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Challenges on modelling debris flows triggered by permafrost melting: the study case of the debris flow in the Mulas River in 2013.

Desafíos en la modelización de los flujos de escombros causados por fusión de permafrost: caso de estudio del flujo de detrito del río Mulas de 2013.

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ABSTRACT: Debris flows that pose a threat to high mountainous areas of the Subtropical Andes are often triggered by extreme rainfall and snow/ice melting. However, due to the current climate change, the causes of geo-climatic events have mutated, and higher temperatures affecting permafrost areas in the periglacial environment have been causing violent debris flow events in Andes mountain areas over the last decade. On 7th February 2013, a large and violent debris flow occurred in the Mulas River, causing damage to a mountain village, leaving people isolated and causing severe economic damages. The event was correlated with combined weather factors in a sensitive periglacial, and it was described in the field by estimating the volume and velocity. The 7F event was simulated by two hydraulic models, HEC-RAS and R Flow, trying to reconstruct debris flow behavior using field information for model calibration.

KEYWORDS: debris flows, paraglacial-periglacial environment, hydraulic models, reanalysis.

1. INTRODUCTION

Debris flows are a hazard in the mountainous environments of the Central Andes mainly due to their sudden nature. These widespread events typically originate in the upper catchment areas unnoticed. They use to accumulate material downstream, increasing in volume and causing significant damage in low-lying areas. Historical debris flows have caused significant regional economic losses, resulting in numerous fatalities, destruction of international transportation corridors, damage to road and tourist facilities, destruction of homes, traffic interruptions, and impediments to drinking water supply (Paez et al. 2012; Sepulveda et al. 2015; Moreiras et al. 2018).

The cause of hyper-concentrated and debris flows, the first as mixtures of sediment and water that flow and behave as an intermediate category between a normal flow (mainly water with a low fine sediment load) and an debris flow with higher proportion of coarse sediment than water (Pierson, 2005), has been previously analyzed in the eastern Central Andes (e.g. Moreiras et al., 2018; 2021) distinguishing at least three main patterns. The most frequent triggers are convective storms associated with a moisture pattern forced by the Atlantic Anticyclone during summer season, but precipitations related to westerlies, coming from the Pacific Ocean that occur mainly during the winter season, also are related to geoclimatic events as during cold seasons, humidity plumes of westerlies can also extend to the eastern Andes (Moreiras, 2009; Moreiras et al., 2018). Additionally, another cluster of flows is associated with the melting of snow, permafrost, or glacial ice (Moreiras et al., 2012; Alvarez et al., 2019; Vergara et al., 2020; Moreiras et al., 2021

In general, debris flows in the Central Andes have a specific spatial and altitudinal distribution. Events linked to convective storms occur in lower sectors or lowlands of the Andean basins at altitudes below 2500 m asl. Meanwhile, events linked to westerlies are concentrated in the middle section of Andean basins, ranging from altitudes of 2000 to 3200 m asl (e.g. Moreiras et al., 2021). The spatial distribution can be altered or intensified during warm ENSO-El Niño phases, which are linked to above-average precipitation and intensified summer precipitation. Slope instability is associated with periglacial environment dynamics above 3200 m asl in the high areas of Andean basins (e.g. Moreiras et al., 2018; 2021). Violent flows were recorded in the Mendoza River valley (32°S) during the warmer season due to the partial melting of the frontal mouth of a bared ice glacier and a rock glacier. In cases involving frozen soils, debris flows occur in multiple episodes with successive events on consecutive days (Moreiras et al., 2018).

This case study examines the event that occurred on February 7th,2013 in the Mulas River, denominated as 7F event in this study. This event is unique due to several unknown factors, including the starting sector of the movement, the triggering causes, debris flow parameters, and hydraulic behavior. The study was focused to cover these knowledge gaps and to reconstruct the event by identifying discrepancies between the model and the parameters obtained from field data.

2. OCURRENCE OF THE 7F EVENT

On February 7, 2013, a violent debris/hyper concentrated flow channelized in the Mulas River swept through the Valle del Sol village destroying 3 bridges, affecting communication systems and the drinking water plant (Fig. 1). Consequently, at least 25 people were isolated in this mountain region and potable water service was interrupted.

The starting point of the debris/hyperconcentrated flow was determined by satellite images and field work. The mobilized mass was sourced at 3382 m asl. next to the frontal mount of the Mulas Glacier, a covered glacier in the Morterito subbasin.

2.1. *Probable cause*

The studied remote area lacks on instrumental data so previous soil conditions could not be determined. According to local witnesses no rains occurred during the day of debris flow. The reanalysis of different database concluded that only 6.76 mm rainfall was recorded on the day of the 7F event, and a similar accumulated precipitation (6.69 mm) was found for previous 6 days.

On the other hand, a temperature decrease was determined on the day of the event compared to previous days. According to NCEP, the isotherm drop until 679 meters and this drop was 515 m based on data of ERA 5 base. Still, both maximum and minimum air temperatures do not show a clear upward/downward behavior based on radiosonde records. This do not seem to be correlated with an increase in ground temperature that indicates that the 0°C isotherm began to climb previous days. However, during these days the altitude of 0°C isotherm was above 4700 m asl that mean that soil in the source area (3670 m asl) located near 1,000 m above was not frozen.

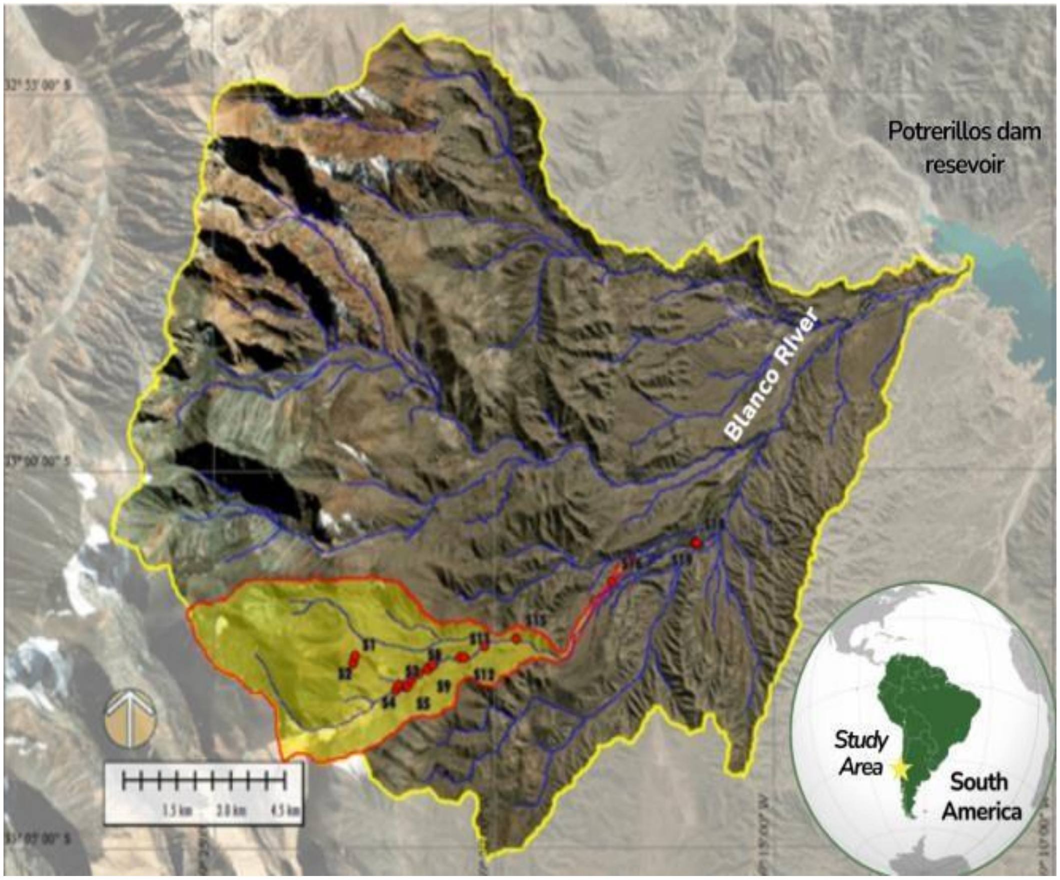

Figure 1. Blanco River Basin (perimeter in yellow line): (A=274.8 km², Hmax=5877 m, hmin= 1351 m), Mulas River subcatchment area (delimited by a red line): (A=26.7 km², Hmax=5877 m, hmin=1826 m). Red dots: Observed site points: S1, S2: main scar, S3: Slice-erosion; S17: Damaged Bridge

2.2. *Debris flow/ hyper-concentrated flow parameters*

Field work was conducted to reconstruct the main morphological parameters of the studied debris/hyperconcentrated flow (Table 1). The source area of the 7F event was identified by remote sensors in the upper basin of the Mulas River in a periglacial environment above 3200 m asl. The saturated debris mass was mobilized down slope until a plain surface where part of mass was deposited and is still preserved. After this point, the flow moved down by four different tracks. Along the main track, a new scar was eroded.

The fluidized debris mass descended 1844 m running out 13 km downslope. The flow velocity was calculated using the method of Rickenmann (1995) (1), where: v is the velocity (m/s), g is the acceleration of gravity (m/s2), r is the mean radius of curvature (m) and β is the angle of the inclined free surface (°). According to this value, the estimated streamflow reached 85 m^3/s with an average height of 2.5 m above the river bed (estimation from field data).

$$V = \sqrt{g.\ r.\ \text{tang}\ \beta} \qquad (1)$$

The maximum elevation reached by the flow along the Mulas River was 6 m, whereas a maximum width of the path was 39 m. The flow moved blocks up to 5 m in diameter and uprooted numerous trees in its path.

Table 1. Main parameters of the 7F debris/hyperconcentrated flow

Hyperconcentrated flow parameters			
H max (m)	3670	Travel distance (km)	13
H min (m)	1826	H/D	0.14
Δ elev. (m)	1844	Q (m^3/s)	85
Relict deposit			
Max width (m)	39	Max high (m)	6

Using the standard area-volume relationship (2) for ice mass of glacier with less than 2 km² area (Thyyen et al., 2022), the volume of permafrost thawing was estimated in 0.09 hm^3.

$$V = 0.024 \cdot A^{1.36} \qquad (2)$$

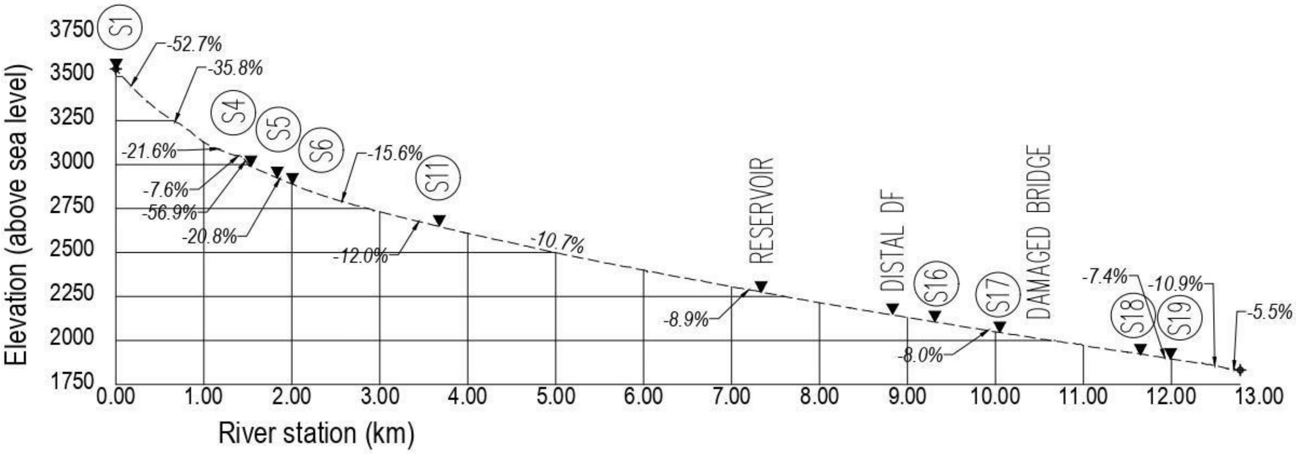

Figure 2: Topographic profile of stream centerline showing slopes of the model sections and location of sites (check points) along the debris/hyperconcentrated flow trajectory.

3. HYDRAULIC MODELS

The 7F event was simulated by two hydraulic models (Flow-R and HEC-RAS) assuming different parametrization and calibrating with points observed in the field.

HEC-RAS model added fixed-bed non-Newtonian mechanics since 6.0 version (Gibson et al., 2022, HEC, 2023). This approach bulk the fluid to account for the solid volume, and change the fluid properties based on one of the non-Newtonian rheological models (Bingham, O'Brian quadratic, or Herschel-Bulkley). HEC-RAS applies single-phase, rheological approaches to non-Newtonian simulations, based on a non-Newtonian algorithm library called DebrisLib (Gibson et al., 2020).

The 2D depth-averaged Shallow Water Equation (SWE) were used to simulate the run or trajectory of the hyper concentrated flow mass. The SWE model solves volume and momentum conservation equations, and includes temporal and spatial accelerations, as well as horizontal mixing; while the Diffusion Wave Equation (DWE) model ignores acceleration and mixing processes, making it less accurate and more computationally efficient.

The Flow-R model (Horton et. al, 2013) is a deterministic and empirical simulation tool that uses a regular grid and concepts of multiple flow directions to model debris flow, snow avalanches or mudfloods. The modeling results are expressed in flow probabilities, limiting dispersion according to available kinetic energy. This model performs two main operations: source identification and propagation or diffusion. Source identification is based on criteria such as sediment availability, water entry, slope gradient, lithology, contributing area, and slope angle, with curvature and land use improving accuracy. The model calculates the dispersion zone for each source using diffusion algorithms based on the slope. In addition, the model estimates the distance travelled by the debris flow, taking into account friction losses and a limit on kinetic energy, thus avoiding the need to estimate the moving mass, which can be difficult for large regions.

The initial border conditions for hydraulic model were obtained from different hydrographs estimated from glacier volume equation (1) distributed in 2 hours baseflow. The peak flow resulted on 28 up to 35 m³/s.

For both models, the TanDEM-X Digital Elevation Model IDEM (Intermediate DEM) with a resolution of 10 m was used, and were provided by the DLR (German Space Agency) through the acquisition of TerraSAR-X and TanDEM-X images for research project proposal (Burgos, 2017).

To calibrate parameters for each rheological model, inundation boundary polygons and measured depths from post-event debris lines were compared. Figure 2 shows the observation points (sites-S) on a longitudinal topographic profile along the riverbed.

3.2. *Simulation results*

HEC-RAS

Volumetric concentration (Cv) between 60 and 65% gave good results for HEC-RAS model. Shear stress of 700 Pa and viscosity of 300 Pa/s were the best calibrated. The Manning coefficient was adopted at 0.05 for the bottom of the channel and 0.08 for floodplains.

This model predicts very well the intrinsic parameters of the 7F debris/hyperconcentrated flow. Maximum mixture flows between 70 to 90 m³/s at lower station (S19 and S20) were predicted by the model. This value matches very well with the initial streamflow estimation of 85 m^3/s.

Likewise, the flow elevation (depth) and width simulated for this event were consistent with values obtained in the field. Debris flow elevations were predicted between 2 and 3 m by the model, while the width of the flow resulted between 30 and 40 m.

According to this simulation the flow velocities exceeded 4 m/s in some sections. However, greater uncertainties resulted in the flow velocity than in the maximum depth of flow as is shown in the Fig. 4.

Flow-R model

The model requires to assume a melted permafrost volume. In this way, a flood wave of 35 m^3/s was transmitted at the beginning, with initial flows of 70 to 90 m^3/s. The model was adjusted by calibrating the rheological parameters to match the widths and heights measured in field at 20 control points (S1 to S20).

This model better predict the location of the initial zone of the 7F flow. This model predicted with higher probability those trajectories of the debris/hiperconcentrated flow that were checked in the field. Moreover, only this model reconstruct the trajectory that followed this debris /hyperconcentrated flow in the site S4 where a huge eroded area was documented.

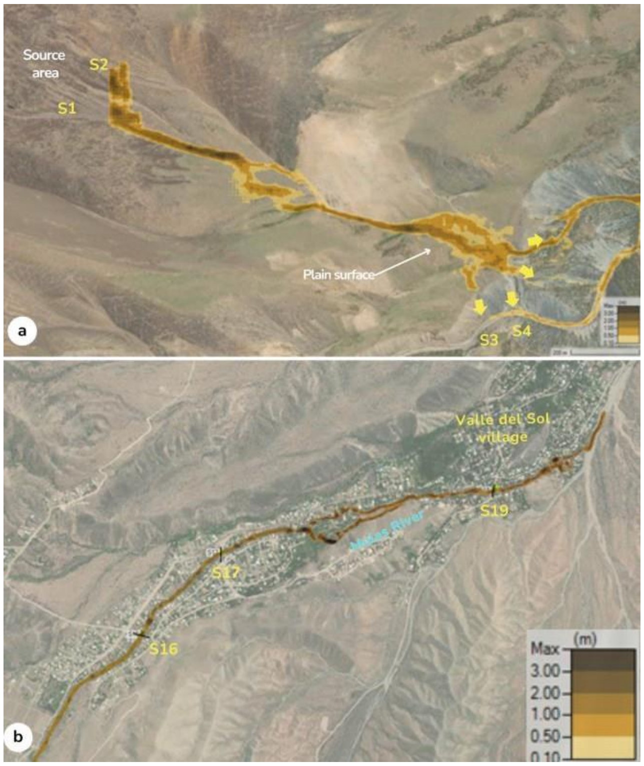

Figure 3: Google images showing the maximum elevation (depth) of the debris/hiperconcentrated flow modeled by HEC-RAS: a. Source area, and b. distal flow zone (see sites location in topographic profile in Fig 2).

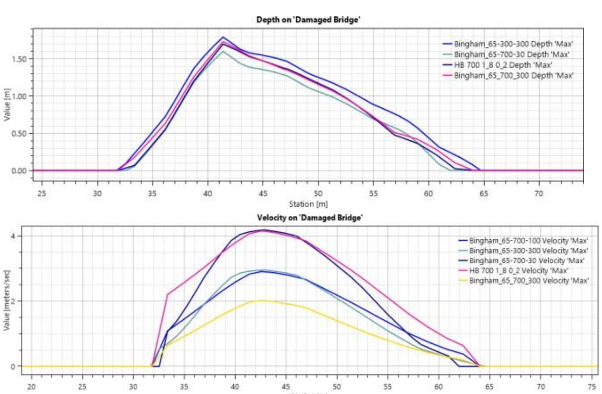

Figure 4: Hydraulic cross-sectional profile of water depths and flow velocities at S17 (Damaged Bridge Station).

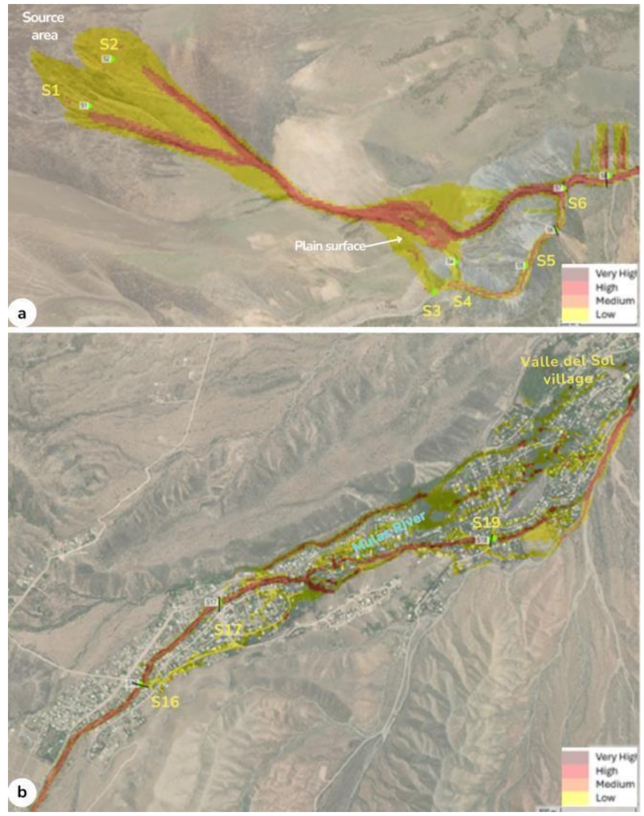

Figure 5: Debris/hyperconcentrated flow propagation probability simulated by FlowR model: a. source area and b. distal lower zone. Site 17 corresponds to the main bridge completely damaged by the 7F flow

4 FINAL REMARKS

A combination of multiple factors played a role in triggering the violent 7F event in 2013. Even though a low precipitation was estimated by sensor data, this rainfall over an unfrozen satured soil due to permafrost thawing could be the cause of the initiation of this debris flow. This finding highlights the sensitivity of periglacial sector to slope instability leading to this type of event.

The boundary conditions of these hydraulic models can be precipitation (rain on-grid method) or hydrographs in tributaries (for wave transits). The latter method was used in this study, assuming a melted permafrost volume. The model was adjusted by calibrating the rheological parameters to match the widths and heights measured in field.

Both used hydraulic models differ in their performance. HEC-RAS model is better at simulating the flow parameters; while the Flow R model is better at predicting the most likely flow trajectory. Despite the uncertainties, hydrodynamic modelling provides the temporal component for hazard analysis of debris flows at the regional scale. By running scenarios with different trigger conditions, such as hydrographs, it is possible to distinguish areas at risk with different temporal frequencies and impact intensities. This can provide important information for cost-benefit analysis and mitigation planning.

5 ACKNOWLEDGEMENTS

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