed with the help of the 2D numerical model Lave2D (Rickenmann et al., 2003) dedicated to the computation of debris-flow spreading. This model is based on shallow-water equations and on the assumption that the mechanical properties of the flowing material are properly represented by a Herschel-Bulkley rheological model, which is reasonable on this site. Each scenario will be defined as a set of input parameters: the total debris-flow volume, the peak discharge at the fan apex and the rheological parameters – yield stress, density and consistency. Simulations will be carried out on a high-resolution 1 m x 1 m DEM based on an airborne Lidar survey.

Fig 7. gives a preliminary example of such computation (with no practical pertinence), using a rough DEM and for a debris-flow volume of 50,000 m^3. The recent acquisition of a precise DEM based on a Lidar survey will improve the assessment of the affected areas related to debris-flow scenarios. Once all hazard maps are available, we can quickly and easily estimate the downstream consequences of any collapse or triggering process observed upstream and we can define protection measures accordingly.

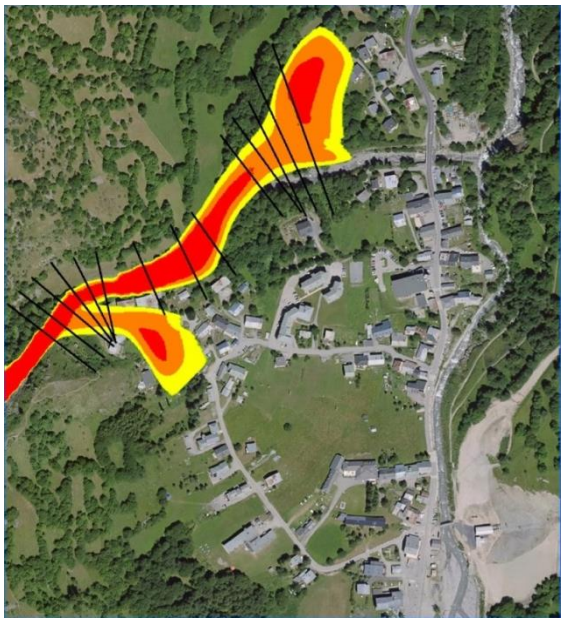

Fig. 7. Tentative example of computation of the area affected by debris flows for a single scenario, this example of a 50,000 m^3 debris-flow spreading computed using a rough DEM is given for illustrative purpose only.

7. Conclusions

We have presented the principles of a protection strategy based on the concept of integrated management of natural risks and its application on the Rieu Benoît catchment, Valloire municipality, Savoie, France. The main threat on this site results from the recent activation of a lateral landslide which is likely to drastically increase the intensity of phenomena in this debris-flow-prone catchment. We have mainly presented the monitoring activity developed to improve understanding of the cascading effects, which, from a landslide collapse, may lead to debris-flow spreading in the urbanized areas of the Valloire ski resort. This study will help defining event scenarios and assessing the corresponding hazards more accurately. The next steps will consist in: 1) defining the features of a permanent alert system to be installed and transferred to the local municipality, and 2) collaborating with the local municipality to define a crisis management plan (information, warning, evacuation of the population…).

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