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Debris flow hazard assessment by means of numerical simulations: implications for the Rotolon creek valley (Northern Italy)

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Abstract: On 4th November 2010, a debris flow detached from a large debris cover accumulated above the lowermost portion of the Rotolon landslide (Vicentine Pre-Alps, NE Italy) and channelized in the valley below within the Rotolon Creek riverbed. Such event evolved into a highly mobile and sudden debris flow, damaging some hydraulic works and putting at high risk four villages located along the creek banks. A monitoring campaign was carried out by means of a ground based radar interferometer (GB-InSAR) to evaluate any residual displacement risk in the affected area and in the undisturbed neighbouring materials. Moreover, starting from the current slope condition, a landslide runout numerical modelling was performed by means of DAN-3D code to assess the impacted areas, flow velocity, and deposit distribution of the simulated events. The rheological parameters necessary for an accurate modelling were obtained through the back analysis of the 2010 debris flow event. Back analysis was calibrated with all of the available terrain data coming from field surveys and ancillary documents, such as topographic, geomorphological and geological maps, with pre- and post-event LiDAR derived DTMs, and with orthophotos. Finally, to identify new possible future debris flow source areas as input data for the new modelling, all the obtained terrain data were reanalysed and integrated with the GB-InSAR displacement maps; consequently, new simulations were made to forecast future events. The results show that the integration of the selected modelling technique with ancillary data and radar displacement maps can be a very useful tool for managing problems related to debris flow events in the examined area.

Keywords: Debris flow; DAN-3D; GB-InSAR; Numerical modelling; Deep Seated Gravitational Slope Deformation (DSGSD); Rotolon Creek

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Introduction

Debris flows are water-laden collapsing masses of soil and fragmented rock encompassing a wide range of characteristics and varying widely in magnitude (Jakob 2005), composition (Coussot and Meunier 1996), and initiation process (Coe et al. 2008). Some of these phenomena start in loworder streams, both in riverbeds and overbank deposits, because of the intense runoff, or to overland flow, mobilizing sediment without slope instability phenomena (Brayshaw and Hassan 2009). Other debris flow types are related to slope failures that rush down mountainsides, subsequently funnelling into stream channels and forming thick deposits on valley floors (Iverson 1997). The latter type in particular is usually associated with intense erosion along their path, which can lead to a substantial increase in volume, runout distance, and disruptive energy. All these aspects may eventually cause severe damage to infrastructure and endanger people, especially in populated mountainous areas, where most human activities are concentrated in valley floors (Pazzi et al. 2016), coinciding with debris flow impact areas (i.e., the area impacted by the flow during its descent, which has the maximum flow areal spreading since the beginning of the run).

For this reason, the prediction of landslide runout and its effect is essential in landslide risk assessment. The main quantitative methods, useful to obtain it, can be classified as either empirical or analytical. Empirical methods operate on observational data correlations to calculate the extent of the runout zone (Hsü 1975; Corominas 1996). Analytical methods try to predict the motion of the landslide mass from initiation to deposition, providing estimates of hazard extent and intensity (Savage and Hutter 1989; Iverson 1997). The latter models perform the time-wise numerical solution of the equations of motion and advance the location of the simulated landslide incrementally, computing the spatial distribution of landslide hazard intensity parameters, such as flow velocity and depth (Hungr 1995).

The latter approach was applied to the Rotolon creek valley (Little Dolomites chain, NE Italy) which hosts populations from ancient times and it is historically prone to landslide processes (Trivelli et al. 1991). These gravitational instabilities are induced by the local geological and geomorphological features, such as very steep slopes characterized by highly fractured and weathered rocks. Following a period of heavy and persistent rainfall, on 4th November 2010, a debris flow detached from the debris cover of the lowermost portion of the Rotolon landslide, channelizing into the Rotolon creek riverbed, mixing with water, and evolving into a highly mobile debris flow with a travel distance of approximately 4 km. This event damaged several hydraulic works, such as weirs, fords, and bank protections, putting at high risk the infrastructures (e.g., bridges and roads alongside the watercourse) and especially four villages situated along the creek banks (Maltaure, Turcati, Parlati and Recoaro Terme) (Frodella et al. 2014). On 8th December 2010, a GB-InSAR monitoring campaign was carried out to assess the landslide residual displacements and support the local authorities for the emergency management (Fidolini et al. 2015). In this framework, a landslide geomorphological mapping was performed (Frodella et al. 2014, 2015), together with the design and implementation of an early warning system, and a landslide trigger/runout analysis (Frigerio et al. 2014; Bossi et al. 2015a, b). In this work, a back analysis of the 2010 event was carried out using a 3D numerical code called DAN-3D (McDougall and Hungr 2004; Hungr and McDougall 2009), refining the analysis carried out by Bossi et al. (2015b) and integrating information coming from different disciplines, comprising geomorphology, hydraulics, and geotechnical data. DAN-3D was chosen because it was developed for the simulation of extremely rapid shallow landslides movements, even in complex topographies (McDougall and Hungr 2004, Salvatici et al. 2016a, b). Moreover, the DAN-3D code was considered for the studied debris flow since it is based on the “equivalent fluid” theory, which is capable of simulating entrainment and corresponding rheology changes (Hungr 1995).

Furthermore, the DAN-3D simulated results were validated by means of two essential comparisons between i) the flow geometrical parameters obtained by the pre- and post-landslide event high resolution DTMs (2 m grid resolution) and ii) the modelled flow velocities along selected cross-sections, with the ones estimated from the empirical equations of Chow (1957), Mizuyama et al. (1992), and Rickenmann (1999) (Figure 1a). Finally, a forecast analysis was carried out to evaluate possible future debris flow events. This analysis required to find a new possible landslide source area and volumes, to use the post-event DTM as topography, and to use the rheological parameters of back analysis. The more difficult task is usually represented by the identification of new possible landslide reactivation zones (i.e., source areas). In this work, such area was detected with high precision through the integrated analysis of the radar displacement maps (Fidolini et al. 2015) and the geomorphological field evidence (Frodella et al. 2014; 2015). Starting from this source area, new simulations were performed, taking into account the 2010 event back analysis rheological parameters and the new possible landslide detachments, whose volumes were calculated by means of a statistical analysis of the 2010–source area thickness.

1 Study Area

The study area is located in the western sector of the Veneto region (Northern Italy), in the Vicentine Pre-alps, on the south-eastern flank of the Little Dolomites chain, which are part of the Agno river basin (Figure 1a). The Rotolon landslide affects limestone and dolomitic formations belonging to the South Alpine Domain (early Triassic-early Jurassic) (Barbieri et al. 1980; Figure 1b), covering an area of approximately 626,000 m^2 and developing from approximately 1700 m to 1100 m a.s.l. (Frodella et al. 2014, 2015; Fidolini et al. 2015). For its areal extension, morpho-structural characteristics (presence of trenches, counter-slope scarps, sub-horizontal fractures in correspondence with the landslide toe, accessory instability phenomena, and kinematic very slow displacement of large fractured rock masses (Agliardi et al. 2009)), this landslide presents the features of a "*Sackung*"-type Deep Seated Gravitational Slope Deformation (DSGSD), according to Zischinsky (1969).

The landslide area can be divided into two sectors: i) an upper Detachment sector and ii) a lower Dismantling sector (Frodella et al. 2014). The Detachment sector has a mean slope of approximately 30° and is located nearby the landslide crown: it is characterized by tensional fractures, trenches and crests and largely comprises colluvial, rockfall and rock avalanche materials, with very coarse and heterometric clasts and scattered boulders. The Dismantling sector has a slope mean angle of approximately 34° and is characterized by mainly cobble-sized blocks and scattered boulders in coarse sandy matrix, coming from the Detachment sector rock slopes. This area is particularly prone to debris flow, as documented by recent bibliographies (Trivelli 1991; Altieri et al. 1994; Bossi et al. 2015b) and historical documentation available since 1573 (Schneuwly-Bollschweiler et al. 2012). The 2010 debris flow event started along the right bank sector of the Rotolon landslide detrital cover, at approximately 1400 m a.s.l., and settled at approximately 550 m a.s.l., with an adopt height of approximately 850 m. The collapsed material, characterized by a volume of approximately 320,000 m^3 (Bossi et al. 2015b) spread along 4 km, was formed by very coarse and heterometric clasts, ranging from cobbles to boulders with scattered blocks (decimetric to decametric in size) in a coarse sandy matrix.

2 Analytical Methods

2.1 DAN-3D numerical model

Many dynamic models exist; particularly, the DAN-3D numerical code (McDougall and Hungr 2004; Hungr and McDougall 2009) was selected to model the 4th November 2010 debris flow event. The model uses the Lagrangian numerical method to solve the depth-average integrated Saint-Venant equations, adapted from Smoothed Particle Hydrodynamics (SPH). This numerical code assumes a simplified approach of "equivalent-fluid" (Hungr 1995) with an internal frictional rheology, governed by an internal friction angle and a basal rheology. The latter was chosen by using some implemented rheological kernel: i) frictional; ii) Bingham; iii) Voellmy; iv) Newtonian and v) plastic. These kernels are usually selected based on an empirical calibration procedure, in which a case study is subjected to trial-and-error back analysis. The choice of the rheology leads to different results: for example, a frictional model produces relatively high velocities and forward-tapering deposits, while a Voellmy model predicts lower velocities and forward-bulging deposits (Hungr and Evans 1996). Furthermore, DAN-3D can simulate the entrainment while considering the "erosion rate" factor, defined as the ratio between the final slide volume, the initial slide volume and the length of the erodible zones. The model requires three input files: topography (path file),

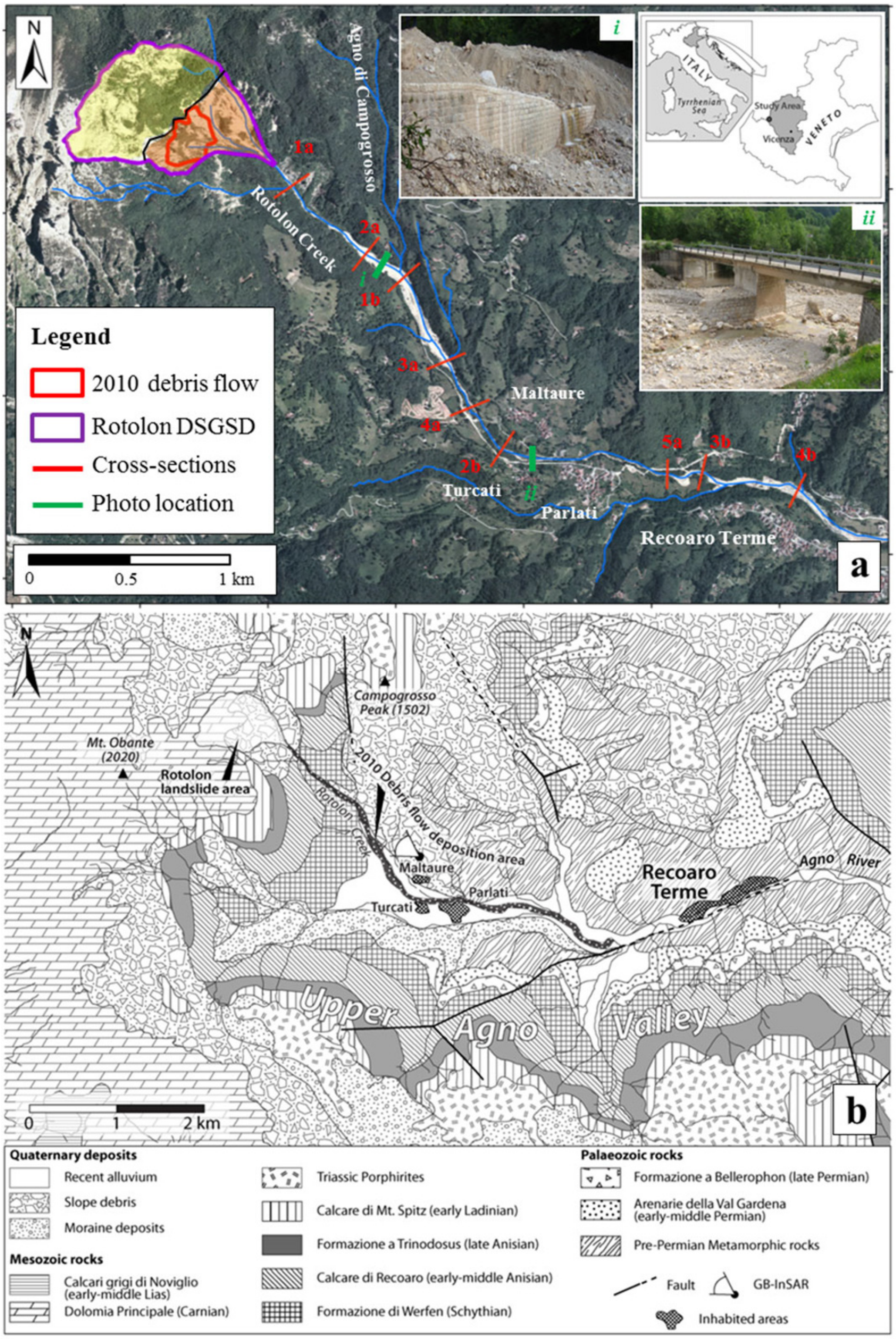

Figure 1 Overview of the study area: a) the Rotolon DSGSD landslide (violet line), with the local hydrographic network (blue lines) and all the main villages in the valley. The 4th November 2010 debris flow source area is highlighted in red. Yellow indicates the Detachment sector, orange indicates the Dismantling sector (according to Fidolini et al. 2015), and the black line divides the two sectors. Numbered red lines are the analysed cross-sections. i) and ii) are two examples of the infrastructures located along the creek. b) Geological map with radar position (modified from Fidolini et al. 2015).

source area (source file), and number of materials used with different rheology and erosion (erosion file). According to the related recent bibliography (Yifru 2014; Nocentini et al. 2015; Schraml et al. 2015, Salvatici et al. 2016 a, b; Morelli et al. 2016) and examining the dynamic of the event through its deposit, the Voellmy rheological kernel was chosen for the entire stretch. This rheology assumes the resistance as the sum of a frictional and a turbulent term:

$$\tau = f\sigma_z + \frac{\rho g v_x^2}{\xi} \tag{1}$$

where τ (N/m²) is the share stress, f (-) is the frictional component of resistance, which controls the runout distance, σ_z (kg/m²) is the normal stress, ξ (m/s²) is the turbulence parameter, which controls the flow velocity, introduced by Voellmy (1955) and in landslide dynamics it represents all possible sources of velocity-dependent resistance. ρ (kg/m³), g (m/s²) and v_x (m/s) are the density, the gravity, and the velocity, respectively. The Voellmy model is useful because it requires only two parameters to calibrate. When the flow moves rapidly, the turbulent term controls the friction and the frictional term prevails when the flow moves slowly.

The pre-event topography was modified with post-event topography by subtracting the deposit thickness of the source area to obtain the perfect path file for the model. The source thickness was calculated by subtracting post- and pre-event 2-meter-high resolution DTMs and isolating the source area (Morelli et al. 2010). To perform simulation of the studied event, a constant rheology along its path was not considered. The landslide runout propagation, in fact, was divided into three parts, according to the most evident fluvial morphological variability: i) narrowing and enlargements; ii) hydraulic jumps and curvatures; iii) possible contributions from minor tributaries; and iv) the presence of several hydraulic works for flow control, such as weirs, fords, gabions, retaining walls and other bank protections. Subsequently, a forecast analysis was carried out to individuate risk scenarios. The new model was applied to the post-event topography, considering the rheological parameters obtained for the 2010 debris flow event back analysis and assuming a new possible events source area provided by the analysis of cumulative monthly displacement maps calculated from radar data.

2.2 Empirical flow velocity estimation

Most equations available in the literature estimate the translation velocity of the frontal part or the maximum (mean cross-sectional) velocity along the debris flow surge (Hungr et al. 1984). To validate the back analysis, the flow velocity assessment represents a useful parameter. In the latter framework, the velocity of the Rotolon event was estimated using two different equations:

i) the back-calculation method of the Forced Vortex Equation for super-elevation, which requires an estimate of the bend's radius of curvature (Chow 1959; Hungr et al. 1984; Revellino et al. 2004; Zanchetta et al. 2004; Prochaska et al. 2008):

$$v = \left(\frac{gR_c\Delta h}{w}\right)^{0.5} \tag{2}$$

where g (m/s²) is the acceleration of gravity, Δh (m) is the super-elevation of the debris wave in the channel bends, w (m) is the channel width and R_c (m) is the curvature radius. The radius of curvature can be calculated in the field using the relation between the two cross-section arc lengths and their angular (azimuth) difference or taken from the topographic map. The equation assumes that flow is subcritical, the radius of curvature is equal for all streamlines, and every streamline's velocity is equal to the mean flow velocity (Pierson and Scott 1985).

ii) the method of velocity prediction, based on the maximum discharge (Rickenmann 1999; Zanchetta et al. 2004):

$$v = 2.1{Q_p}^{0.33}S^{0.33} \tag{3}$$

where Q_p (m³/s) is the maximum discharge and S (-) is the channel bed slope.

The flow's radius of curvature was calculated where debris flow travels around a bend (cross-sections 1b-4b, Figure 1a). It was obtained both from a graphical processing using a 1:5000 topographic map and from the application of the method of Prochaska et al. (2008) and its empirical equations. The super-elevation of debris flow (h) in the channels bed was calculated from an integrate analysis between a 2010 November orthophoto, post-event DTM, and field observation. On the other hand, at each cross-section from 1a to 5a

(Figure 1a), the velocity estimation was based on Rickenmann's (1999) flow equations, considering the approximate maximum discharge (Q_p), assessed using two empirical relationships between peak discharge and volume of the debris flow (Mizuyama et al. 1992; Rickenmann 1999)

2.3 Ground Based Interferometric Synthetic Radar (GB-InSAR)

GB-InSAR is a remote sensing technique widely used for ground displacements and slope movements monitoring with metric or sub-metric resolution and submillimetre accuracy (Rudolf et al. 1999; Tarchi et al. 2003; Antonello et al. 2004; Nolesini et al. 2013; Bardi et al. 2014; Frodella et al. 2016). This instrumentation provides a remotely sensed measurement of ground displacements from an installation point on a solid base facing the observed scenario. GB-InSAR radar systems generate an electromagnetic wave belonging to the microwave portion of the electromagnetic spectrum and measure the echo of scattering surfaces. The technique working principle is the evaluation of the phase difference, pixel by pixel, between two pairs of averaged sequential SAR images of the same scenario, constituting an interferogram (Bamler and Hartl 1998). From the obtained interferogram, considering the time spanning between two or more subsequent coherent SAR image acquisitions, it is possible to derive a map of the displacements along the sensor line of sight (LOS), with selectable sampling frequency. To monitor the source area of the 2010 landslide, a GB-InSAR system was located in the village of Maltaure, at an average distance of 3 km with respect to the debris flow source area and the surrounding debris cover (Figure 1b). The antenna moved along a 2.7 m rail, and the SAR image range resolution (spatial resolution along the direction perpendicular to the rail) was approximately 3 m, while the azimuth resolution (spatial resolution parallel to the synthetic aperture) was between 1.6 m and 9.3 m (with a 500 m and 2900 m sensor-target distance, respectively). The landslide monitoring activity was carried out from 8th December 2010 to 31st March 2013 (Fidolini et al. 2015) (Figure 2a). By comparing the landslide geomorphological field observations (Frodella et al. 2014, 2015) with the obtained GB-InSAR displacement maps, a potential source area of possible future debris flow was detected (Figure 2b). The radar displacement maps were elaborated in a MATLAB environment to automatically extract from the cumulated displacement maps all the areas affected by movements higher than a selected threshold value. The latter was automatically calculated by the MATLAB code as the minimum displacement among all the minimum displacement monthly values. The extracted areas were analysed in the ArcGIS™ and in Golden Software SURFER™ environments to obtain the new critical sector, which could be the potential source area of future possible events. This critical sector is characterized by the peak cumulative displacements recorded in the monitored area (Figure 2b), confirming that it is characterized by intense ground deformation and erosional processes. Furthermore, as confirmed by geomorphological evidence, the thermographic

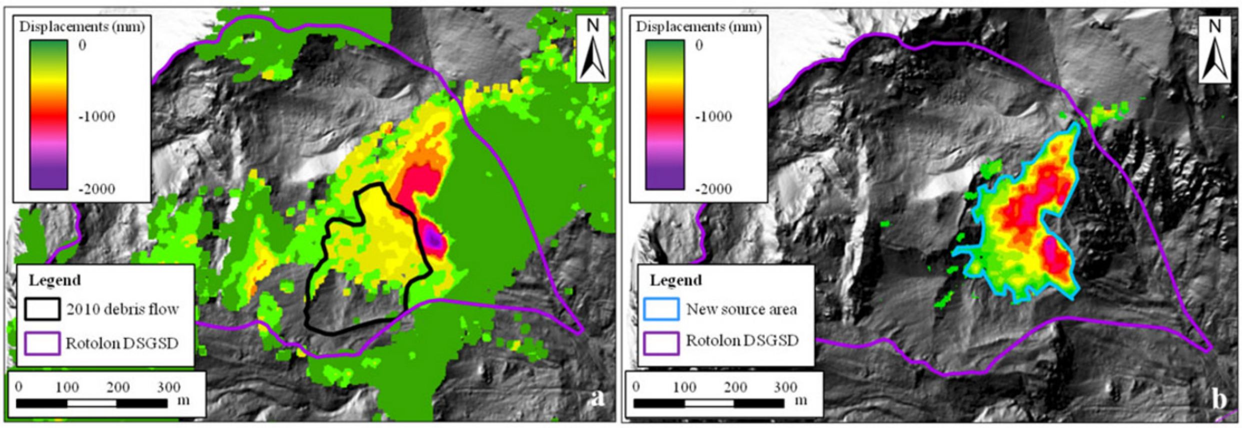

Figure 2 Cumulative displacement map recorded by GB-InSAR a) between December 2010 and March 2013 within the black outlined 2010 debris flow event source area; b) the MATLAB code elaboration and the new possible source area (shown in blue).

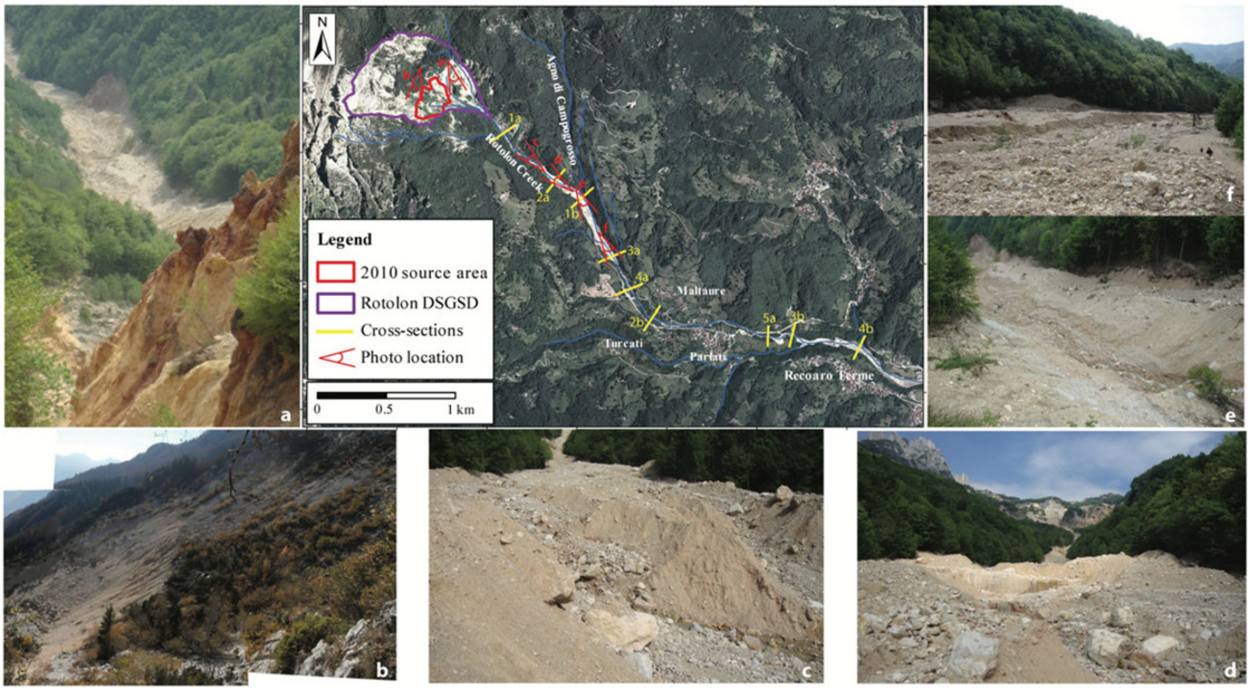

Figure 3 Location of photos acquired during field surveys following the 2010 landslide event: a) proximal deposit below the source area, b) residual source area, c, d, e, f) 2010 debris flow deposits in the valley upstream the urbanized area.

surveys, the rainfall temporal distribution and the modelled drainage pattern (Frodella et al. 2014, 2015), this abovementioned detected area is characterized by the presence of ephemeral creeks which contribute to the sub-surface water circulation. In addition, that this area, part of a DSGSD Dismantling sector, is made of a very permeable detrital cover with high slope angle sectors (mean value of 34°), it is usually assumed that in case of exceptional heavy rainfall (very concentrated events or accumulated waters for a long and uninterrupted period as occurred in November 2010) this area can be affected by debris sector detachments, which therefore trigger debris flows.

3 Results and Discussions

3.1 Numerical model: back analysis

Knowledge of measurable characteristics of a real event, such as runout distance, geometric distribution of deposits, velocities, and time duration of the flow motion, is fundamental issues for landslide runout back analysis based on numerical models. In this case study, the morphometric results of simulations (i.e., deposits distribution as areal spread, thickness, and travel distance) were calibrated using the difference between the pre- and post-event high-resolution DTMs (2×2 m cell resolution) of the studied valley with the support of field investigations (Figure 3). Whereas the flow velocity was calculated by empirical equations, described in section 2.2. The best results of the back analysis DAN-3D simulation were obtained using three types of materials (for materials, DAN-3D means the rheological properties) with different frictional coefficients (*f*) and turbulence parameters (ξ) (Table 1) in the Voellmy kernel. The considered model has an erosion rate of 1.1 × 10^{-4} (-) and a maximum erosion depth of 5 m only in the first material. These values were established by the volume analysis of Bossi et al. (2015). In summary, the main elements that, in our opinion, most influenced the flow dynamics (and therefore the

Table 1 Parameters of each material with Voellmy rheology: friction (*f*) and turbulence (ξ).

Material No.	Range of altitude (m a.s.l.)	*f*	ξ (m/s²)
Material 1	1420 - 920	0.18	500
Material 2	920 - 780	0.12	1000
Material 3	780 - 560	0.01	1000

choice of rheological parameters) are as follows: i) the high plano-altimetric changes in the riverbed and the consequent variability of hydraulic sections; ii) the presence of two weirs at approximately 940 m a.s.l. that intercept the natural distribution of sediments; iii) the presence of the confluence of an ephemeral tributary of the Rotolon Creek (Agno di Campogrosso Creek) located at approximately 900 m a.s.l. (Figure 1a), which, during periods of intense rainfalls, is characterized by a high river discharge contributing to the debris transport and fluidification (Bossi et al. 2015b); iv) the persistence of bank protections for a significant stretch upstream from the villages of Turcati and Maltaure; v) the presence of a narrowing section (i.e., a road bridge with a reinforced pylon in the middle of the riverbed) (Figure 1a). The exposed build-up of sediments around this bridge following the 2010 debris flow event suggested that its shape and dimension contributed to slowing down and stopping much of the coarser clast and boulder flow portions, while the remaining finer sediments flowed downstream along the creek bed for approximately two kilometers (Figure 2). Therefore, this bridge was considered a key element also for the terminal stages of the new simulations.

The parameters used in the Voellmy rheology successfully simulated the deposit thicknesses and the areal distribution of the 2010 event, matching positively the order of magnitude of those measured with the differences between pre- and post-event DTMs (Figure 4a). Particularly, the modelled flow in the sector upstream the Agno di Campogrosso confluence (Figure 4b) shows a good accordance with the maximum thickness of approximately 10 m reached by the debris flow (Figure 4a). The comparison between the debris flow thickness and DAN-3D results was weighed also in other key locations along the creek bed, especially with respect to the same cross-sections used for the velocity estimation (Figure 4). The maximum obtained thickness difference was approximately 1.5 m, as shown in cross-section 3a (Figure 4). The calculated debris flow impact area was approximately 245,000 m^2, while the area covered by the modeled deposits was 250,000 m^2. A good correlation was found between the deposited volume calculated through the difference of DTMs (DoD analysis) by Bossi et al. (2015b) and that found via DAN-3D modeling. The volume obtained by means of the DoD procedure was approximately 372,000 m^3, whereas the DAN-3D volume was approximately 371,000 m^3. A very good accordance was obtained between the modeled results and the DTM analysis; nevertheless, localized differences between the abovementioned results were generated, mainly due to the input data and particularly to the model path processing stages.

3.2 Velocity calculations

The resulting mean flow velocity estimations are shown in Table 2. Here, these values were also compared with the results of the numerical model velocity in the same cross-section (Figure 1a, Figure 5). This was possible because the DAN-3D code can calculate the maximum velocity at each

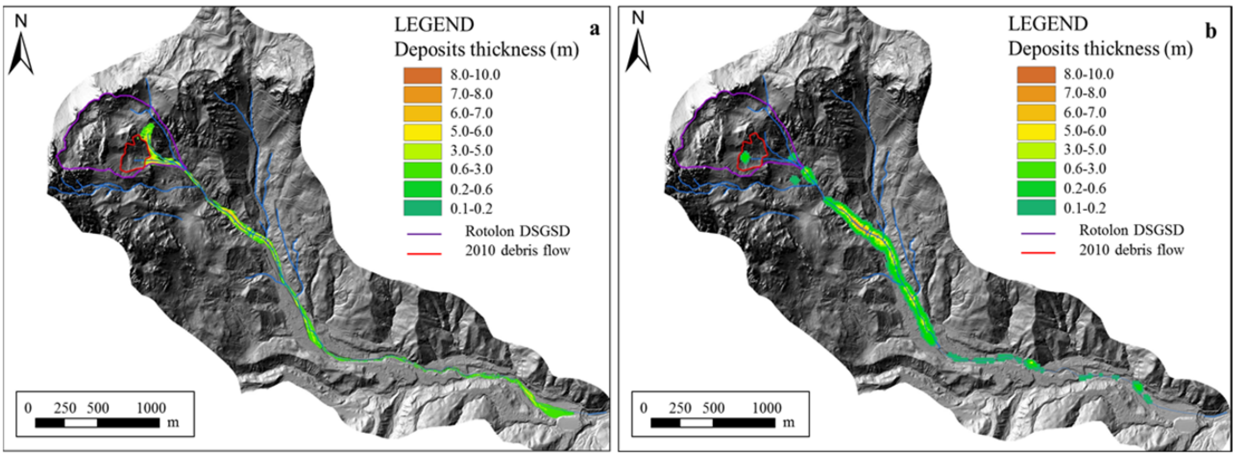

Figure 4 Comparison between a) the deposit thicknesses resulting from the deference of two DTMs (pre- and post-event), b) the deposit thicknesses resulting from the back analysis using DAN-3D. The violet line is the Rotolon landslide DSGSD and the red one is the source area of the 2010 debris flow.

point of the impact area. The velocities, calculated as the mean of maximum velocity for each cross-section using DAN-3D, were in good agreement with all the values obtained using the equations of Rickenmann (1999) and Mizuyama et al. (1992), ranging from 32.0 m/s (section 1a) to 6.6 m/s (section 4b, Table 3). By comparing the flow velocity profiles obtained through the abovementioned equations and the modeled results (Figure 6), it was possible to observe a similar trend along the overall debris flow travel distance, with an initial exponential deceleration and a decrease of mean velocity in the final section. Higher velocities were recorded in the first two sections (1a, 2a) falling within Material 1 (Table 1) of the runout model, where erosion occurs. The major difference between the calculated and modeled velocities was evident in the upstream part of the debris flow sector, while in the middle and lower flow sectors, the obtained velocities showed similar values (sometimes almost coincident) (Table 3).

Table 2 The parameters calculated at each mean velocity along cross-sections: S (°) is the slope, w (m) is the flow width, h (m) is the flow super-elevation, Qp_1 (m^3/s) and Qp_2 (m^3/s) are the Rickenmann (1999) and Mizuyama et al. (1992) discharge, respectively, and R (m) is the curvature radius.

Section No.	S (°) Slope	w (m) Flow width	h (m) Super-elevation of the flow	Qp_1 (m^3/s) Discharge (Rickenmann 1999)	Qp_2 (m^3/s) Discharge (Mizuyama et al. 1992)	R (m) Radius of curvature
Section 1a	14			4400	3000	
Section 2a	9			4400	3000	
Section 1b	9	35	2.7			236
Section 3a	7			4400	3000	
Section 4a	6			4400	3000	
Section 2b	9	10	0.6			125
Section 5a	4			4400	3000	
Section 3b	6	10	1			142
Section 4b	7	9	3.2			40

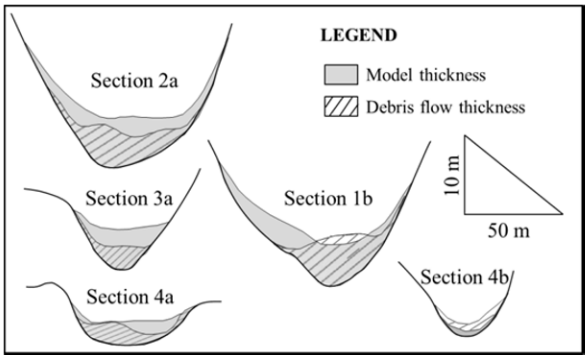

Figure 5 Comparison between deposit thicknesses along some cross-sections (vertical exaggeration 5): striped grey area denotes the real debris flow thickness; grey area denotes the modelled thickness (for their map localization, refer to Figure 1a).

Table 3 Mean flow velocity measured with respect to selected cross-sections (for their map locations, refer to Figure 1a)

Section No.	v (m/s)			
	Chow 1959	Rickenmann 1999	Mizuyama et al. 1992	DAN-3D, maximum velocity
Section 1a		21.2	18.7	32.1
Section 2a		18.4	16.3	22.5
Section 1b	14.1			17.3
Section 3a		17.1	15	16.6
Section 4a		15.6	13.8	14.2
Section 2b	11.8			13.5
Section 5a		13.6	12	8.4
Section 3b	11.5			8.2
Section 4b	5.6			6.6

3.3 Assessment of back analysis accuracy

The goodness of the DAN-3D numerical models result has already been tested in many works (Hungr and Evans 1996; McDougall 2006). In this paper, it was investigated and verified by comparing simultaneously the numerical modeling outcomes with both field observations and derived data coming from empirical equations and maps processing. Particularly, the runout distance represents the main parameters for model calibration. Furthermore, other calibration parameters were used, such as deposits thickness and velocity along the landslide path. Figure 7a shows the comparison between the model velocity results and the calculated data. Here it is evident that the modeled velocities are in good agreement with the estimated ones. However, only on the slope just below the source area the velocity predicted by the dynamic analysis is much greater than those estimated by empirical equations because of the entrainment coefficient inserted in this part of the simulation. Moreover, in Figure 7b the comparison between the thicknesses values measured during the field investigations and those predicted by numerical simulations is exhibited. From this it emerges that the used model predicts the overall deposit thickness, as just observed in the cross-sections (Figure 1, Figure 5), with a range of accuracy of approximately 20%. Consequently, as regards the general rheological behaviour, the Voellmy kernel proved to be particularly suitable to reproduce the debris flow dynamics demonstrating a strong topographic control and providing good results in terms of velocity and distribution of deposits.

3.4 Possible event forecasting procedure

To assess the Rotolon valley exposure to possible future debris flow events, new DAN-3D simulations were carried out, combining the extension of the source area established by means of the displacement map analysis (Figure 2b) and the rheological parameters obtained by means of the 2010 event back analysis (Table 1). Usually, the estimate of a hypothetical volume potentially prone to collapse represents a difficult task, even in the case of accurate field measurements. Therefore, to overcome this problem, three credible volumes were estimated for the possible new source area extension (Figure 2b), starting from three different thickness values (3.5 m, 6.7 m and 19.2 m respectively, mode, average and maximum values) derived from a statistical analysis of the 2010 source area thicknesses. This method was applied while considering that the source debris materials of the new possible event have the same emplacement and thickness of the past event source area. The method considered the 2010 event deposits thickness frequency distribution histogram and used the statistical values to find new volumes (Figure 8). In this context, the three volume values calculated were as follows: i) mode (165,000 m^3), ii) average (304,000 m^3), and iii) maximum (894,000 m^3). The runout outcomes showed that using the mode and average values, the modelled debris flow in any case stops upstream of Turcati and Maltaure villages; the maximum deposit thicknesses were 8.0 m and 8.5 m, respectively (Figure 9a, b). On the other hand, using the maximum volume value, the resulting

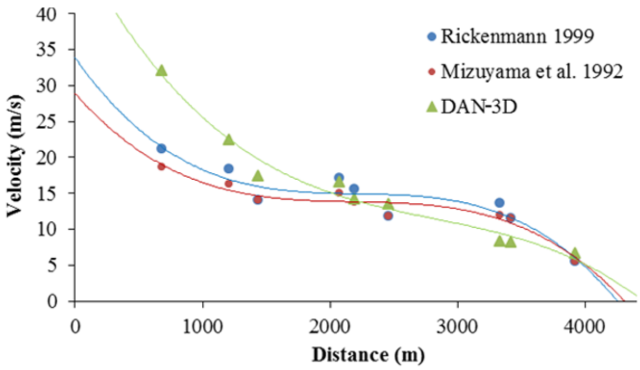

Figure 6 Velocity profiles calculated by using Rickenmann (1999) equations (blue line), Mizuyama et al. (1992) equation (red line) and DAN-3D simulation (green line).

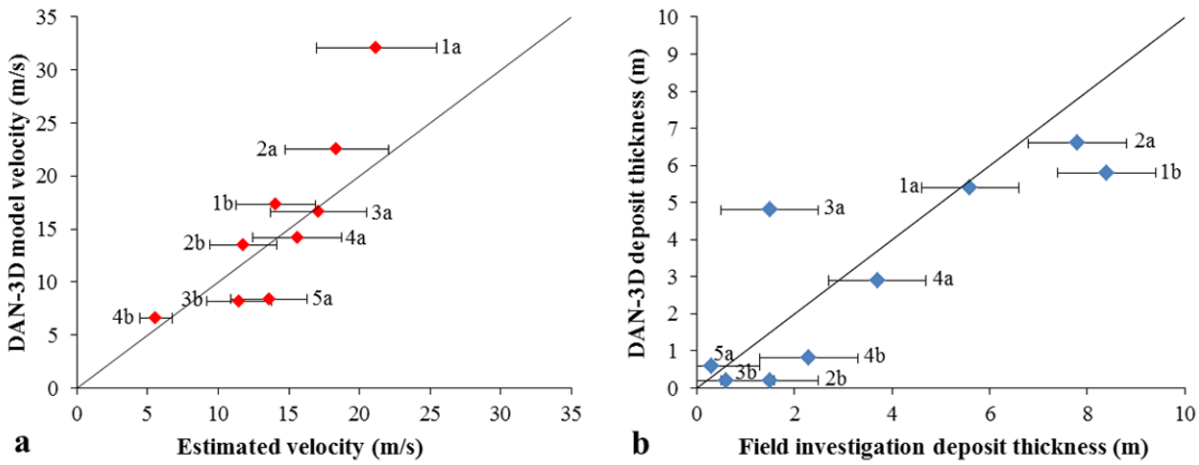

Figure 7 Comparison of modelled and estimated velocities and deposit thicknesses at each cross-section: a) comparison between DAN-3D and empirical equation velocity, b) between DAN-3D and field-estimated deposit thickness. The continuous black line indicates the theoretically perfect correlation.

debris flow showed highly mobile and very rapid features and can reach the Recoaro Terme village, even overflowing the riverbanks, with dangerous implications for the inhabitants (Figure 9c). In this case, the maximum deposit thickness was approximately 9.5 m. The main difference between these simulations is the distribution of deposits and the different impact areas, which range from approximately 263,000 m² using the mode volume to approximately 1,000,000 m² using the maximum volume. Furthermore, a critical debris flow volume assessment was performed based on the possible future events capable of reaching the villages of Turcati and Maltaure. The obtained critical volume was 373,000 m³ (slightly more than the statistically calculated average value and less than half of the maximum value), while the average thickness of its source area was approximately 8.0 m (Figure 9d).

4 Conclusions

The 4th November 2010 debris flow event that detached from the Rotolon DSGSD detrital cover was modelled by means of DAN-3D numerical code, and its results were discussed. The runout

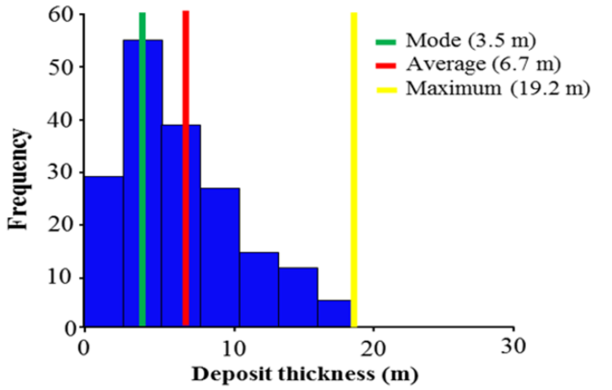

Figure 8 Statistical analysis of the deposit thicknesses of the 2010 event**.**

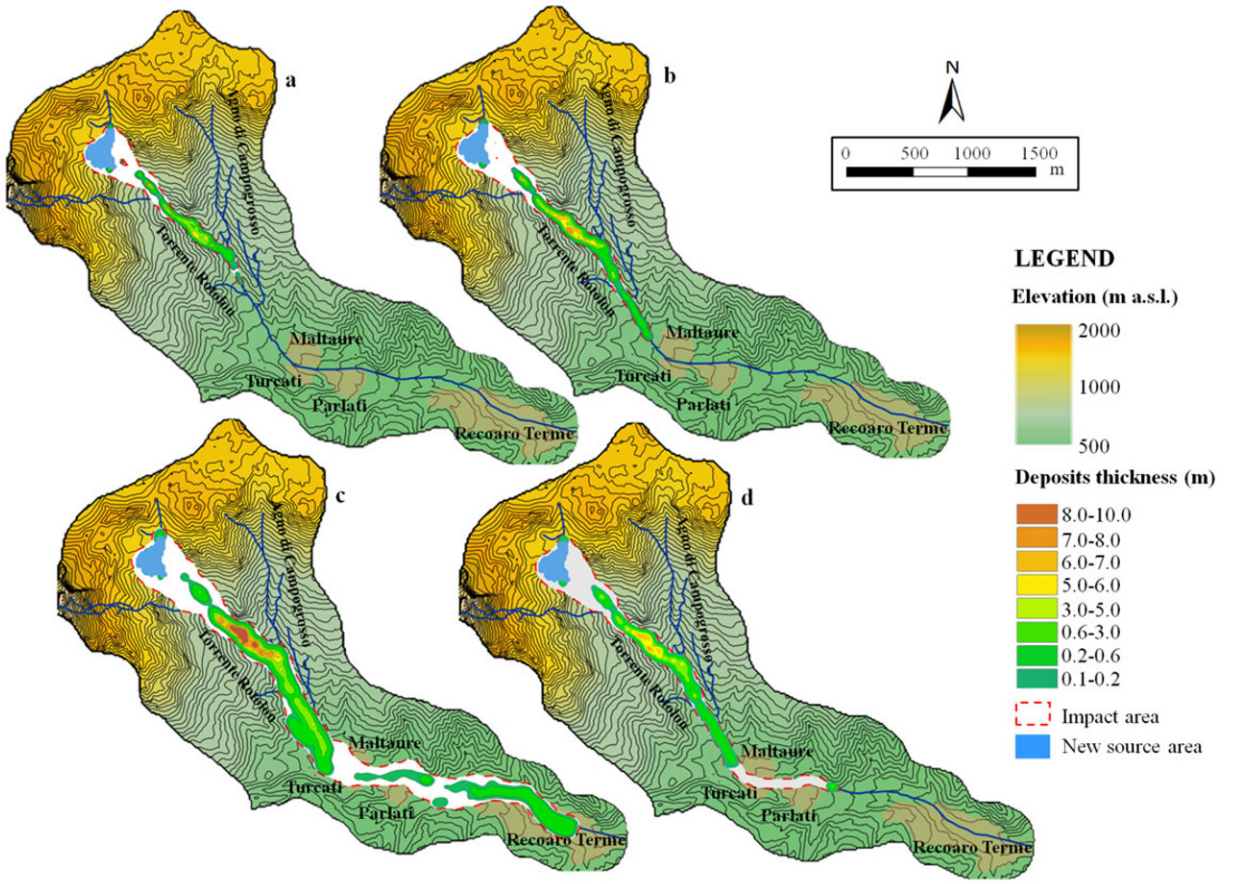

Figure 9 Forecast analysis of future possible events with different values of collapsing volumes: a) mode (165,000 m³), b) average (304,000 m³), c) maximum (894,000 m³) and d) critical (373,000 m³). The considered source area is the area shown in Figure 2, represented in blue. The red dashed area includes the impact area of the modelled debris flows: it contains variable deposit thicknesses (chromatic scale) and not covered areas (white sectors).

simulation shows that amongst the available rheological kernels, the best rheology in the used model is the Voellmy-type. The latter was applied to each of the three materials, in which the path of the landslide was conventionally subdivided. After some attempts made by varying the rheological reference parameters, the 2010 event back analysis could reproduce with high accuracy: i) the debris flow impact area; ii) deposit thickness; iii) velocity; iv) the final flow erosion volume. To assess the Rotolon valley exposure to possible future debris flow events, based on the back analysis results, a forecasting analysis was performed. This analysis was obtained by means of DAN-3D simulations, considering i) the same input data of the back analysis; ii) a new possible source area detected by means of GB-InSAR displacement data analysis; and iii) different hypothesized thicknesses by means of statistical considerations based on the differences between the pre- and post-2010 debris flow event DTMs. These simulations produced impact area maps useful for evaluating the different future debris flow scenarios within the Rotolon valley. The obtained results show that the integration of the modelling technique with ancillary data (such as detailed geomorphological and topographic maps, location and characteristics of the hydraulic works along the creek bed), together with the GB-InSAR-derived displacement maps, can be a very useful tool for the scientific community and local administrations to manage the problem related to debris flow events in the examined area. This working method could represent a standard procedure in cases of areas prone to different types of debris flow in the case of GB-InSAR displacement monitoring. Nevertheless, the final reliability of the proposed method lies in the skill of expert operators regarding the choice of plausible volumes of possible future debris flow events.

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