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SUSCEPTIBILITY MAPPING OF SHALLOW LANDSLIDES INDUCING DEBRIS FLOWS: A COMPARISON OF PHYSICS-BASED APPROACHES

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EXTENDED ABSTRACT

La valutazione della probabilità spaziale e temporale di accadimento di frane superficiali pluvio-indotte, del tipo scorrimento-colata rapida di detrito, attraverso l'utilizzo di modelli matematici, rappresenta una sfida per l'analisi del rischio da frana, in particolare quando le informazioni sono limitate o non disponibili. In tale ambito, un fondamentale strumento predittivo è rappresentato dall'accoppiamento delle modellazioni idrologica e di stabilità del versante che, tuttavia, richiedono l'approfondita conoscenza delle proprietà idrologiche e geotecniche dei materiali geologici coinvolti nonché del clima e della topografia. Nei bacini alpini le frane superficiali pluvio-indotte, del tipo *soil slip* (Campbell, 1975) e *debris slide* che inducono *debris flows* (Hungr *et alii*, 2014), sono piuttosto ricorrenti e rappresentano uno dei fenomeni naturali più pericolosi, a cui sono notoriamente associate 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). L'assetto morfologico dei rilievi della Valtellina, generalmente caratterizzato da versanti con elevata acclività, la variabilità degli spessori e delle condizioni stratigrafiche dei depositi di copertura, prevalentemente detritici (*debris*), e le proprietà idro-meccaniche degli stessi, sono considerabili come fattori predisponenti ai fenomeni di instabilità. Da tutto ciò deriva una complessa relazione di causa-effetto tra l'accadimento di questo tipo di frane e l'occorrenza di eventi pluviometrici di elevate intensità e/o durata. 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.

In questa prospettiva, diversi metodi e approcci qualitativi o quantitativi per la valutazione della suscettibilità da frana a scala distribuita sono stati proposti in letteratura (Guzzetti *et alii*, 1999; Reichenbach *et alii*, 2018). La modellazione numerica della risposta idrologica di un versante ad un evento pluviometrico, a partire da modelli fisicamente basati, rappresenta uno dei metodi quantitativi. Tuttavia, spesso i modelli idrologici trattano la copertura del suolo come un'unità omogenea ed isotropa, con la consapevolezza che la distribuzione spaziale delle proprietà sia geotecniche che idrologiche del suolo possa essere ragionevolmente dedotta solo da un numero limitato di prove in campo o in laboratorio. Pertanto, la distribuzione e l'accuratezza dei dati riguardanti la distribuzione spaziale e lo spessore dei depositi di copertura, nonché le relative proprietà idromeccaniche, possono influenzare fortemente l'applicabilità di tali approcci quantitativi.

Nel presente lavoro si presentano i risultati del confronto di modelli fisicamente basati, utilizzati per la valutazione della suscettibilità all'innesco di frane superficiali in tre siti ricadenti nella Valtellina. L'analisi è stata completata considerando gli effetti di disponibilità, risoluzione e tipologia dei dati riguardanti la distribuzione, lo spessore e le proprietà dei depositi di copertura. Per tale scopo, sono stati considerati i modelli TRIGRS (*Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability*) e il *Climatic Rainfall Hydrogeological Modeling Experiment* (CHRyME). Le mappe di suscettibilità delle frane superficiali sono state ottenute a scala locale (di versante) modellando gli effetti delle condizioni idrologiche e pluviometriche rappresentative degli eventi franosi che hanno colpito i Comuni di Tartano nel 1987, Dubino nel 2000 e Albaredo nel 2002. Lo studio evidenzia le difficoltà nella modellazione numerica distribuita della stabilità dei pendii, dipendenti dalla disponibilità di proprietà idrologiche e geotecniche dei depositi di copertura, distribuite spazialmente. 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 su contesti montani simili.

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ABSTRACT

The assessment of timing and potential locations of rainfall-induced shallow landslides through mathematical models represents a challenge for the assessment of landslide hazard, especially in cases with limited or not available data. In fact, modeling slope hydrological response and stability requires accurate estimates of unsaturated/saturated hydraulic and geotechnical properties of materials involved in landsliding, as well as climate and topography. Such aspect is relevant for the prediction of location and timing of landslide events, which is greatly needed to reduce their catastrophic effects in terms of economic losses and casualties. To such a scope, we present the comparison of results of two physics-based models applied to the assessment of susceptibility to shallow rainfall-induced landslides in Valtellina region (northern Italy). The analyses were carried out considering effects of availability, resolution and type of data concerning spatial distribution, thickness and properties of soils coverings. For such a scope, the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) and the Climatic Rainfall Hydrogeological Modeling Experiment (CHRyME) models were considered. The study emphasizes issues in performing distributed numerical slope stability modeling depending on the availability of spatially distributed soil properties which hamper the quality of physic-based models. Further analyses aimed at 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 modeling*

INTRODUCTION

Rainfall-induced shallow landslides, such as soil slips (Campbell, 1975) or debris slides inducing debris flows (Hungr *et alii*, 2014) represent one of the most hazardous natural phenomena for different geological, geomorphological and climatological environments, causing severe economic losses and casualties. These phenomena are widely described in the scientific literature (Calcaterra *et alii*, 2000; Jakob & Hungr, 2005; Salvati *et alii*, 2010; Baum *et alii*, 2011; Dowling & Santi, 2013; Mirus *et alii*, 2020) as commonly involving soils mantling weathered/un-weathered bedrock (Crosta *et alii*, 2003; De Vita *et alii*, 2006; Revellino *et alii*, 2013; Cevasco *et alii*, 2014; Fusco *et alii*, 2015; Tufano *et alii*, 2016; Abbate *et alii*, 2019; Guerriero *et alii*, 2019). In Alpine catchments, shallow landslides are quite recurrent and their initiation is associated to high-intensity rainstorms, prolonged rainfall with moderate intensity or snow melting (Moser & Hohensinn, 1983; Crosta, 1998; Crosta & Frattini, 2002; Abbate *et alii*, 2021). During the last decades, the Valtellina valley (northern Italy, Fig. 1) suffered several historical catastrophic shallow landslide events. Since landslide events occurred in May 1983 event, characterized by hundreds of rainfall-induced shallow landslides inducing debris flows (Cancelli & Nova 1985, Guzzetti *et alii*, 1992, Crosta *et alii*, 2003), other significant landslide events affected the Valtellina valley. Among them, the 16th-19th July 1987 of Tartano town (Guzzetti *et alii*, 1992), the November 17th 2000 of Dubino town (Crosta *et alii*, 2003) and the 14th-16th November 2002 of Albaredo (Dapporto *et alii*, 2005) can be mentioned.

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 became critical for slope stability in specific sectors of a slope depending on hydraulic and geotechnical properties as well as thicknesses of soils involved. In fact, such process may lead to a local decrease of shear strength, because of reduction of both apparent cohesion and effective stress, and an increase of driving forces due to the increase of the unit weight (Fredlund & Morgenstern, 1977; Lu & Likos, 2004; Lu *et alii*, 2010). In such a framework, the prediction of prone areas to slope instability and timing of landslide triggering is greatly needed to reduce fatalities and economic losses. Therefore, numerical models simulating slope hydrological response and stability can be used to such a scope even if requiring accurate estimates of unsaturated/saturated hydraulic and geotechnical properties of soil coverings, as well as climate and topography. For this reason, distributed modeling represents a challenge for landslide susceptibility assessments, especially when data are limited or not available. In this perspective, several qualitative or quantitative methods and approaches for distributed landslide susceptibility assessment were proposed in literature (Guzzetti *et alii*, 1999; Aleotti *et alii*, 2004; Reichenbach *et alii*, 2018). The application of quantitative methods, such as physics-based numerical modeling of slope hydrologic response, were already carried out for selected areas of Italian Alps (northern Italy) (Borga *et alii*, 1998; Lanni *et alii*, 2012), Oltrepò Pavese (north-western Italian Apennines) (Bordoni *et alii*, 2015), Umbro-Marchean Apennines area (central Italy) (Gioia *et alii*, 2015), Sannio Apennine and peri-Vesuvian areas (southern Italy) (Frattini *et alii*, 2004; Grelle *et alii*, 2014; Napolitano *et alii*, 2015; De Vita *et alii*, 2018; Lizarraga & Buscarnera, 2019; Tufano *et alii*, 2019; Fusco *et alii*, 2021). However, often hydrological models treat the soil cover as a homogeneous, isotropic unit with the assumption that the spatial distribution of both hydraulic and soil properties can be reasonably inferred only from a limited number of either field or laboratory tests. Thus, distribution and accuracy of data concerning properties of soil cover and their spatial distribution and thickness may strongly affect the applicability of these quantitative approaches. Consequently, analysis of the hydrological response in heterogeneous and/or layered soil profiles affected by shallow landslides is complex and represents a challenging task to be accomplished.

Accordingly, the aim of this research was the assessment of susceptibility to shallow landslides considering the effect of resolution and spatial distribution of data regarding soil thickness and hydro-mechanical properties. For such a scope, distributed numerical analysis of slope stability were carried out for three representative sites of the Valtellina valley (northern Italy) (Fig.1) by using and comparing two physics-based models. Susceptibility maps of shallow landslides were obtained by a local scale modeling of hillslope hydrological response under rainfall conditions related to Tartano 1987, Dubino 2000 and Albaredo 2002 landslide events. The proposed approach emphasizes current issues in carrying out numerical slope stability modeling in mountain slopes, such those of the Valtellina valley, where strong spatial heterogeneity of soil cover occurs with a low spatial resolution soil properties are available.

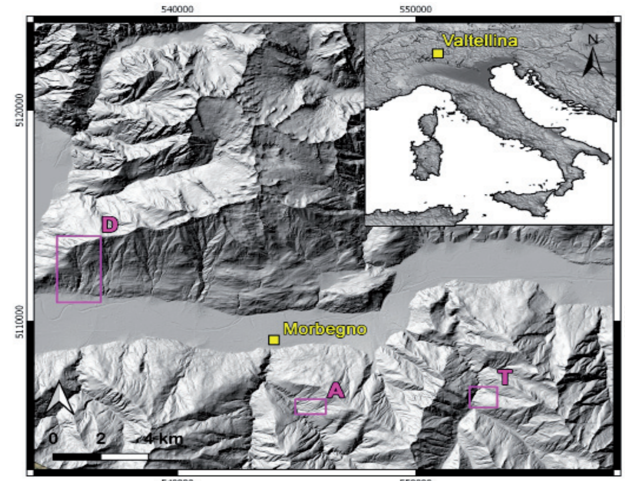

Fig. 1 - Test sites in Valtellina valley (northern Italy) considered in this study (D, Dubino; A, Albaredo; T, Tartano). (WGS84/UTM 33N)

DATA AND METHODS

Overview of the study areas

A coupled hydrological and slope stability modeling was performed considering 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). At the regional scale, the valley is EW oriented and stretching along about 120 km and with a morphology strongly affected by the tectonic activity of the regional fault "Insubric Line", a major Alpine lineament (Schimd *et alii,* 1986). The Valtellina valley is mainly characterized by metamorphic (e.g., gneiss, micaschists, phyllites and quartzites), igneous (e.g., andesites, basalts, granites, gabbri), and subordinate sedimentary rocks (e.g., dolomites, limestones). The middle-lower parts of the valley flanks are covered by glacial, fluvio-glacial, and colluvial deposits with variable thickness. Slopes characterizing the area result shaped with typical U-shape alpine valleys, 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 by rainfall-induced slope instabilities such as soil slips or landslide-induced debris flows (Cancelli & Nova, 1985; Crosta *et alii*, 2003; Dapporto *et alii*, 2005).

Hydrological and slope stability modeling

Numerical modeling was completed considering two numerical models: Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) model (Baum *et alii, 2008)*and Climatic Rainfall Hydrogeological Modeling Experiment (CHRyME) (Abbate *et alii*, 2023). In detail, TRIGRS is a distributed model that simulates slope hydrological response and stability for the spatial and temporal prediction of landslide susceptibility (Mirus & Loague, 2013; Gioia *et alii*, 2015; Fusco *et alii*, 2021). 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 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). Instead, CRHyME is a Python numerical code, still in an ongoing development and testing phase. It represents an extended version of the classical spatially distributed rainfall-runoff models. The main novelty is the physical simulation of rainfall-triggered processes such landslides, floods, erosion and solid transport. CRHyME works using available worldwide databases about morphology, land coverage, soil composition and hydro-mechanical properties. With CRHyME is possible to evaluate the soil moisture through the hydrological assessment of a catchment level using a continuous simulation driven by rainfalls data. Then, shallow landslide triggering is done including predicted soil moisture within the Harp 1D infinite slope model where stability parameters (i.e. friction angle and cohesion) are defined in function of the soil properties.

Numerical models settings

According to both TRIGRS and CHRyME structure, the hydrological and slope stability modeling were carried out considering a 90 m and a 5 m resolution Digital Elevation Models (DEMs), available from HydroSHEDS core data (www.hydrosheds.org) and Geoportale della Lombardia (www.geoportale.regione.lombardia.it), respectively. The same elevation data were 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).

Since TRIGRS and CHRyME consider differently the physical model of the soil cover, two different approaches were adopted considering the same input data. Specifically, a representative spatially uniform model, based on a single-layered homogeneous soil column for each grid cell, was defined for TRIGRS. 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 (Destinazione d'Uso dei Suoli Agricoli e Forestali; www.regione.lombardia.it). In CRHyME similar inputs about hydraulic and geotechnical properties of soils were considered. In particular: Corine Land Cover (Copernicus, 2018) were taken into account for soil coverages; Soil Grids database (Hengl *et alii*, 2017) was considered for computing soil physical properties such as granulometry and depth; hydraulic and geotechnical properties were retrieved by the 3D soil hydraulic database of Europe (Toth *et alii*, 2017) for modeling the unsaturated soil regime. Reference values of friction angle and cohesion were weighted against soil composition (i.e. % sand, silt and clay) in order to compute slope stability.

For both models an initial soil water pressure head distribution was required. For such a scope, representative values were set according to codes structure. An iterative approach based on varying soil water pressure head in unsaturated conditions (suction) was carried out for the TRIGRS model by changing the depth of a virtual groundwater table below the model domain. Instead, for CRHyME a reasonable value of soil moisture is required as input parameter. To retrieve such an initial hydrological condition, a pre-simulation of at least 1 year before the simulated event was carried out. Hourly intensity (I) and duration (D) values of July 1987, November 2000 and 2002 landslide-triggering rainfall events were set as boundary condition for both models. Time series were recorded by rain-gauges of the Agenzia Regionale per la Protezione dell'Ambiente network (ARPA; www.arpalombardia.it) located in Piazza Brembana, Colico and Bema towns, which were considered as representative for Tartano, Dubino and Albaredo sites, respectively (Fig. 2). Once set both TRIGRS and CHRyME models were applied to estimate FoS time series depending on the rainfall ones (Fig. 2). Thus, susceptibility maps were set to show the distribution of unstable areas, namely pixels

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 the setting of TRIGRS model of the three test sites. 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; (ϕ') = effective friction angle; (c') = effective cohesion.

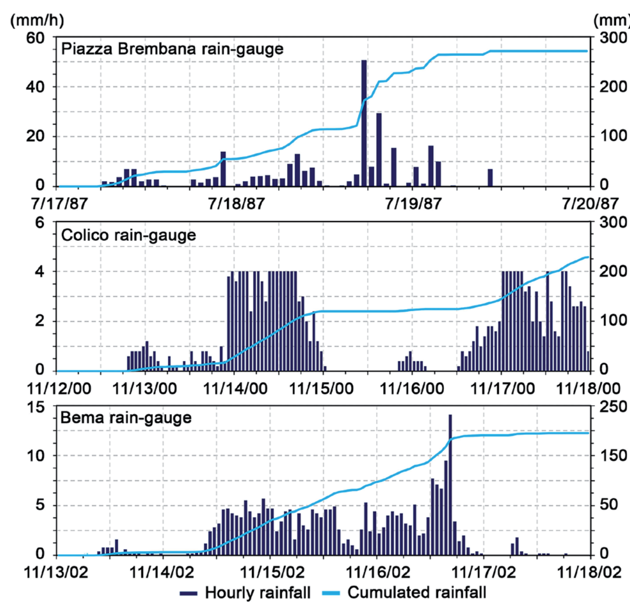

Fig. 2 - Rainfall time series considered for modeling Tartano 1987, Dubino 2000 and Albaredo 2002 landslide events. Hourly data were recorded by Piazza Brembana, Colico and Bema rain-gauges of ARPA Lombardia network (www.arpalombardia.it).

with FoS ≤ 1 values, and likely unstable areas, or 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 by the consideration that these values are close or can be approximated to the limit equilibrium condition (FoS = 1) by truncation. Finally, slope stability maps resulted were compared with the modeled landslide events and other historical ones from the Italian Landslides Inventory (IFFI; Trigila *et alii*, 2018). However, since the rainfall time-series could be not considered explicitly representative due to possible lack of reliable recordings, the comparisons are only to demonstrate that the potentially unstable zones identified through TRIGRS and CHRyME models correspond to previous slope instabilities.

RESULTS

The coupled hydrological and slope stability modeling allowed as principal result maps of unstable and likely unstable cells across test areas (Fig. 3).

Maps obtained for Tartano test site, with a spatial resolution of 90 m, show similar distribution of unstable and/or likely unstable cells (Fig. 3A-B). For both models these cells were mainly observed in the southern sector of the tested site, along a regular open slope where an increase of slope angle occurs. In detail, maps revealed that a great number of unstable and/or likely unstable cells are close or coincide with triggering areas of the July 1987 landslide event and with other inventoried events and areas with diffuse shallow instabilities. This matching was observed performing better for TRIGRS (Fig. 3A) than for CHRyME models (Fig. 3B). However, both models identified other potentially unstable areas not coinciding with the landslide inventory. These cells were recognized occurring mainly close to secondary hydrographic networks or where abrupt local morphological discontinuities occur. Finally, a finer distribution of unstable and/or likely unstable cells was achieved by TRIGRS modeling with 5 m resolution (Fig. 3C) as it was recognized by the good matching with all inventoried landslide events and diffuse shallow instabilities areas. These results strongly depend on the higher resolution of the DEM used. 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.

A different distribution of unstable and/or likely unstable cells was revealed comparing maps obtained by TRIGRS and CHRyME modeling with 90 m resolution for Dubino site (Fig. 3D-E). In particular, the comparison of maps with the triggering areas of the November 2000 landslide event and other inventoried ones revealed a matching that is lower for TRIGRS than for CHRyME. Modeled unstable and/or likely unstable areas are few and localized in the TRIGRS map (Fig. 3D), while distributed across the lower-western and the north-eastern sectors of the slope characterize in the CHRyME one (Fig. 3E). However, as for the Tartano site, potentially unstable areas coinciding or not with the landslide inventory were modeled from both TRIGRS and CHRyME. On the contrary, a good matching was observed comparing the distribution of unstable areas modeled by TRIGRS (Fig. 3F) and the CHRyME ones. In this case, unstable cells were observed close to both some head-basin of main channels and open slope areas and well matching the landslide inventory. Unstable and/or likely unstable areas were observed mainly in the lower sector of the Dubino test site, where occasional changes in slope angle or morphological discontinuities occur. As obtained for the Tartano site, the distribution strongly depends on the resolution of the DTM used.

Maps of Albaredo site resulting by TRIGRS and CHRyME models showed a different distribution of unstable areas (Fig. 3G-H). Generally, TRIGRS resulted in very localized unstable areas characterized by a limited correlation with the triggering areas of November 2002 landslide event, except for few cases (Fig. 3G). On the contrary, a better match was obtained by CHRyME model (Fig. 3H). In this case, a diffuse distribution of unstable and/or likely unstable cells were recognized mainly occurring in close proximity to both channels of the hydrographic network and open slopes. A more accurate modeling of unstable areas with a better matching with the landslide inventory was obtained by TRIGRS model with a 5 m resolution (Fig. 3I). In fact, diffuse slope instabilities were identified across the whole considered slope, as obtained by CHRyME model. 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 downslope, in the eastern sector of Albaredo site, where diffuse shallow instability areas were inventoried.

DISCUSSION

Numerical modeling of infiltration process show how dynamic variables, such as hydrological and morphological conditions as well as stratigraphic setting of the involved soils, strongly affect the triggering mechanisms of shallow landslides.

Physics-based models can be applied to predict both temporal and spatial variability of proneness to shallow landslides. However, all of them reveal how difficult it is to characterize soil covers, in terms of soil structure, setting and properties into parameterization of distributed physically based models. In fact, despite some numerical codes take into account heterogeneity of soil mantles, a large number of them requires to discretize soil covers as a single homogeneous and isotropic soil unit with constant hydraulic and geotechnical properties, which are often estimated by empirical relationships based on textural classification.

Thus, the availability of such data, including their accuracy and distribution, may strongly affects results of hydrological and slope stability modeling. The common approach used to define susceptibility maps to rainfall-induced shallow landslides in Valtellina valley considered geomorphological and stratigraphic factors including slope angle, cover thickness and occurrence of natural or artificial discontinuities. 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 hydrological and slope stability (Dapporto *et alii*, 2005; Camera *et alii*, 2014).

Moreover, such analyses were performed at slope scale and

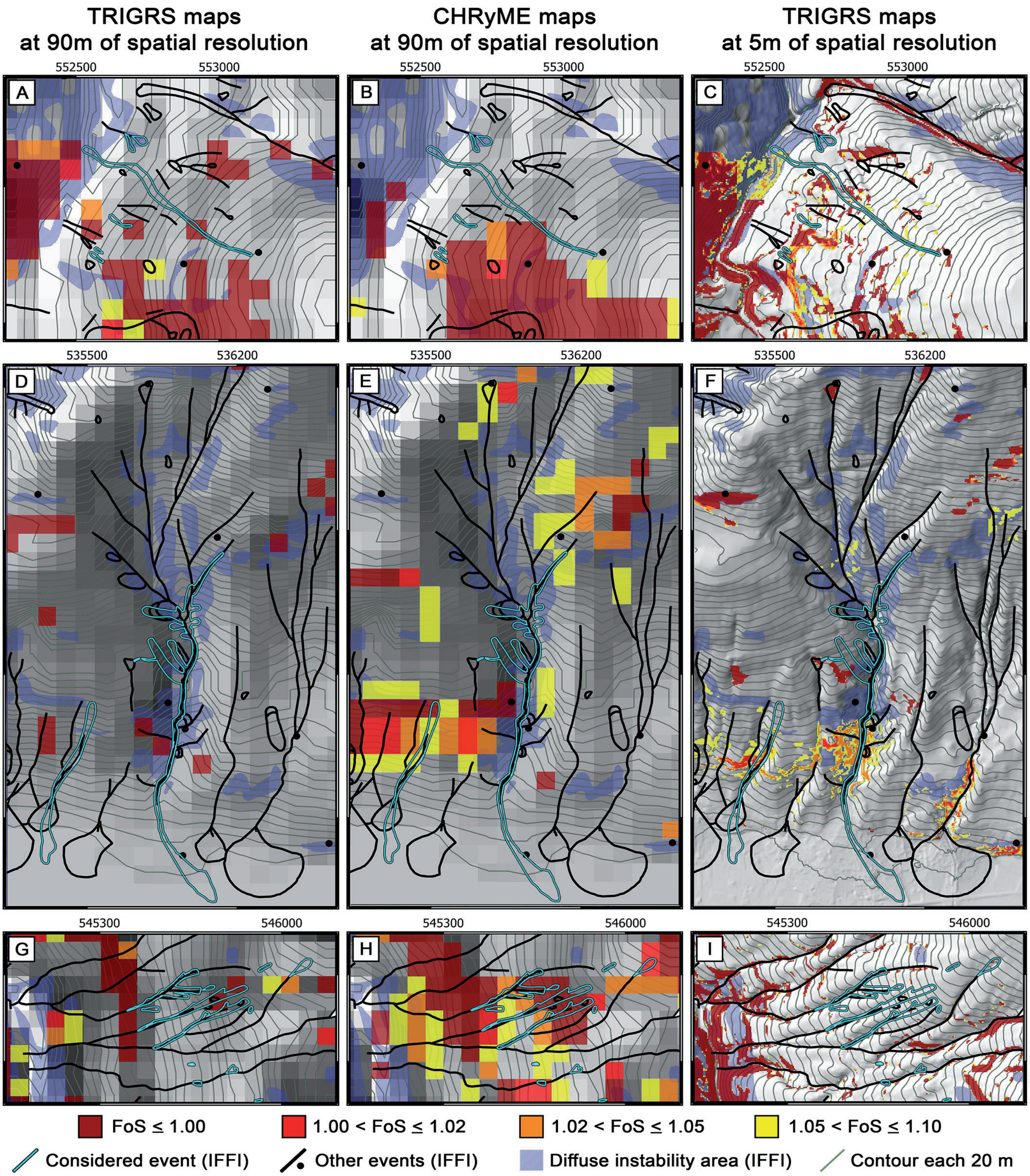

Fig. 3 - Distributed slope stability maps obtained by TRIGRS and CHRyME modeling at 90 m resolution for Tartano (A, B, respectively), Dubino (D, E, respectively) and Albaredo (G, H, respectively) sites, and by TRIGRS modeling at 5 m resolution for Tartano (C), Dubino (F) and Albaredo (I) sites. Unstable (FoS ≤ 1.00) and likely unstable (1.00 ≤ FoS ≤ 1.10) cells were compared with the available landslide inventory from the Italian Landslides Inventory (IFFI), comprising the modeled landslide events. Hillshade maps and contour lines are derived by DEMs with 90 m (A, B, D, E, G, H) and 5 m (C, F, I) resolution. (WGS84/UTM 33N).

the behavior of layered soil covers was modeled parametrizing representative 2D slope models, thus not taking into account the combined influence of the spatial variability of both soil hydraulic and geotechnical soil properties and thickness as well as antecedent soil hydrological conditions. Other attempts were focused on landslide susceptibility mapping at the basin scale through statistically based approaches considering only terrain variables (slope angles, land use, roads, rivers, etc.) and rainfall events (Yordanov & Brovelli, 2020).

According to such an issue, the aim of this research was to assess landslide susceptibility at the distributed scale through the application of numerical models considering both spatial variations in soil thickness and properties as well as both hydrological antecedent conditions and rainfall scenarios. Accordingly, a coupled distributed hydrological and slope stability model was tested for soils covering in three representative areas of the Valtellina valley. The high variability of hydro-mechanical soil properties and thickness can impact the modeling of infiltration processes and thus storage dynamics and pore water pressure distribution. To advance this critical aspect, the distributed modeling was based on two approaches, both depending on the numerical code structure and spatial resolution. Therefore, a representative physical model of spatially uniform soil cover was parameterized for TRIGRS, while a spatially heterogeneous physical one for CHRyME. Furthermore, the effects of different resolution of analysis were tested considering DEM with resolution of 90 m and 5 m.

The results of modeling show zones affected by slope instability which are consistent with the landslide inventory (Fig. 3). The results obtained are expressed by potentially unstable areas whose spatial resolution is generally similar. In detail, areas close to flanks or head-basin of channels, affected by landslides, or where changes in cover thickness or slope angles occur, resulted as characterized by a greater proneness to slope instability. These results are consistent with the prior literature (Guzzetti *et alii*, 1992; Crosta *et alii*, 2003; Dapporto *et alii*, 2005; Camera *et alii*, 2014). Furthermore, they overcome some limitations related to the application of statistically based models, where dynamic variables, such as initial soil hydrological conditions, were not considered (Yordanov & Brovelli, 2020). Soil cover thickness and spatial distribution, as well as rainfall intensity and duration strongly affect the infiltration processes within the cover and then the occurrence of saturated or near-saturated conditions in those "critical" areas. These conditions were modeled better for Tartano (Fig. 3A-B-C) and Albaredo (Fig. 3D-E-F) sites than for the Dubino one (Fig. 3G-H-I). Maps shown that the distribution of unstable areas resulted more accurate for TRIGRS model with a resolution of 5 m than those obtained for with 90 m resolution. Specifically, TRIGRS resulted more suitable to model single landslide events while CHRyME for distributed ones. Such condition was clearly revealed analyzing maps of Tartano and Albaredo cases. However, given that TRIGRS and CHRyME apply the infinite slope approach, which often overestimates unstable areas in comparison to that resulting from field observations, 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.

CONCLUSION

The distributed modeling of slope hydrological response and stability represents a challenge for the assessment of hazard to rainfall-induced shallow landslides if considering heterogeneous and thickness-varying soils. Numerical 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. In such a case, numerical models are commonly based on assumptions of a single homogeneous, isotropic unit. However, such condition cannot be always applied because strongly affected by availability and quality of soil properties data.

According to such an aim, a combined approach for assessing landslide hazard at the slope scale was presented by considering the influence of both spatial distribution of soil thickness and properties and resolution of analysis. The aim was to compare existing approaches when parameterizing physically based models of hydrological response for applications on steep, landslide-prone hillslopes. However, an additional intent was to emphasize how structure of numerical codes and data input may affect distributed modeling. The approach was tested considering three representative sites of the Valtellina valley affected by shallow landslides involving the soil mantle which induce debris flows. The proposed physics-based approach highlights the influence of the availability of spatially distributed soil properties to define and improve input data for physics-based modeling.

Results obtained emphasize the importance of estimating reliable soil hydraulic and geotechnical properties and advances slope hydrologic and stability models under specific rainfall conditions. Moreover, another aspect which has been highlighted is the control due to topography and the type of precipitation phenomena.

This study revealed which of the used numerical codes is suitable for analyzing single landslide events, as for TRIGRS, and for distributed ones, as for CHRyME. For this reason, the first model can be considered more suitable for the back analysis of landslide events, while the second one for a scenario analysis. Finally, the approach presented can be considered for further analysis aimed at the definition of the probability of landslide spatial distribution, related to a specific value of rainfall threshold, which is essential to assess landslide hazard maps at a distributed scale over a mountainous district. In this way, results of this research could facilitate the development of a consistent early-warning system, considering seasonally variable landslide hazards.

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REFERENCES

Abbate A., Longoni L., Ivanov V.I. & Papini M. (2019) - *Wildfire Impacts on Slope Stability Triggering in Mountain Areas.* Geosciences, **9**: 417.

Abbate A., Papini M. & Longoni L. (2021) - *Analysis of meteorological parameters triggering rainfall-induced landslide: a review of 70 years in Valtellina.* Nat. Hazards Earth Syst. Sci., **21**: 2041-2058.

Abbate A. (2022) - *Hydrogeological hazards evaluation under climate change scenarios: an application of the CRHyME model (Climatic Rainfall Hydrogeological Modelling Experiment).* PhD Thesis. http://hdl.handle.net/10589/187061.

Aleotti P. (2004) - *A warning system for rainfall-induced shallow failures*. Eng. Geol., **73**: 247-265.

Baum R.L., Savage W.Z. & Godt J.W. (2008) - *TRIGRS—A Fortran Program for Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis, Version 2.0.* Open-File Report 2008-1159. U.S. Geological Survey: Reston, VA, USA, 75.

Baum R.L., Godt J.W. & Coe J.A. (2011) - *Assessing susceptibility and timing of shallow landslide and debris flow initiation in the Oregon Coast Range, USA.* Ital J. Eng. Geol. Environ.: 825-834.

Borga M., Dalla Fontana G. & Da Ros D. (1998) - *Shallow landslide hazard assessment using a physically based model and digital elevation data.* Environmental Geology, **35**: 81-88.

Calcaterra D., Parise M., Palma B. & Pelella L. (2000) - *The influence of meteoric events in triggering shallow landslides in pyroclastic deposits of Campania, Italy.* In Landslides in Research, Theory and Practice; Conf. Proc.; Thomas Telford Publishing: London, UK: 209-214.

Campbell R.H. (1975) - *Soil Slips, Debris Flows, and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California.* In US Geological Survey Professional Paper, **851**: 51.

Cancelli A. & Nova R. (1985) - *Landslides in soil debris cover triggered by rainstorm in Valtellina.* Proc. 4th Int. Conf. and Field Workshop on Landslides, Tokyo, **1**: 267-272.

Camera C.A.S., Apuani T. & Masetti M. (2014) - *Mechanisms of failure on terraced slopes: the Valtellina case (northern Italy).* Landslides, **11**: 43-54.

Cevasco A., Pepe G. & Brandolini P. (2014) - *The influences of geological and land use settings on shallow landslides triggered by an intense rainfall event in a coastal terraced environment.* Bull. Eng. Geol. Environ., **73**: 859-875.

Crosta G.B. (1998) - *Regionalization of rainfall threshold: an aid to landslides hazard evaluation.* Env. Geol., **35**: 131-145.

Crosta G.B. & Frattini P. (2002) - *Rainfall thresholds for triggering soil slips and debris flow.* Proc. 2nd Plinius Int. Conf. on Mediterranean Storms, Siena, Italy.

Crosta G.B., Dal Negro P. & Frattini P. (2003) - *Soil slips and debris flows on terraced slopes.* Nat. Haz. Earth Syst. Sci., **3**: 31-42.

Dapporto S., Aleotti P., Casagli N., Polloni G. (2005) *Analysis of shallow failures triggered by the 14-16 November 2002 event in the Albaredo valley, Valtellina (Northern Italy).* Adv. Geosci., **2**: 305-308.

Del Prete M., Guadagno F. & Hawkins A. (1998) - *Preliminary report on the landslides of 5 May 1998, Campania, southern Italy.* Bull. Eng. Geol. Environ., **57**: 113-129.

De Vita P., Agrello D. & Ambrosino F. (2006) - *Landslide susceptibility assessment in ash-fall pyroclastic deposits surrounding Mount Somma-Vesuvius: Application of geophysical surveys for soil thickness mapping.* J. Appl. Geophys., **59**: 126 -139.

De Vita P., Fusco F., Tufano R. & Cusano D. (2018) - *Seasonal and event-based hydrological and slope stability modeling of pyroclastic fall deposits covering slopes in Campania (Southern Italy).* Water **10**(9): 1140. https://doi.org/10.3390/w10091140

Dowling C.A. & Santi P.M. (2013) - *Debris flows and their toll on human life: a global analysis of debris-flow fatalities from 1950 to 2011.* Nat. Hazards **71**(1): 203-227.

European Environment Agency (EEA) (2018) - *Corine Land Cover (CLC) 2018,* Version 20.

Frattini P., Crosta G.B., Fusi N. & Dal Negro P. (2004) - *Shallow landslides in pyroclastic soils: A distributed modelling approach for hazard assessment.* Eng. Geol., **73**: 277-295.

Fredlund D.G. & Morgenstern N.R. (1977) - *Stress state variables for unsaturated soils.* J. Geotech. Eng. Div. 1977, **103**: 447-466.

Fusco F., Mirus B.B., Baum R.L., Calcaterra D. & De Vita P. (2021) - *Incorporating the effects of complex soil layering and thickness local variability into distributed landslide susceptibility assessments.* Water, **13**: 713.

Fusco F., Bordoni M., Tufano R., Vivaldi V., Meisina C., Valentino R., Bittelli M. & De Vita P. (2022) - Hydrological regimes in different slope environments and implications on rainfall thresholds triggering shallow landslides. Nat. Haz, **114**: 907-939.

Gioia E., Speranza G., Ferretti M., Godt J.W., Baum R.L., Marincioni F. (2015) - *Application of a process-based shallow landslide hazard model over a broad area in central Italy.* Landslides, **13**: 1197-1214.

Grelle G., Soriano M., Revellino P., Guerriero L., Anderson M.G., Diambra A., Fiorillo F., Esposito L,.Diodato N. & Guadagno F.M. (2014) -

Space-time prediction of rainfall-induced shallow landslides through a combined probabilistic/deterministic approach, optimized for initial water table conditions. Bulletin of Engineering Geology and the Environment, **73**: 877-890.

Guerriero L., Guadagno F.M. & Revellino P. (2019) - *Estimation of earth-slide displacement from GPS-based surface-structure geometry reconstruction*. Landslides, **16**: 425-430.

Guzzetti F., Crosta G.B., Marchetti M. & Reichenbach P. (1992) - *Debris flows triggered by the july 17-19, 1987 storm in the valtellina area (northern Italy)*. In Proc. of the Intern. Symp. Iterpraevent, Bern, Swiss.

Guzzetti F., Carrara A., Cardinali M. & Reichenbach P. (1999) - *Landslide hazard evaluation: A review of current techniques and their application in a multi–scale study, central Italy.* Geomorphology, **31**: 181-216.

Hengl T., Mendes de Jesus J., Heuvelink G.B.M., Ruiperez Gonzalez M., Kilibarda M. & Blagotić A. (2017) - *SoilGrids250m: Global gridded soil information based on machine learning*. PLoS ONE, **12**(2).

Hsieh P.A., Wingle W. & Healy R.W. (2000) - *VS2DI – A Graphical Software Package for Simulating Fluid Flow and Solute or Energy Transport in Variably Saturated Porous Media.* U.S. Geological Survey Water–Resources Investigations Report, 9-4130.

Hungr O., Leroueil S. & Picarelli L. (2014) - *The Varnes classification of landslide types, an update.* Landslides, **11**: 167-194.

Jakob M. & Hungr O. (2005) - *Introduction.* In: Hungr O, Jakob M (eds) *Debris-flow hazards and related phenomena*. Springer-Praxis, Berlin, **1**(7).

Iverson R.M. (2000) *Landslide triggering by rain infiltration*. Water Resour. Res., **36**: 1897-1910.

Lanni C., Borga M., Rigon R. & Tarolli P. (2012) - *Modelling shallow landslide susceptibility by means of a subsurface flow path connectivity index and estimates of soil depth spatial distribution.* Hydrol Earth Syst Sci., **16**: 3959-3971.

Lizarraga J.L. & Buscarnera G. (2018) - *Spatially distributed modeling of rainfall-induced landslides in shallow layered slopes.* Landslides, **16**: 253-263.

Lu N. & Likos W.J. (2004) - *Unsaturated soil mechanics*. Wiley, New York, **556.**

Lu N., Godt J.W. & Wu D.T. (2010) - *A closed–form equation for effective stress in unsaturated soil*. Water Resour. Res. **46**.

Mirus B.B. & Loague K. (2013) - *How runoff begins (and ends): Characterizing hydrologic response at the catchment scale*. Water Resour. Res., **49**: 2987-3006.

Mirus B.B., Jones E.S. & Baum R.L. (2020) - *Landslides across the USA: occurrence, susceptibility, and data limitations.* Landslides, **17**: 2271-2285.

Moser M. & Hohensinn F. (1983) - *Geotechnical aspects of soil slips in Alpine regions*. Eng. Geol., **19:** 185-211.

Napolitano E., De Vita P., Fusco F., Allocca V. & Manna F. (2015) - *Long-Term Hydrological Modelling of Pyroclastic Soil Mantled Slopes for Assessing Rainfall Thresholds Triggering Debris Flows: The Case of the Sarno Mountains (Campania—Southern Italy)*. In: Lollino et al., Engineering Geology for Society and Territory, **2**: 1567-1570.

Reichenbach P., Rossi M., Malamud B.D., Mihir M. & Guzzetti F. (2018) - *A review of statistically–based landslide susceptibility models*. Earth Sci. Rev., **180**: 60-91.

Revellino P., Guerriero L., Grelle G., Hungr O., Fiorillo F., Esposito L. & Guadagno F.M. (2013) - *Initiation and propagation of the 2005 debris avalanche at Nocera Inferiore (Southern Italy)*. Italian Journal of Geoscience, **132**(3): 366-379.

Richards L.A. (1931) - *Capillary conduction of liquids through porous mediums*. J. Appl. Phys., **1**: 318-333.

Salvati P., Bianchi C., Rossi M. & Guzzetti F. (2010) - *Societal landslide and flood risk in Italy*. Nat. Haz. Earth Syst. Sci., **10**: 465-483.

Schimd S.M., Zingg A. & Handy M. (1986) - *The kinematics of movements along the insubric Line and the emplacement of the lvrea Zone.* Tectonophysics, **135**: 47-66.

Smith J.B., Godt J.W., Baum R.L., Coe J.A., Ellis W.L., Jones E.S. & Burns S.F. (2017) - *Results of hydrologic monitoring of a landslide-prone hillslope in Portland's West Hills, Oregon, 2006–201.* U.S. Geological Survey Data Series, **1050**(10).

Trigila A., Iadanza C., Bussettini M., Lastoria B. (2018) - *Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio (in Italian)*. Rapporto **287**.

Tóth B., Weynants M., Pásztor L. & Hengl T. (2017) - *3D soil hydraulic database of Europe at 250 m resolution.* Hydrol. Proc., **31**: 2662-2666.

Tufano R., Fusco F. & De Vita P. (2016) - *Spatial modeling of ash-fall pyroclastic deposits for the assessment of rainfall thresholds triggering debris flows in the Sarno and Lattari mountains (Campania, southern Italy).* Rend. Online Soc. Geol. It., **41**: 210-213.

Tufano R., Cesarano M., Fusco F. & De Vita P. (2019) - *Probabilistic approaches for assessing rainfall thresholds triggering shallow landslides. The study case of the peri-vesuvian area (southern Italy)*. It. Jour. of Eng. Geol. and Env., **1**: 105-110..

Van Genuchten M.T. (1980) - *A closed form equation for predicting the hydraulic conductivity of unsaturated soils*. Soil Sci. Soc. Am., **44**: 892-898.

Wu W. & Sidle R.C. (1995) - *A distributed slope stability model for steep forested basins.* Water Res. Res., **31**: 2097-2110.

Yordanov V. & Brovelli M.A. (2021) - *Application of various strategies and methodologies for landslide susceptibility maps on a basin scale: the case study of Val Tartano, Italy.* Appl. Geomat., **13**: 287-309.

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