Deciphering dynamics and magnitude of a recent debris-flow disaster in Vratna Dolina

Juan Antonio Ballesteros Canovas, PhD.[1]; Milan Lehotsky[2]; Karel Silhan[3]; Sladek Jan[2]; Anna Kidova[2]; Radek Tichavsky[3]; Pavel Stastny[4]; Markus Stoffel[5]

ABSTRACT

The capacity to describe extreme debris-flow events responsible of large disasters is clearly limited by the usual lack of records and direct observations. Post-event field recognition is a powerful tool to overcome these limitations and to deliver baseline data for a better process understanding. In this communication, we combine post-event field recognition and dendrogeomorphic approaches to describe an extreme debris-flow event which took place in Vratna valley (Slovakia) in 2014 and to quantify its magnitude. Additionally, we analyse the meteorological triggers of the flow. Results provide insights for an improved characterization of extreme events in this region, and are thought to be useful to calibrate physically-based models in order to implement risk reduction strategies.

KEYWORDS

debris flow, post-event field recognition, tree-ring, peak discharge, Vratna dolina

INTRODUCTION

Rainfall-induced landsliding represents one of the most common triggers of massive debris flow in many mountain environments. Soil moisture saturation commonly results in a decrease of soil cohesion, which in turn can result in intense sediment transfer into steep channels. As a result, powerful mass movements can be one of the downstream consequences (Jakob and Hungr, 2005) with recorded transfers of up to ~109 m^3 and intense geomorphic changes, mostly related with scour erosion and sediment deposition on flatter terrains.

In order to reduce disaster risk, an appropriate description, analysis and interpretation of extreme debris-flow events will be essential. However, in the Slovakian context, but also in other mountain regions, limited knowledge still exists on how big such extreme events are and how they are affected by ongoing and future climatic changes. This question is not trivial, as limited records generally exist in mountain areas, thus avoiding to draw reliable conclusions about their expected magnitude, triggers and geomorphic impacts.

Systematic post-event field recognition is a valuable approach to document the affected areas, magnitude and flow type of recent high-magnitude events (Marchi and Cavalli, 2007). This

1 University of Bern, Bern, SWITZERLAND, juan.ballesteros@dendrolab.ch
2 Slovak Academy of Sciences, Bratislava
3 University of Ostrava, Department of Physical Geography and Geoecology
4 Slovak Hydrometeorological Institute
5 dendrolab.ch - The Swiss Tree-Ring Lab. Institute for Geological Sciences. Baltzerstrasse 1+3, 3012 Bern Climate Change an Climate Impacts (C3i) Institute for Environmental Sciences 7 route de Drize, 1227 Carouge-Geneva

approach combines several data sources, including fresh botanical or geological evidence, gauging records, direct observation or technical documents. By carrying out post-field recognitions, researchers and practitioners will gain new insights about catchment response as well as about the effectiveness of existing mitigation measures. Beyond these advantages, outcomes from post-field event recognition and indirect proxies are extremely valuable to calibrate physically-based models and define scenarios so as to delimit hazard zones.

In this communication, we report observation and measurements from post-event field recognition where we aimed at quantifying the extraordinary debris-flow event of 21 July 2014 in Vranta Dolina (Malá Fatra National Park, Slovakia) after intense rainfalls. The extraordinary nature of the July 2014 debris flow in Vratna valley is underlined by its large geomorphic imprint, and direct economic losses in the order of 6 million US$, mainly due to fan deposition in a ski resort and erosion processes of transport infrastructures downstream of the resort. During the event, 122 tourists remained isolated and had to be rescued the next day.

METHODS

Study site: The Vratna valley is located in the northern part of the Malá Fatra Mts (Slovakia). The catchment has an area of almost 18.4 km^2 with high relief energy of up to 1000 m. The siteis characterized by complex geology (limestone, dolomites, sandstones, and quartzite). The upper slopes (up to 30 – 40°) are covered by alpine meadows, dwarf mountain pines and rock outcrops. In the central part, the valley is covered with spruce and beech forests. At the lower part of the valley, the valley bottom is defined by a narrow gorge (ca. 20 m). Gauging records do not exist for Vrátňanka Brook. The valley belongs to the Malá Fatra National park and is considered as an important all-season tourist centre.

Methodological steps: Two field surveys were carried out after the debris-flow event. The first field survey was performed immediately after the event on 23 July 2014, and focused on the middle and lower sections of the catchment. During this first survey, debris-flow damage, the extension of debris deposits, and flood stage based on fresh indicators has been analysed and reported. Eyewitness information related with the event was also recorded. In addition, we collected aerial pictures taken from a helicopter of the upper part of the catchment to determine fresh geomorphic imprints of erosion at the hillslopes. The second field survey was performed during September 2014. During this survey, we (i) described the geomorphic imprints related with the debris-flow event in the middle and upper parts of the catchment, (ii) perform a survey for peak discharge estimation and modelling, and (iii) investigated past debris-flow activity based on tree-ring analyses (Stoffel and Corona, 2014).

For the geomorphic characterization, we delineated the upper failure zones, the middle transport (and erosion) zone, and the lower deposition zone, as well as the bedload sediment-laden floodwater zone. Field mapping was combined with free access videos and aerial imagery, as well as with field measurements using a total station and laser range finder. In the middle zone affected by both transport and erosion, four channel reaches connected with the main sediment sources and presenting stable cross-section were surveyed in detail. Two more river reaches located in the bedload sediment-laden floodwater zone was surveyed as well in order to determine the evolution of peak discharge along the entire catchment. Cross-sections were characterized by presenting fresh paleostage indicators on trees (PSI) and high water marks (HWMs; Ballesteros-Cánovas et al., 2015) related with the debris-flow event.

Past debris-flow activity was investigated based on tree-ring analyses of scarred trees growing on the cone (Stoffel and Corona, 2014). Event detection was based on injuries, tangential rows of traumatic resin ducts (TRD) and abrupt growth suppression/releases and reaction wood. For cross dating and the detection of growth anomalies, we also sampled undisturbed Norway spruce (Picea abies) trees growing in nearby areas.

We then used the continuity equation:

$$Q=A\cdot V\ (m^3\ s\text{-}1)$$

… to estimate peak discharge of the debris-flow event, where A is the cross-sectional area (m^2) and V is the mean velocity of the flow (m s-1). At the middle transport/erosion zone, the mean debris flow velocity (VDF) was estimated by the empirical equation as a function of the flow depth (H, given by HWMs) and channel slope (I in %) (Rickenmann, 1999):

$$VDF = 4.83 \times H0.5 \times I0.25$$

At the sediment-laden floodwater zone, the mean flow velocity (VF) was alternatively obtained by using the critical-depth method (Webb and Jarret, 2002). This method is specially recommended to determine peak discharge of paleoflood events in mountain streams up to 7% slope subjected presenting critical cross-section, because the peaks discharge estimation is independently of roughness. Mathematically, the flow velocity is estimated by equalling the Froude Number to 1 (F=1):

$$VF = (g \times dh)\ 0.5$$

where g is the gravitational acceleration and dh the flow depth provided by the height of HWMs or PSIs (dh=A/T , with A= cross sectional area of the flow and T= the width of the free surface).

Finally, we also characterized the meteorological conditions related with the triggering of this extreme debris-flow event. To this end, we used gridded observation fields from the freely available E-OBS and TRMM datasets as well as rain gauge records from the Štefanová station (49o13´57´´, 19o03´41´´, 632 m asl) located 3 km far from the ski resort and 5 km from the source area of the debris flow at Chleb peak.

RESULTS

Geomorphic imprint of the disaster and debris-flow quantification

The methodology has allowed description of the geomorphic imprint and quantification of the magnitude of the extreme debris-flow in Vratna valley in 2014.

The failure zone was characterized by 33 patches, ca. 136 000 m^2 in total, on north, north-west and west-facing slopes with angles between 22 and 33°. Distinct scarps of up to 1.5 m in height along the upper and lateral margins of the failure zones distinguish the failure surfaces from adjacent undisturbed slopes. Their upper margins are usually developed at the contact with the downslope lines of dwarf mountain pine patches. Undisturbed sediment exposed in the scarps indicates that failed material consists primarily of a soil body and clast-supported regolith and that the initial mechanism of failure in these debris flows was sliding.

The transport/erosion zone is composed by nine first- and second-order channels with lengths between 260 and 950 m, and average gradients of 22° to34°. Debris-flow erosion washed out the colluvium or exposed fresh outcrops of the bedrock. Downstream, the debris flows removed most of the forest vegetation along the channels, which supposes an important input of large woody debris (LWD) to the system. The vertical erosion and transport of debris flows was intense, mostly manifested on the heads of the original fans as fan head trenches (example zone 5: analysed channel 100 m long with 10 m wide, an average slope by almost 20° defining between 3-4 m of vertical erosion). A large amount of fresh sediment marks and scars on trees defines the maximum flow heights were observed in channel reaches where quartzite outcrops. At these sites, we also estimated peak discharges using the methods described above (see Figure 1). The total discharge contributing to the main fan was 419.2m^3/s.

The sediment zone: The main deposition is located at the junction of four feeder valleys and fan heads covering the upper and middle parts of the main valley. The 1-3 m thick deposition covered a surface 500 m in length and 20-50 m in width of an old debris fan, defining a volume of roughly 75,000m^3. Clasts do not display impact marks, suggesting that the flow was laminar. Sand and pebbles occupy the interstices between the boulders and cobbles.

The existing ski resort operated as an obstacle to the flow which led to its deceleration and mass deposition as well as to flow bifurcation. This infrastructure was seriously damaged by the flowing mass which penetrated inside and deposited there an up to 1-2 m thick layer. The fan toe, used as a parking area, was impacted by the mixed gravel-sandy and LWD deposition up to 0.5 m thick and 39 cars have been removed and damaged by the debris-flow current.

The main very coarse (boulder-cobble) debris-flow mass followed the main, fourth-order channel and moved downstream. On the fan-toe with an average of 11° gradient, the already entrenched channel (ca. 3 m) incised again into bedrock (up to 1 m), doubled its width (up to 15 m) and undercut the access road. Several cars from the parking area were thereby damaged.

Suspended load sediment-laden floodwater zone: This area exhibits a different response to the debris-flow event in comparison with those previously mentioned. The upper part of this zone is ca. 1,700 m long with a relatively wide valley floor (100-150 m), unconfined channel, relatively low banks and low slope (on average 1.5°) inhibited further transport of coarse mass within the channel. However, the trash lines, avulsions and sandy deposition reflect the flood demine of the suspended sediment load during the prevailing time of the debris flow event. Downstream along the ca. 800 m gorge the flow eroded the route at several places so that it was unpassable for cars. At this level, peak discharge was reconstructed at 103 and 117.5 m^3/s for sites 5 and 6, respectively. According to official reports, 20,000 m^3 of the deposited material has been removed, ca. 5 km of the Vrátňanka Brook including the reaches in Terchová village had to be channelized again after the event resulting in overall costs of restoration works of 12 M€.

Meteorological context and trigger

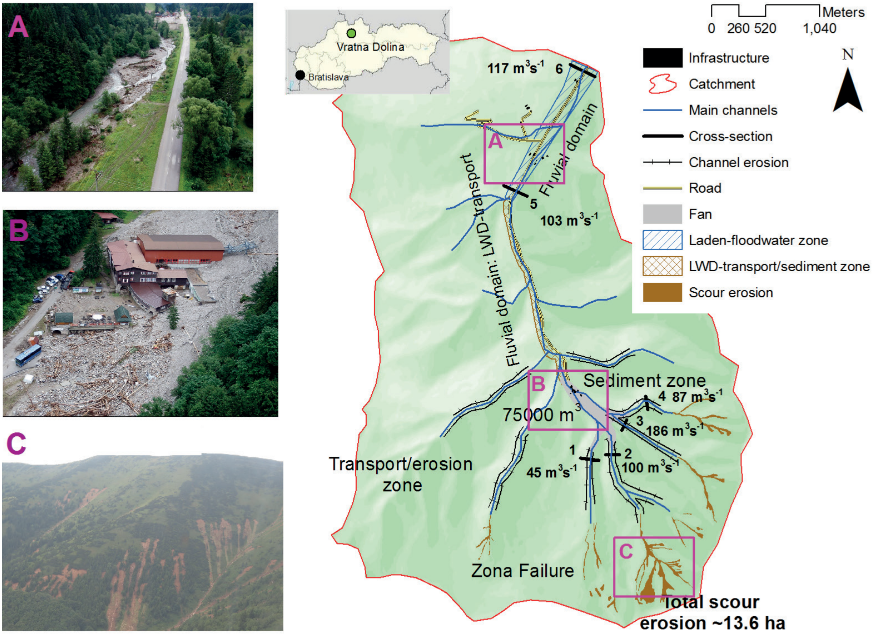

Figure 1: Geomorphological sketch of the Vratna Dolina catchment. The cross section 1 to 6 represent the location were the peak discharges were reconstructed.

From a meteorological perspective, the synoptic situation related with this extreme debris-flow event is characterized by a shallow trough of low pressure spread from the North Sea over the Alpine and Carpathian areas on 20 July 2014, which moved over SE Moravian and W Slovakia the subsequent day (Figure 2). At the same time, warm and humid air masses crossed Slovakia, and a low pressure system at high atmospheric layers in N Italy left an unstable vertical distribution of air pressure. The co-occurrence of convergent air circulation, air humidity, and convection systems left intense and short-lived precipitation over the Malá Fatra region. According to rainfall data from the local gauge station, the core of the downpour occurred from 15:30 to 17:00 with 52 mm (daily total 62 mm). The course of the downpour indicates two rainfall events/waves: a first one 15:30 - 16:05 with 18 mm and a second one from 16:05 to 17:00 with 34 mm. At short term, the maximum rainfall intensity that took place during the first wave was between 50–60 mm/h, and during the second wave almost 60–80 mm/h.

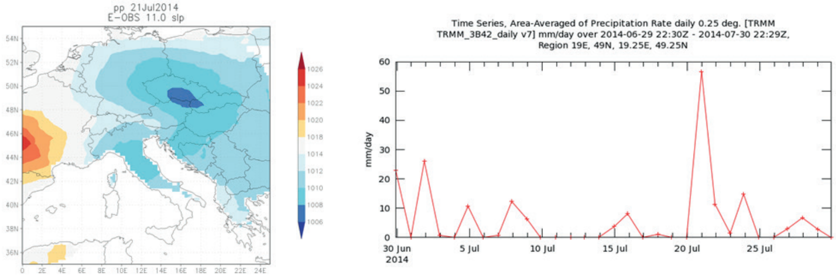

Figure 2: Surface field pressure retrieved from E-OBS dataset and daily area-average precipitation at the study site for the entire month (TRMM dataset).

Past debris flow activity at the study site

Despite of the lack of gauge station records, historical archives suggest that similar large flow events could have taken place in the catchment in 1848 (Kapasný, 2008). Tree-ring analysis suggests that in recent decades, at least six events occurred on the two cones located in the upper ski resort. The oldest event on cone 1 was dated at 1959 (1965 on cone 2) and the youngest to 1998 (2008 on cone 2). Synchronous process activity on both cones occurred in 1965 and 1991. The event chronologies on both cones are shown in Figure 3. This paleo-reconstruction suggests a recurrence interval of 9.2 years for cone 1, and 7 years for cone 2 over the last ~50 yrs.

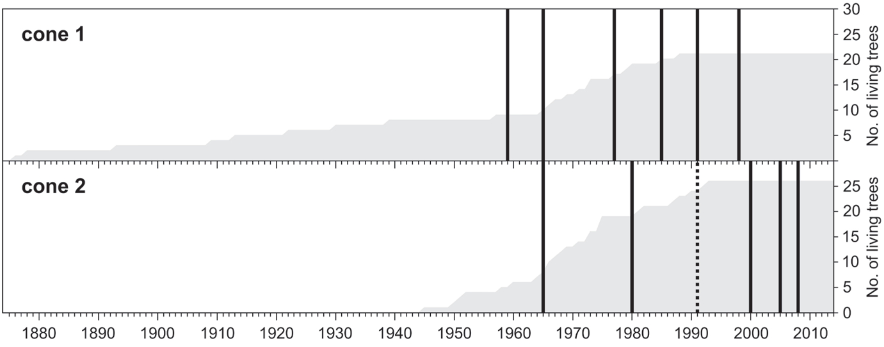

Figure 3: The chronologies of past events on both studied cones. Full black line – sure event (Wit ≥ 1 and at least two trees with signal in tree ring series), dashed black line – probably event (at least two trees with signal but Wit < 1)

CONCLUSIONS

The field surveys carried out after the event coupled with available aerial pictures and different climatological dataset have allowed to quantify and describe the extreme debris flow in Vratna Dolina during July 2014. We have described the geomorphic imprint of this event, and evaluated its erosion, transport and sedimentation capacity. Our observation and quantification revels that both large amount of sediment and woody debris were transported during the event, with a major deposition zone that matches with the location of the ski resort facilities. The subset of observations here reported can be used to calibrate debris flow models (i.e. RAMMS model) and provide reliable scenarios for future extreme events, which could then be used to help the planning and implementation of future infrastructure development in the region. Moreover, our observation related with climate-linkages and meteorological triggers could be used to improve our understanding of rainfall threshold for triggering extreme debris flow events in the region, and consequently useful for early warning system proposes. Therefore, despite the exceptional weather conditions during the event, we could report historical and tree-ring records suggesting that debris-flow events have taken place frequently in the area.

Our observations can be used to provide inputs for the modeling of extreme scenarios which could then be used to help the planning and implementation of future infrastructure development in the region. Moreover, our outcomes can be used to improve our understanding of climate-extreme event linkages in European mountains.

REFERENCES

- Ballesteros-Cánovas, J.A. Stoffel, M. St. George, S. Hirschboeck, K. (2015). A review of flood records from tree rings. Progress in Phisical Geogrpahy. In press.
- Jakob M., Hungr O., Jakob D.M. (2005). Debris-flow hazards and related phenomena. Berlin, Springer.
- Marchi, L., Cavalli, M. (2007). Procedures for the documentation of historical debris flows: application to the Chieppena Torrent (Italian Alps). Environmental management 40(3): 493-503.
- Rickenmann, D. (1999). Empirical relationships for debris flows. Natural hazards 19(1): 47-77.
- Stoffel, M., Corona, C., 2014. Dendroecological dating of geomorphic disturbance in tress. Tree Ring Res. 70, 3-20.
- Webb RH., Jarrett RD. (2002). One Dimensional Estimation Techniques for Discharges of Paleofloods and Historical Floods. Ancient Floods, Modern Hazards: 111-125.