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Evaluating landslide response in a seismic and rainfall regime: a case study from the SE Carpathians, Romania

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SUPPLEMENTARY DATA

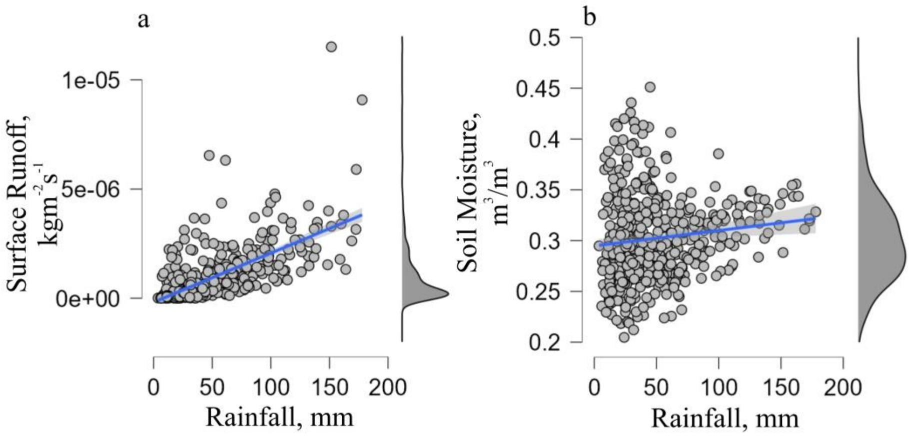

Fig. S1: Correlation of Rainfall, Surface Runoff, and Soil Moisture at monthly scale during the years 1982-2019. Blue line indicates linear regression and shaded region around it refers to 95% confidence interval. Data Source: McNally et al. 2018.

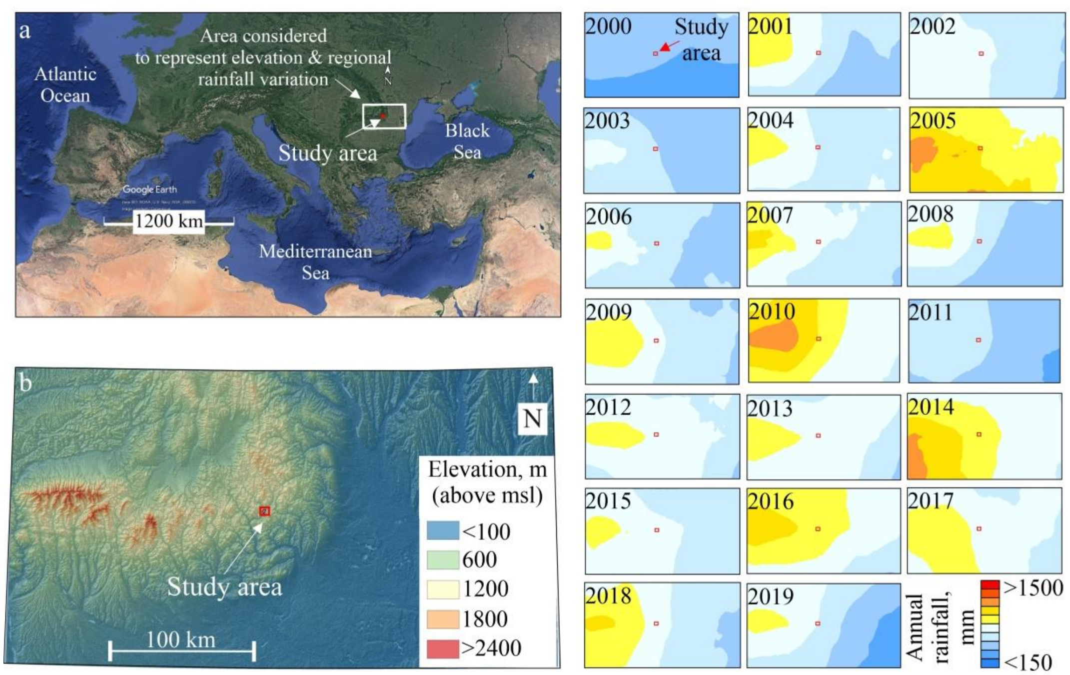

Fig. S2: Regional rainfall variation. Inset 'a' shows the location of study area and extent used to represent elevation and regional rainfall variation. Image Source: Google earth. Inset 'b' shows regional elevation map. Data Source: SRTM. Rainfall data source: GPM_3IMERGDF v.06 (Huffman et al. 2019).

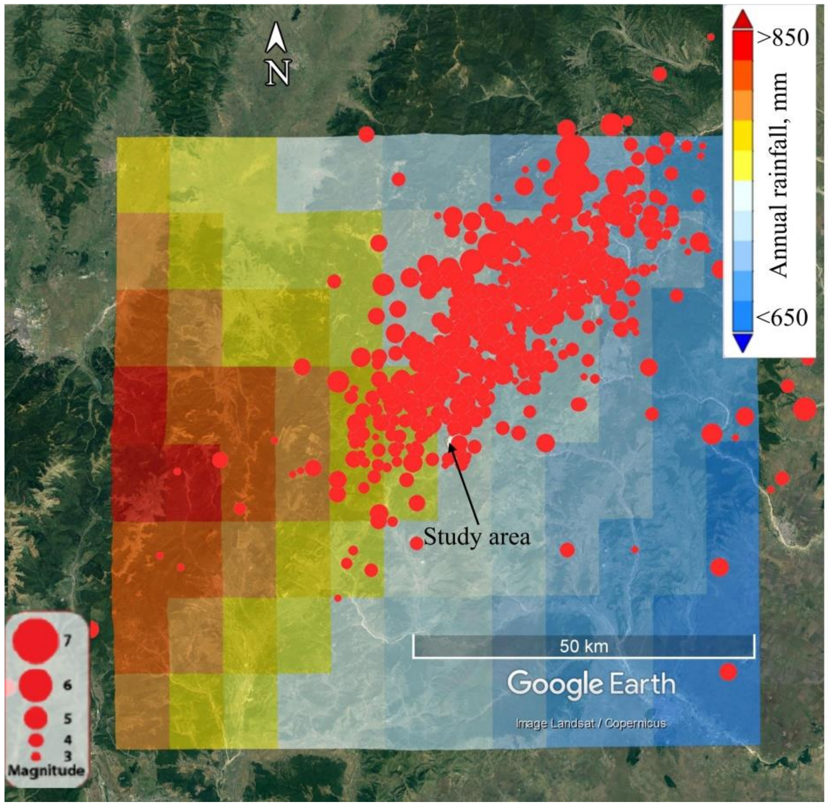

Fig. S3: Rainfall and Earthquake distribution around study area. Daily Rainfall data is time averaged (2000-2019) to show spatial distribution. Rainfall Data Source: GPM IMERG Final Precipitation (Huffman et al. 2019). Earthquake Data Source: National Institute for Earth Physics, Romania.

Note: The present study is intended to evaluate the hillslope response under extreme Rainfall and Earthquake conditions. More emphasis was given to understand the particular hillslope 'Varlaam' response. Further, correlating rainfall and earthquake at slope level might be difficult because both triggering factors operate and affect at different scale. Earthquakes even with the distant epicentres (250–300 km) have triggered landslides in the region (Havenith et al. 2016), whereas rainfall varies within kilometers (Supp. Fig. 3). Another limitation exists with the availability of high resolution rainfall data. At present, the best possible spatial resolution for the daily rainfall data, available for the study area, is 0.1° (Huffman et al. 2019).

Governing equations of the RAMMS Debris Flow model

A Voellmy-Salm (Voellmy 1955; Salm, 1993) Fluid-flow continuum Model

Although the avalanche/debris flow is made up of discrete granules, it has been assumed as a continuum. It implies that the depth and length of the flowing mass are large compared to the dimensions of a typical particle. While the mass density of the material making up the individual grains might be constant, noticeable variations in bulk density may exist as a result of variations in void spaces between grains. Such fluid-flow continuum has following assumptions (Bartelt et al., 1999);

- Flowing material is modeled as a fluid continuum of mean constant density ρ.
- The flow width is known.
- A clearly defined top flow surface exists.
- The flow height, $h(x, t)$, is the average flow height across the section, i.e. the flow height is level over the flow width, $w(x)$.
- The vertical pressure distribution is hydrostatic. Centripetal pressures which modify the hydrostatic pressure distribution are not accounted for.
- Flow velocity and depth are unsteady and non-uniform.

Such flow moves in an unsteady and non-uniform motion and is characterized by two main flow parameters, which are the flow height H(x, y, t) (m) and the mean velocity U(x, y, t) (m/s). The initial height (or release area depth) is determined by the user when defining the source area of the debris flow as a polygon. Thus, the Voellmy-Salm model uses the following mass balance equation for such a flow:

$$\partial_t H + \partial_x (HU_x) + \partial_y HU_y = Q(_{xyt})$$

Where, Ux and Uy are the velocities in the x and y directions respectively, and Q(x, y, t) (m/s) is the mass production source term, also called the entrainment rate (Q >0) or deposition rate (Q<0).

The principles of conservation of momentum are invoked to provide the governing differential equations describing depth-averaged flow movement in conservative form in the x and y directions;

$$\partial_t (HU_x) + \partial_x \{c_x HU^2{}_X + g_z k_{a/p} H^2 /2\} + \partial y (HU_x U_y) = S_{gx} - S_{fx}$$

and

$$\partial_t (HU_y) + \partial_y \{c_y HU^2{}_y + g_z k_{a/p} H^2 /2\} + \partial y (HU_x U_y) = S_{gy} - S_{fy}$$

Where, c_x and c_y are profile shape factors that are determined by the DEM. The $k_{a/p}$: $k_{\text{active (tensile)/passive (compressive)}}$ is the earth pressure coefficient that is set to 1 to model the flow hydrostatically. Here, $k_{a/p} = 2+ [1\pm \{1-(1+\tan^2\delta) \cos^2\phi\} \wedge^{1/2} / \cos^2\phi - 1]$ (Savage and Hutter, 1991).

Where, δ is bed friction angle and ϕ is material friction angle. However, to avoid the complexities caused by bed friction angle, slope angle, dry friction, μ, and cohesion on the active/passive coefficient, formula has been simplified in the form of Rankine theory;

$$k_{a/p} = \tan^2 (45°\pm\phi/2) \text{ (Rankine, 1857 ; Bartelt et al. 1999)}$$

$$k=k_a\ (\partial U/\partial_X > 0) \text{ during flow along the slope}$$

$$k=k_p \ (\partial U/\partial_X < 0) \text{ during deposition of runout}$$

Where, $\partial U/\partial_X$ refers to velocity gradient in longitudinal (along the slope) direction.

The S_g and S_f refer to acceleration (driving factor) and friction (frictional resistance factor), respectively.

$$S_{gx} = g_x H \text{ and } S_{gy} = g_y H$$

Where, g is acceleration due to gravity and H is flow height. Further, with an assumption that shear deformations during flow are concentrated at the base of the flow, the basal shear resistance consisting of a dry Coulomb-like friction (μ) and a Chezy-like resistance (ξ), has been given as;

$$S_f = \mu\sigma + (\rho g U^2)/\xi$$

The Chezy-like resistance is famous as "turbulent" friction, term used by Voellmy (1955) since the mathematical formulations are similar to the well-known turbulent Chezy equation (Herschel, 1897; Chow, 1959) used in open-channel-flow hydraulics.

Where, σ is the normal stress that is dependent on the flow height (H) through the following equation;

$$\sigma = \rho g H \cos\psi$$

Where, ψ is slope angle. Later, in view of the observations of debris flow as coherent visco-plastic flow and its similarity to snow avalanche, nonlinear relationship between normal stress and shear stress was proposed (Platezer et al. 2007). This allowed the inclusion of cohesion (c) in the equation with the following modification.

$$S_f = \mu\sigma + (1-\mu)\ c - (1-\mu)\ c \exp^{(-\sigma/c)} + (\rho g U^2)/\xi$$

This formula ensures that $S_f \rightarrow 0$ when both $\sigma \rightarrow 0$ and $U \rightarrow 0$. It increases the shear stress and therefore causes the avalanche or debris flow to stop earlier, depending on the value of c (RAMMS, v.1.7). Recently, Zimmermann et al. (2020) have noted that such cohesive interaction improved the accuracy of the observed deposition of hillslope debris flow.

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