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INTEGRATED ANALYSIS OF TRIGGERING AND RUNOUT SUSCEPTIBILITY TO LANDSLIDE-INDUCED DEBRIS FLOWS IN ALPINE CATCHMENTS

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EXTENDED ABSTRACT

Le frane superficiali pluvio-indotte, del tipo scorrimento-colata di detrito, rappresentano uno dei fenomeni naturali più pericolosi a livello mondiale. Ciò dovuto anche alla crescita degli insediamenti urbani che ha spinto la popolazione a colonizzare aree a rischio, dove le azioni di previsione e prevenzione rappresentano oggi una sfida per la comunità scientifica. Nei bacini alpini italiani, le frane superficiali pluvio-indotte del tipo soil slip (Campbell, 1975) e debris slide che innescano successive colate di detrito (debris flows, Hungr *et alii*, 2014) sono piuttosto ricorrenti e inducono frequenti perdite economiche e di vite umane. A riprova di ciò possono essere annoverati diversi eventi franosi catastrofici che, negli ultimi decenni, hanno interessato la Valtellina (Lombardia, nord Italia). Dopo l'evento del maggio 1983 (17 vittime e 5000 sfollati), può essere citato l'evento del luglio 1987 (53 vittime e 25000 sfollati), quello del 17 novembre 2000 (1 vittima) e, infine, quello del novembre 2002 (2 vittime). Tali fenomeni si sono sviluppati in un contesto in cui l'assetto morfologico dei rilievi, generalmente caratterizzato da versanti con elevata acclività, la variabilità degli spessori e delle condizioni stratigrafiche dei depositi di copertura, prevalentemente detritici, e le proprietà idro-meccaniche degli stessi, sono da considerare come fattori predisponenti. Da tutto ciò deriva una complessa relazione causa-effetto tra l'occorrenza di eventi pluviometrici di elevate intensità e/o durata e l'accadimento di questo tipo di frane. Esse, infatti, si verificano comunemente in condizioni di infiltrazione transitoria in suoli inizialmente insaturi. A seconda dell'eterogeneità dei suoli coinvolti, per quanto riguarda le proprietà idromeccaniche e gli spessori, durante eventi piovosi di elevata intensità e lunga durata, un aumento della pressione interstiziale, fino alla saturazione, può diventare critico per la stabilità di specifici settori di un versante. Nonostante tali fenomeni coinvolgano inizialmente volumi di materiale limitati, la pericolosità derivante dalle colate detritiche può essere significativa anche in relazione all'elevata magnitudo potenziale, modulata dalla quantità di sedimento presente lungo il percorso di propagazione (capace di sostenere la crescita volumetrica del flusso) e dalla lunghezza dello stesso. Pertanto, lo sviluppo di approcci utili alla previsione della posizione delle aree di innesco, nonché dei percorsi, dei volumi e dei parametri cinematici delle potenziali colate detritiche è estremamente importante ai fini della pianificazione del territorio.

In questa prospettiva, il presente lavoro mostra i risultati dell'applicazione di un approccio, basato sulla back analysis di fenomeni pregressi, potenzialmente fruibile ai fini della redazione di mappe di suscettibilità all'innesco, transito e invasione riferita ad eventi di colata detritica simili a quelli che hanno colpito tre Comuni della Provincia di Sondrio (Tartano nel 1987, Dubino nel 2000 e Albaredo nel 2002), considerati come riferimento per le analisi. L'approccio metodologico è basato sulla modellazione numerica della stabilità dei pendii e della propagazione dei fenomeni, tenendo conto degli effetti di disponibilità, risoluzione e tipologia dei dati riguardanti la distribuzione, lo spessore e le proprietà geotecniche e idrauliche dei depositi di copertura. Le mappe di suscettibilità sono state ottenute a scala di versante mediante una modellazione degli effetti delle condizioni idrologiche e pluviometriche rappresentative degli eventi franosi pregressi, attraverso l'utilizzo del codice TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability; Baum *et alii*, 2008). Successivamente, la modellazione della propagazione è stata eseguita utilizzando il modello DAN3D (Hungr & McDougall, 2009), considerando i volumi coinvolti e lo spessore della colata detritica derivati dalle mappe di suscettibilità ottenute e dai dati bibliografici. Ai fini della modellazione è stato adottato il modello reologico di Voellmy, la cui parametrizzazione è stata basata su un approccio trial and error considerando la forma delle frane disponibili. L'approccio qui presentato ha consentito l'identificazione delle aree di innesco, transito e invasione dei fenomeni di colata detritica considerati. I risultati evidenziano le potenzialità di tale approccio, unitamente alle limitazioni inerenti alla disponibilità di dati sulle proprietà idro-meccaniche dei suoli e sulla loro distribuzione spaziale. Nell'ambito della mappatura di suscettibilità, l'approccio presentato può essere utilizzato per valutare la possibile fase di propagazione di nuove potenziali colate detritiche riconosciute da evidenze geomorfologiche e dalla modellazione numerica. Ulteriori analisi finalizzate alla definizione della distribuzione spaziale della probabilità di accadimento di una frana, correlata ad uno specifico valore di soglia delle precipitazioni, possono essere utili per la mappatura multiscala della pericolosità da frana, anche in contesti montani simili.

ABSTRACT

In the last decades the Valtellina valley (northern Italy) has suffered from several catastrophic rainfall-induced shallow landslide events inducing debris flows. The growing of urban settlements has driven population to colonize areas at risk, where prediction and prevention actions are nowadays a challenge for geoscientists. Debris flows are widespread in mountain areas because occurring along steep slopes covered by loose regolith or soil coverings. Under such conditions, heavy rainfall events might cause slope instabilities due to the increase in pore water pressure depending on hydraulic and geotechnical properties as well as thicknesses of soil covers. Despite the initial small volumes, debris flows hazard is significant due to the sediment entrainment and volume increase of the involved material, high velocity and runout distance. In such a framework, predicting timing and position of slope instabilities as well as paths, volumes, and velocity of potential debris flows is of great significance to assess areas at risk and to settle appropriate countermeasures. In this work, back analyses of debris flows occurred in representative sites of the Valtellina valley were carried out with the aim of understanding their features and providing a methodological basis for slope to valley scale susceptibility mapping. Numerical modeling of slope stability and runout was completed allowing the identification of the detachment, transport, and deposition zones of previously occurred landslides, including other potentially unstable ones. Results from this study emphasize issues in performing distributed numerical modeling depending on the availability of spatially distributed soil properties which hamper the quality of physics-based models. In the framework of hazard mapping and risk strategy assessments, the approach presented can be used to evaluate the possible runout phase of new potential debris flows recognized by geomorphological evidence and numerical modeling. Furthermore, analyses aimed to the probabilistic assessment of landslide spatial distribution, related to a specific value of rainfall threshold, can be considered as potentially applicable to multi-scale landslide hazard mapping and extendable to other similar mountainous frameworks.

Keywords: *shallow landslides, debris flow, susceptibility mapping, physics-based modelling, Voellmy rheology, back analysis.*

INTRODUCTION

Rainfall-induced shallow landslides represent one of the most hazardous natural phenomena for different geological, geomorphological and climatological environments in the world, causing severe economic losses and casualties. Soil slips (Campbell, 1975) or debris slides inducing debris flows (Hungr *et alii*, 2014) are widely described in the scientific literature (*e.g.* Jakob & Hungr, 2005; Dowling & Santi, 2013; Mirus *et alii*, 2020) as commonly involving soils mantling weathered bedrock (Cevasco *et alii*, 2014; Fusco *et alii*, 2015; Tufano *et alii*, 2016; Guerriero *et alii*, 2018; 2023). In Alpine catchments, shallow landslides are quite recurrent. Their initiation is associated to high-intensity or prolonged rainfall or snow melting (Abbate *et alii*, 2021; Panzeri *et alii*, 2022). The Valtellina valley (northern Italy, Fig. 1) suffered of several historical catastrophic shallow landslide events. Since the May 1983 landslide event, with hundreds of rainfall-induced shallow landslides inducing debris flows (Guzzetti *et alii*, 1992), other significant ones affected the area, among them: the July 16th-19th 1987 at Tartano (Guzzetti *et alii*, 1992); the November 17th 2000 at Dubino (Crosta *et alii*, 2003); and the November 14th-16th 2002 at Albaredo (Dapporto *et alii*, 2005).

Rainfall-induced shallow landslides commonly occur under conditions of transient infiltration into initially unsaturated soils. During critical rainfall events the increase in pore water pressure may become critical for slope stability in specific sectors of a slope depending on hydraulic and geotechnical properties as well as thicknesses of soils involved (Fredlund & Morgenstern, 1977; Lu & Likos, 2004). Debris flows are normally funneled into pre-existing gullies and first- or second-order drainage channels. In both cases, the initial volume of the landslide may increase substantially due to the mobilization of available slope material and entrainment into the moving flow. The accumulation zone is usually located at the foothill and may correspond to a pre-existing alluvial fan. In such a framework, predicting timing and position of slope instability as well as paths, volumes, and kinematic parameters of potential debris flows is greatly needed to assess areas at risk and to settle appropriate countermeasures. To such a scope, back analyses of landslides through numerical modeling can be considered even if it represents a challenge for landslide risk assessment, especially if data concerning unsaturated/saturated hydro-mechanical soil properties, as well as climate and topography are limited or not available. Triggering mechanisms and runout characteristics can be explored using empirical and deterministic models. Quantitative methods to simulate slope hydrologic response and runout, or erosive processes, were already considered for selected areas of Italian Alps (northern Italy) (Radice *et alii*, 2012; Longoni *et alii*, 2016; Corti *et alii*, 2023; Fusco *et alii*, 2023; Abbate *et alii*, 2024;), Oltrepò Pavese (north-western Italian Apennines), Sannio Apennine and peri-Vesuvian areas (southern Italy) (Grelle *et alii*., 2014; Napolitano *et alii*, 2015; Tufano *et alii*, 2019; Fusco *et alii*, 2021; Sepe *et alii*, 2023).

On this basis, this work presents results from back analyses of debris flow events carried out for representative sites of the Valtellina valley with the aim to provide a methodological basis for slope to valley-scale susceptibility mapping. Numerical modeling of slope stability and runout was completed considering the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) and the DAN3D models, respectively. To such a scope, the Tartano 1987, Dubino 2000 and Albaredo 2002 landslide events were modeled (Fig. 1). Analyses allowed the identification of detachment, transport, and deposition zones of recorded landslides, including other potentially unstable ones. Results from this study emphasize issues in performing distributed numerical slope stability modeling depending on the availability of spatially distributed soil properties which hamper the quality of physics-based models. In the framework of hazard mapping and risk strategy assessments, the presented approach can be used to evaluate the possible runout phase of new potential debris flows recognized by geomorphological evidence and numerical modeling. Furthermore, analyses aimed to the probabilistic assessment of landslide spatial distribution, related to a specific value of rainfall threshold, can be considered as potentially applicable to multi-scale landslide hazard mapping and extendable to other similar mountainous settings.

DATA AND METHODS

Overview of the study areas

Numerical modeling of slope stability and runout was completed for three study areas located in the western sector of the Valtellina valley (central Italian Alps, northern Italy, Fig. 1): Tartano, Dubino and Albaredo (Sondrio province). The valley is about 120 km long and E-W oriented, with a morphology strongly related to the tectonic activity of the "Insubric Line" regional fault, a major Alpine lineament (Schimd *et alii*, 1986). Metamorphic (*e.g.*, gneiss, micaschists, phyllites, quartzites), igneous (*e.g.*, andesites, basalts, granites, gabbri), and subordinate sedimentary rocks (*e.g.*, dolomites, limestones) characterize the valley. Furthermore, glacial, fluvio-glacial and colluvial deposits with variable thickness cover the middle-lower parts of the valley flanks.

Morphologically, slopes result typically U-shaped, deriving from the Quaternary glacial processes. In detail, steep slopes (> 30°) characterizing the three test sites are covered by colluvial deposits showing a strong heterogeneity and variable thickness (up to ~2.0 m). Due to morphological and geological predisposing factors these soil covers are generally involved in rainfall-induced slope instabilities such as soil slips or landslide-induced debris flows (Cancelli & Nova, 1985; Crosta *et alii*, 2003; Dapporto *et alii*, 2005). The modeled landslide events of Tartano 1987, Dubino 2000 and Albaredo 2002, involved the shallower soil cover and propagated faster and channelized through the existing hydrographic network.

Hydrological and slope stability modeling

Hydrologic and slope stability modeling was completed considering the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) model (Baum *et alii*, 2008). By the assumption of a single-layered, homogeneous soil cover with spatially variable thickness and initial soil moisture conditions, the governing equations of TRIGRS are based on a linearized solution of Richards (Richards, 1931) equation

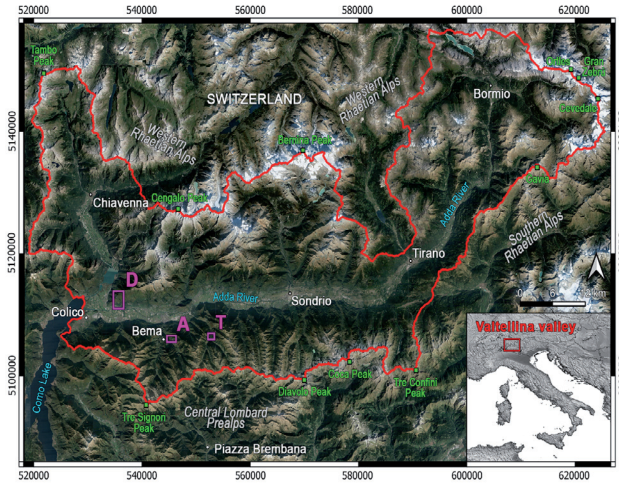

Fig. 1 - Study areas of the Valtellina valley (northern Italy): Dubino (D), Albaredo (A) and Tartano (T) sites. (WGS84/UTM 33N)

proposed by Iverson (Iverson, 2000). Thus, a one-dimensional infinite-slope-stability analysis (Hsieh *et alii*, 2000) is used by TRIGRS to determine the Factor of Safety (FoS).

According to TRIGRS structure, the hydrological and slope stability modeling was carried out considering a 5 m resolution Digital Elevation Model (DEM), available from Geoportale della Lombardia (www.geoportale.regione.lombardia.it). The same elevation data was used to calculate other inputs required for simulations, including flow direction and slope angle maps. Spatial variability of soil cover thickness was derived considering distributed maps of the bedrock depth available from SoilGrids data (European Soil Data Centre – ESDAC; Hengl *et alii*, 2017). A representative spatially uniform model, based on a single-layered homogeneous soil column was considered. Unsaturated/saturated hydraulic and geotechnical properties were defined as mean of values from distributed, non-punctual data from SoilGrids maps and bibliographic ones (Guzzetti *et alii*, 1992; Cancelli & Nova, 1985; Crosta *et alii*, 2003; Dapporto *et alii*, 2005) (Table 1). Moreover, values of soil effective friction angle and cohesion were set differently for areas covered by forests or grasslands, thus considering the effect of root apparatuses on the increase of soil shear strength. For such a scope, these areas were identified considering DUSAF 2018 maps (Land Use of Agricultural and Fortestry Lands; www.regione.lombardia.it). The initial soil water pressure head distribution was set from typical wetting condition of rainy periods. Finally, hourly intensity (I) and duration (D) values were set as boundary condition from time series of the Agenzia Regionale per la Protezione dell'Ambiente rain-gauges network (www.arpalombardia.it) located in Piazza Brembana, Colico and Bema towns, representative for Tartano, Dubino and Albaredo sites, respectively (Fig.s 1 and 2). Susceptibility maps show the distribution of unstable areas, namely pixels with FoS ≤ 1 values, and likely unstable areas, i.e. pixels with FoS values ranging between 1.01 and 1.10. The choice of the FoS range to assume as indicative of slope instability was derived considering that these values are close or can be approximated to the limit equilibrium condition (FoS = 1) by truncation. Finally, slope stability maps obtained by modeling, were compared with the modeled landslides and other historical ones from the Italian Landslides Inventory (IFFI; Trigila *et alii*, 2018).

However, since rainfall time-series could not be considered explicitly representative due to possible lack of reliable recordings, the comparisons are only to demonstrate that the potentially unstable zones identified through TRIGRS models correspond to previous slope instabilities.

	TRIGRS models		
Parameter	Tartano	Dubino	Albaredo
K_{sat} (m/s)	2.58×10^{-6}	1.97×10^{-6}	1.91×10^{-6}
θ_s (ad.)	0.449	0.409	0.400
θ_r (ad.)	0.041	0.041	0.041
α (ad.)	0.0157	0.0125	0.0092
γ_{nat} (N/m^3)	1.45×10^4	1.41×10^4	1.42×10^4
ϕ' (°)	38.0	38.0	36.0
c' forests (Pa)	1.00×10^4	4.00×10^4	1.00×10^4
c' grasslands (Pa)	5.00×10^3	5.00×10^3	2.00×10^3

Tab. 1 - Unsaturated and saturated hydraulic and geotechnical soil properties used for setting of TRIGRS models. Keys to symbols: (K_{sat}) saturated hydraulic conductivity; (θ_s) saturated volumetric water content; (θ_r) residual volumetric water content; (α) van Genuchten's (1980) fitting parameter of soil water retention curve; (ø') = effective friction angle; (c') = effective cohesion

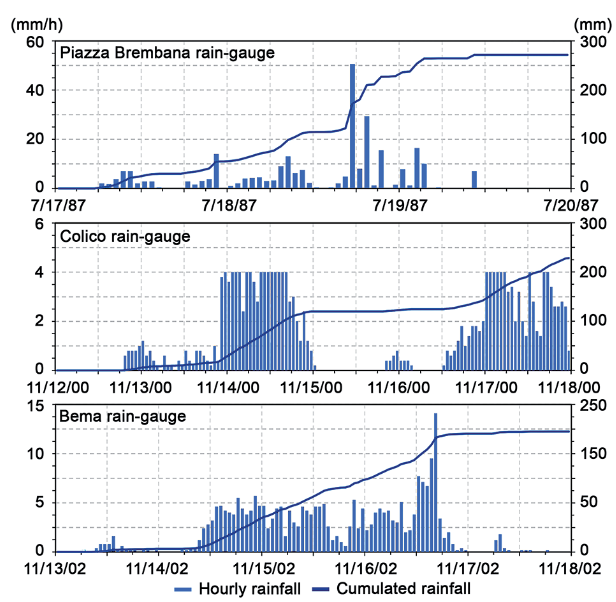

Fig. 2 - Rainfall time series considered for modeling Tartano 1987, Dubino 2000 and Albaredo 2002 landslide events. Hourly data were recorded by Piazza Brembana, Colico and Bema rain-gauges of ARPA Lombardia network (www.arpalombardia.it)

Landslides runout modeling

Runout modeling of landslides was conducted employing the Smoothed Particles Hydrodynamics method (Benz, 1990; Monaghan, 1992) as implemented in the DAN-3D software (McDougall & Hungr, 2004). DAN-3D is based on a numerical solution of the depth-averaged Lagrangian equations of motion for an "equivalent fluid" (Hungr, 1995), thus allowing for simulating the propagating landslide mass as a hypothetical material governed by a simple rheological relationship. The model can describe the motion of the mass in terms of its dynamic characteristics, including total runout distance, velocity and discharge of the flowing mass, and thickness distribution (both instantaneous and maximum).

To set the DAN-3D models *i*) the same post-event DEM of the affected slope used for TRIGRS analysis was used; *ii*) the thickness distribution of the source volume was reconstructed; and *iii*) physical, mechanical, and rheological parameters of the material involved (unit weight, dynamic friction angle, etc.) were considered. Furthermore, material entrainment during flow runout was modeled, providing a mapped distribution of slope materials and their characteristics, an erosion rate, and the maximum thickness of erodible material. The erosion rate and the rheological model employed, along with its associated parameters, were calibrated based on bibliographic and field information (*e.g.*, landslide path geometry including final elongation, deposit distribution, and local thickness, estimated velocity, etc.). The Voellmy (1955) rheological model, modified by Hungr (1995), was chosen for runout modeling. Material properties, such as unit weight, were derived by SoilGrids maps and bibliographic ones (Guzzetti *et alii*, 1992; Cancelli & Nova, 1985; Crosta *et alii*, 2003; Dapporto *et alii*, 2005) (Table 2). The dynamic friction coefficient and turbulence coefficient were estimated using trial and error, considering the extent of landslide and deposit thicknesses. The analysis output comprised a temporal map of flow depths, a map of post-event sediment distribution, and a map of maximum velocities.

RESULTS

Susceptibility mapping

The coupled hydrological and slope stability modelling allowed as principal result the mapping of unstable and likely unstable cells across study areas (Fig. 3). Results for Tartano site revealed that a great number of potentially unstable cells are close or coincide with triggering areas of the July 1987 landslide event and with both other events inventoried and areas with diffuse shallow instabilities (Fig. 3B). Generally, slope instabilities were modeled close to both main drainage network and open slope areas, where occasional morphological discontinuities, increase in slope angle and a thinning or downslope truncation of the soil cover occur (Fusco *et alii*, 2017).

DAN3D models			
Parameter	Tartano	Dubino	Albaredo
Number of particles	2000	2000	2000
Erosion rate	7.5×10^{-3}	6.6×10^{-3}	7.7×10^{-3}
Material Unit Weight (kN/s^2)	20.0	18.0	18.0
Smoothing Length Constant	4.0	9.0	4.0
Velocity Smoothing Coeff.	0.40	0.49	0.20
Layer thickness (m)	1.50	1.80	1.50
Length (m)	705	1800	600
Travel angle (°)	28.0	20.0	31.0
Friction Coefficient	0.07	0.08	0.07
Turbulence Coeff. (m/s^2)	200	200	300
Internal Friction Angle (°)	36.0	35.0	36.0
Initial Volume (m^3)	130	650	220
Final Volume (m^3)	18000	150000	15500

Tab. 2 - Main parameters required for DAN-3D modeling

For the Dubino site potentially unstable areas coinciding or not with the landslide inventory resulted close to both some head-basin of main channels and open slope areas and well matching the landslide inventory (Fig. 3F). However, a lower matching with the triggering areas of the November 2000 landslide event and other inventoried ones was observed. Finally, maps of Albaredo site resulted in very localized unstable areas with a good matching with the landslide inventory (Fig. 3L). In this case, unstable areas resulted close or coinciding with flanks or head-basin of channels affected by landslides. Furthermore, other potentially unstable pixels resulted where diffuse shallow instability areas were inventoried.

Landslides runout

Results of landslide runout modeling along the considered slopes from the detachment zone to the slope base, depicting flow thickness and the area affected are shown in Figure 3. In detail, the landslide mass (i.e., the flow front) of the Tartano event advanced ~900 m downslope in 120 seconds after the detachment (Fig. 3C), following the parallel slope creek and reaching the lower valley. The mass completely travelled along the slope and the flow reached ~2.5 m of thickness in several areas (Fig. 3C). However, some suspended deposits were modeled along the path as well. The landslide propagated downslope with a velocity of ~8.0 m/s, accelerating up to ~10 m/s and decelerating several times (Fig. 3D). The higher velocity of ~15 m/s and the subsequent deceleration was reached at the slope base. Concerning the Dubino landslide event, two landslides were modeled (Fig. 3E).

The flows advanced ~600 m (in 100 seconds) and ~1500 m (in 200 seconds) downslope after the detachment. The channeled flow fronts followed the slope creek down to the foothill, reaching a thickness of ~2.0 m and ~3.0 m, respectively (Fig. 3G). The runout occurred downslope with a velocity of ~8.0 m/s, accelerating in one of the two cases up to ~14 m/s and decelerating several times after the detachment (Fig. 3H). Finally, for the Albaredo case, three landslides modeled advanced downslope after the detachment: ~800 m (in ~140 seconds) for the two larges and ~600 m in ~80 seconds for the smaller one (Fig. 3M). The flow fronts followed the slope creek and partially stopped before the lower valley. Landslides masses reach a thickness up to ~3.5 m (Fig. 3M), while the runout occurred downslope with velocity up to ~10.0 m/s, accelerating and decelerating several times (Fig. 3N).

DISCUSSION

Back analyses carried out by coupling numerical modeling of slope stability and runout allowed the identification of the detachment, transport and deposition zones of landslides which affected three sites of the Valtellina valley. Following, physics-based models were applied to predict both temporal and spatial variability of proneness to shallow landslides and their runout.

Results obtained revealed the sensitivity of numerical models to input variables such as soil structure, thickness and geotechnical/hydraulic properties. In fact, the availability and reliability of such data, including their spatial distribution, may strongly affect modeling results. Previous studies carried out in the area were focused to understand the relationship between landslide source areas and predisposing or triggering factors (Crosta *et alii*, 2003), or to model slope stability (Dapporto *et alii*, 2005; Camera *et alii*, 2014). However, no attempts to model their runout were found.

Accordingly, a coupled slope stability and runout model was tested for soils covering of three representative areas of the Valtellina valley. Modeling of infiltration process showed how dynamic variables, such as hydrological and morphological conditions as well as stratigraphic setting of the soils involved, strongly control the triggering mechanisms of shallow landslides. Instead, the runout modeling provides information on the evolution of the Tartano 1987, Dubino 2000 and Albaredo 2002 landslide events, simulating the deposit's thickness and the velocity distribution along the runout path. Areas close to flanks or head-basin of channels, affected by landslides, or where changes in soil thickness or slope angles occur, resulted as characterized by a greater proneness to slope instability. Their distribution is consistent with the landslide inventory and the prior literature (Guzzetti *et alii*, 1992; Crosta *et alii*, 2003; Dapporto *et alii*, 2005; Fig. 3) and overcome some limitations related to the application of statistically-based models (Yordanov & Brovelli, 2020). However, given that TRIGRS applies the infinite slope approach, which often overestimates unstable areas, all the proposed analysis can be conceived as conservatives. Other unstable areas identified not coinciding with landslide events inventoried can be related to site specific conditions (such as stratigraphic setting or cover discontinuity) which were not modeled explicitly. Finally, some results could be also dependent on modeled rainfall events whose records derive from rain-gauges far from initial landslide source areas.

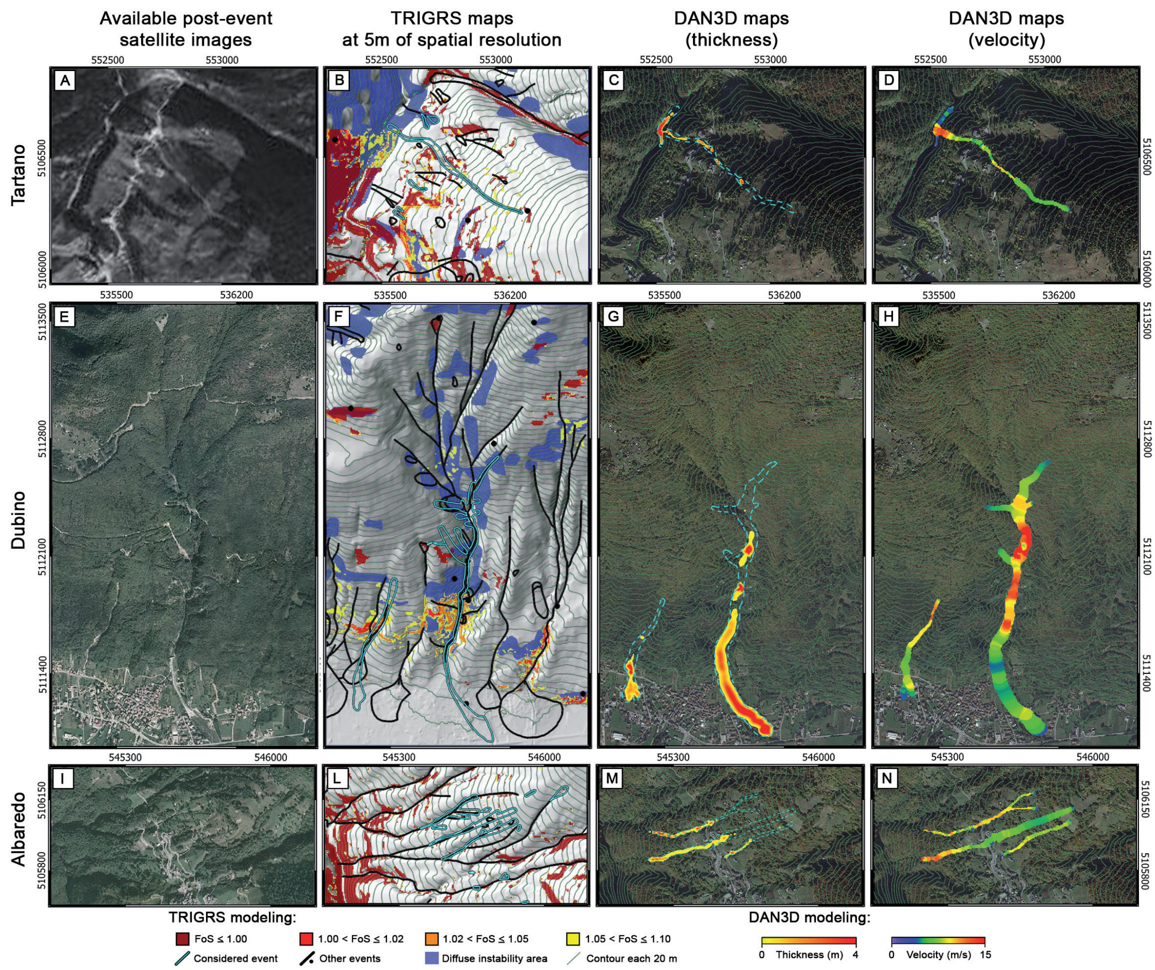

Fig. 3 - Modeling results: 1) Satellite post-event images available for Tartano (A), Dubino (E) and Albaredo (I) sites. 2) resulting slope stability maps, including unstable (FoS ≤ 1.00) and likely unstable (1.00 ≤ FoS ≤ 1.10) cells (B, F, L, respectively), were compared with the considered (modeled) landslide events available from the Italian Landslides Inventory (IFFI), comprising both other inventoried ones and areas indicated as affected by diffuse instabilities; 3) maps showing the final deposit distribution in terms of thickness (C, G, M) and velocity (D, H, N) after the runout of Tartano, Dubino and Albaredo landslide events, respectively. (WGS84/UTM 33N)

The landslide runout was completed with DAN-3D, considering the single-phase Voellmy rheology as representative of flow behavior with respect to the calibrated parameters. No data regarding the runout velocity and flow thickness were available, thus these parameters were not considered during the trial-and-error calibration. Consequently, some implications on the results, such as uncertainty in the velocity distribution, shape of the runout zone and runout distance, and the thickness of the deposited material, could be revealed. However, similar to other preceding cases that occurred in the area (*e.g.*, Tresenda, 1983, Guzzetti *et alii*, 1992; Buglio & Ardenno, 2000; Crosta *et alii*, 2003), the modeled runouts occurred with considerable velocity along existing channels (Fig. 3). This condition played a controlling role in the development of the landslide phenomena, which evolved from soil slips or debris slides to debris flows. For the Valtellina valley slopes, the runout may vary from several tens of meters up to few kilometers. Thus, predicting distance, as well as magnitude of depositional zones, landslide velocity, volume, and discharge, is essential for designing of mitigating measures.

However, the application of DAN-3D may include uncertainties related to rheological model and parameters calibrated.

CONCLUSIONS

Modeling of slope stability and landslide runout represents a challenge to assess the susceptibility related to rainfall-induced shallow landslides at slope- to valley-scale. As known, the availability of spatially distributed data may hamper the quality of physics-based models when performing back analyses. Modeling of slope stability through codes which do not consider heterogeneous physical slope models are affected by difficulties in characterizing and discretizing stratigraphic settings and spatially variable thickness of soils. Instead, modeling of runout can be affected by limited data concerning volume of material involved including physical, mechanical, and rheological parameters. Accordingly, an approach for assessing landslide susceptibility at the slope scale, which might be suitable for smaller scale analyses, was presented by considering the influence of both spatial distribution of soil thickness and properties and resolution of analysis. On this basis, this work presents results of hydrological, slope stability and runout numerical modeling derived from back analyses of preceding debris flow events. The proposed physics-based approach was tested for three sites affected by shallow landslides inducing debris flows in soil mantling Valtellina valley slopes. The study highlights the importance of estimating reliable soil hydro-mechanical properties when performing slope hydrologic and stability modeling under specific rainfall conditions. Furthermore, modeled debris flow events offered an opportunity to gain insight into the initiation and runout conditions of the landslides and to develop a better understanding of the evolution of landslide hazard at recurrent landslide sites. The presented approach, which is based on a likely-to-occur event, can be considered as suitable for designing risk mitigation measures. Specifically, it can be used to evaluate the possible runout phase of future potential debris flows recognized by geomorphological evidence and numerical modeling. Implementing such measures would bring about considerable economic and environmental benefits. Based on the proposed approach, further analyses could be aimed to the probabilistic assessment of landslide spatial distribution, related to a specific value of rainfall threshold. Thus, it can be considered as potentially applicable to multi-scale landslide hazard mapping and extendable to other similar mountainous frameworks.

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