Monitoring and modelling of debris-flow erosion in the Rebaixader catchment (Pyrenees, Spain)

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Abstract. Debris flow and other torrential processes can entrain large volumes of sediments along their runout path. Since the debris-flow hazard strongly depends on the volume, the research on the entrainment is relevant and has been analysed by multiple approaches in the past. In this study, the erosion volume due to torrential processes has been monitored in the Rebaixader catchment (Spain) by digital elevation models obtained from Uncrewed Aerial Vehicle (UAV) surveys and by the instrumental monitoring system installed in the channel reach. In addition, the entrainment of debris flows has been modelled by the numerical code FLATModel. The results of both approaches show that debris flows in the studied catchment are characterised by a large entrainment and the assumption of landslide-triggered debris flows has been refuted. Important erosion in the gullies of the initiation area has been detected by the UAV data and the numerical modelling. An average annual erosion volume of about 6100 m^3/y has been determined.

1 Introduction

The erosion of sediment, also called entrainment, due to debris flows and other related processes is not only an important research topic, but also affects many practical aspects like mitigation measures or sediment transport into the drainage network, amongst others [e.g. 1].

The entrainment caused by debris flows has been investigated in the laboratory by flume experiments [2,3], by in-situ monitoring using erosion sensors [4], by field observations [5], modelling [6] or geomatic techniques [7–9].

In this study, we present results of the monitoring and modelling of the erosion that we have observed in the debris-flow field laboratory called the Rebaixader catchment.

2 Methods and data

2.1 Monitoring

The Rebaixader catchment is a small (0.53 km^2) and steep drainage basin located in the Central Pyrenees. The initiation zone of the debris flows is situated in a lateral moraine, which drains in an incised channel reach (Fig. 1). Most of the flows pass over the fan before entering the main river.

Two types of monitoring data are available in order to estimate the erosion and sediment yield that occur in the catchment. On one side, yearly photogrammetric surveys by Uncrewed Aerial Vehicle (UAV) have been performed since 2016 using different DJI drones (mostly Inspire 1Pro and 2, www.dji.com/es/inspire-2). On the other side, an instrumental monitoring system is operational since 2009 [10,11]. Therefore, between 2016 and 2021, we have a time period of six years, when both types of datasets can be analysed.

The UAV surveys produce point-clouds, Digital Surface Models (DEMs) and orthophotos (both with a pixel size of 10 cm). The DEMs of two different surveys provide a so-called "DEM of differences" (DoD), which is perfect data to study morphologic changes in the catchment. Herein, we focus on these DoDs.

In addition, the monitoring system allows to determine the total volume of each torrential flow by flow-depth sensors, geophones and video cameras [10].

2.2 Modelling

The 2D finite volume code FLATModel [12] was applied and modelling outputs were compared with monitoring data. A debris flow that occurred in summer 2020, was selected for back-analysis

The static approach of the entrainment module in FLATModel was used, which is based on soil mechanics and compares the bed shear forces, τ_b, with the basal resistance forces, τ_{res}. The entrainment or erosion depth is calculated in each time step, when the following condition is fulfilled

$$\tau_b > h\rho g \cos\theta \tan\phi_{bed} \tag{1}$$

where h is the flow depth, ρ the flow density, g is the gravity, θ is the slope angle of the channel bed and ϕ_{bed} the bulk friction angle of the bed material.

The Voellmy fluid model was selected as most adequate flow resistance law after a first evaluation comparing different laws.

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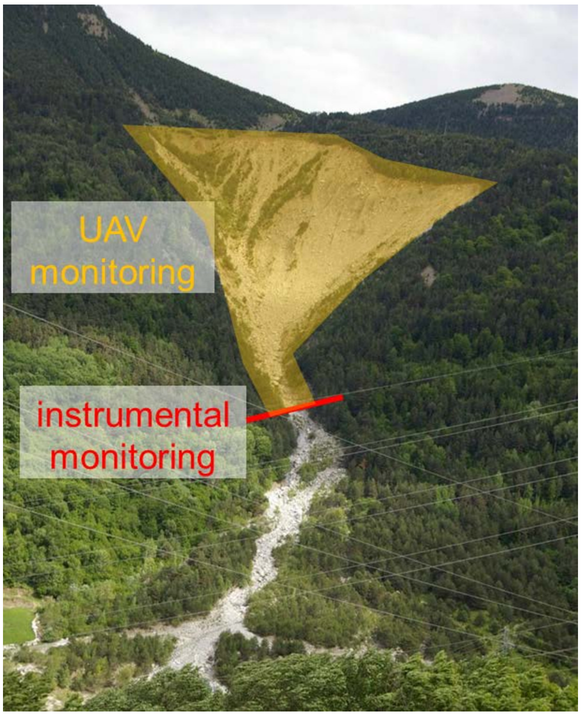

Fig. 1. Oblique view of the Rebaixader catchment indicating the two monitoring types. The area of the UAV monitoring is shown by the orange shaded polygon. The location of the instrumental monitoring is given by the red line.

3 Results

The instrumental monitoring revealed a total annual volume of sediment that was mobilised by the debris flows or debris floods in the catchment and that was detected by the monitoring system, which is installed along the channel reach. Table 1 lists these total volumes and the corresponding numbers of events for each debris-flow season. The total volume of all the detected torrential processes is 36600 m^3, although more than the half of the volume is related to the season 2020. Moreover, the annual sediment yield is about 0.1 $m^3/m^2/y$ assuming an active scarp area of about 6 ha.

Table 1. Debris flows detected by the instrumental monitoring and estimated total annual erosion volume.

Debris-flow season	Number of events	Total annual erosion volume (m^3)
2016	0	0
2017	5	7700
2018	1	2500
2019	1	2000
2020	4	21400
2021	1	3000

The DEMs, DoDs and othophotos derived from the UAV surveys provided many information on the initiation mechanisms of the debris flows, which still was an open question [13]. The DoDs clearly indicate that the debris flows are formed by progressive incorporation of sediment due to entrainment along the gullies in the initiation zone (Fig. 2). Therefore, a triggering mechanism by landslides of considerable volume can be discarded. This hypothesis is also supported by monitoring data of soil moisture in the initiation area

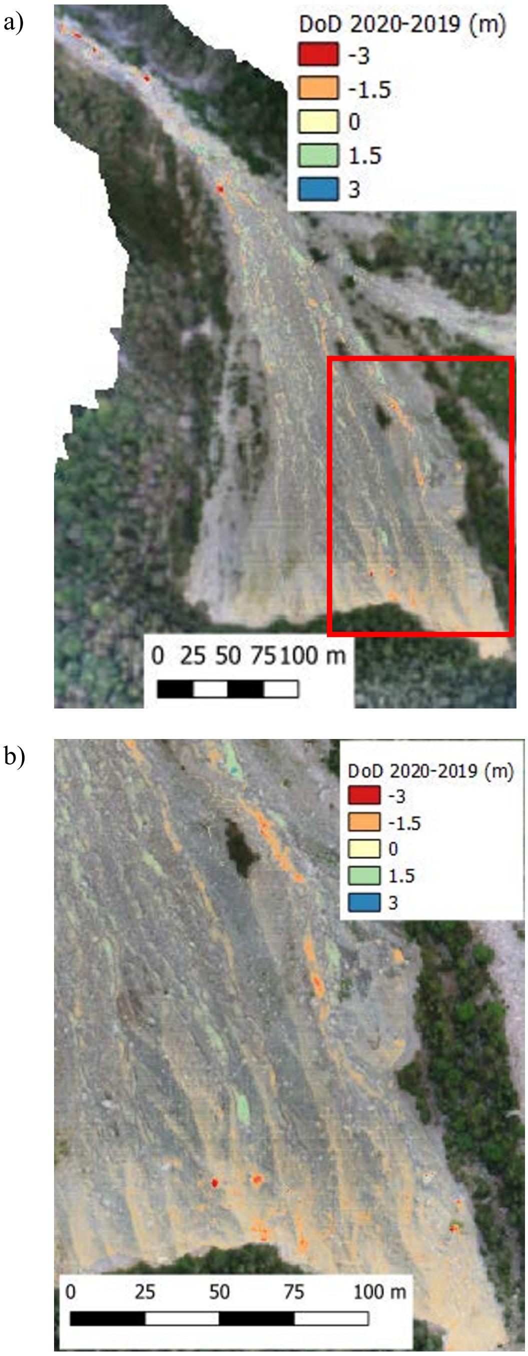

Fig. 2. a) DEM of difference, DoD, obtained from the UAV surveys of 2019 and 2020, which corresponds to the 2020 debris-flow season. b) Zoom into the initiation zone (selected area is indicated by red rectangle in a).

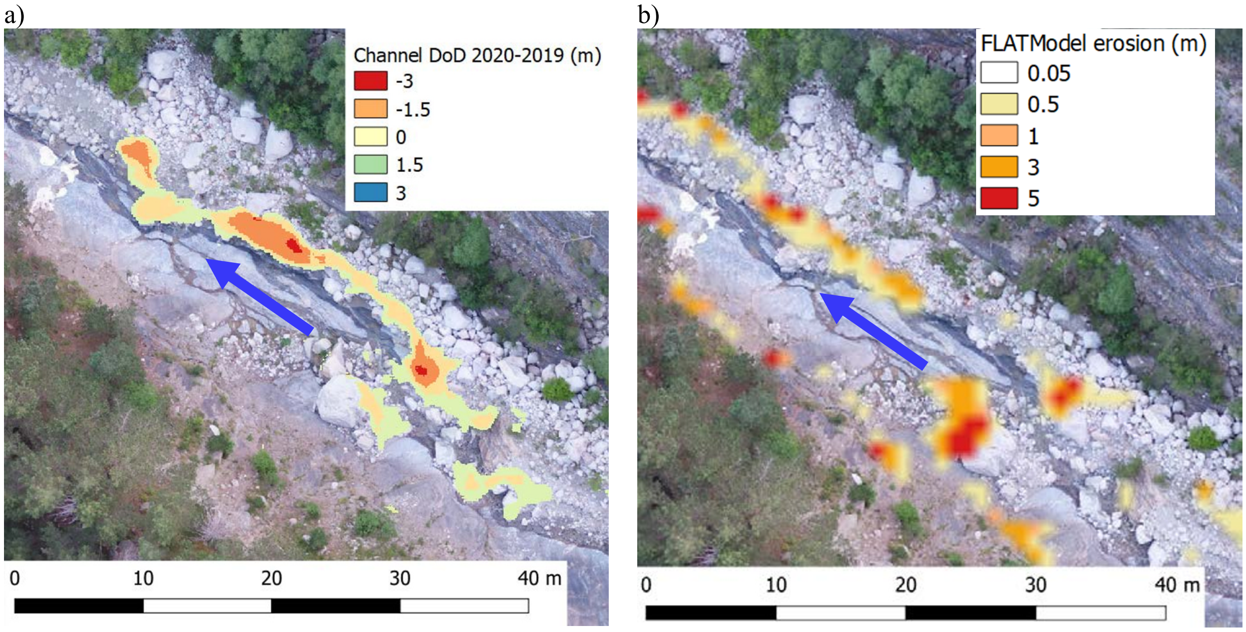

Fig. 3. Comparison between UAV results and numerical modelling. a) DEM of difference, DoD, for the debris-flow season 2020. b) Erosion depth obtained from the numerical modelling using the entrainment module of FLATModel. The blue arrows indicate the flow direction.

In addition, the locations, where large boulders detached in the steep initiation area, could be detected (see two examples in the lowest part of the DoD in Fig. 2b). These boulders often create important rockfalls in the catchment [15].

Interesting results were obtained by the comparison between UAV-data and the numerical modelling. Regarding the simulations, the back-analysis of the 2020 debris flow showed that the best-fit rheological parameters of the Voellmy fluid model were $\mu = 0.15$ and $C = 12.4$ m$^{0.5}$/s. In addition, the optimum value of ϕ_{bed} was about 35º. While μ- and C-values can be compared with other studies and coincide rather well with published data [e.g. 16], a comprehensive interpretation of the ϕ_{bed} - value is more complicate [3, 18]. However, the rather high value of 35º may be explained by the presence of coarse-grained bed sediment and an important amount of large boulders along the flow trajectory.

Finally, the results calculated by the entrainment module of the numerical model of FLATModel were compared with the DoDs obtained from the UAV surveys . Herein, we used the DoD obtained from the 2019 and 2020 flights to compare the detected elevation differences with the erosion depth obtained from numerical code. Fig. 3a shows the erosion and accumulation determined by the DoD in the channel reach. An important erosion up to 3 metres can clearly be observed at the right channel bank. In addition, some accumulation at the upstream part of large boulders was detected. On the other side, the erosion depths calculated by FLATModel are illustrated in Fig 3b. A strong erosion was calculated at both channel banks and also behind large boulders.

The comparison of the two erosion maps revealed that the numerical model achieves satisfying results, since they follow the general pattern observed in the DoD, not only in the channel reach, but also in the initiation area.

4 Concluding remarks

The study confirms the great usefulness of multi-temporal UAV surveys that provide multiple outcomes like high-resolution DEMs, DoDs, orthophotos, amongst others. Our experience gathered in the Rebaixader catchment revealed different problems that have to be taken into account regarding the application of UAV. The steep terrain complicates the definition of an optimal flight plan and the orientation of the camera. The harsh morphology only allowed the installation of a small number of ground control points. Therefore, the alignment of the different point clouds was very complex and included considerable uncertainties.

On the other side, the numerical modelling of the erosion provided satisfactory results, although simplifications were introduced in the input data and the entrainment mechanisms.

In spite of all these uncertainties and simplifications, the comparison between numerical and monitoring results are promising and will provide valuable information to improve our knowledge on the erosion processes of torrential flows.

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