Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X

doi: doi.org/10.53243/RootS2025-34

Effect of vegetation on the triggering of shallow landslides using CRITERIA-3D

G. Sannino[1], F. Tomei[1], M. Bittelli[2], M. Bordoni[3], C. Meisina[3], R. Valentino[4]

[1]*Regional Agency for Prevention, Environment and Energy of Emilia-Romagna Region, Bologna, Italy*
[2] *Department of Agricultural and Food Sciences, University of Bologna, Bologna, Italy*
[3]*Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy*
[4]*Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parma, Italy*

ABSTRACT: The paper deals with an agro-hydro-mechanical model aimed at obtaining time-varying susceptibility maps for rain-induced shallow landslides, including the effect of different types of vegetation in their seasonal life cycles. The model includes a slope stability analysis based on the limit equilibrium method applied to an infinite slope. The mechanical part of the model has recently been implemented in CRITERIA-3D, a method originally developed to calculate the water balance in a cultivated area. The effect of roots is accounted under both hydrological and potentially mechanical point of view (neglected in this note). CRITERIA-3D has been preliminary validated on a test site slope and then it has been applied to two sample areas in the Emilia Romagna Region. Both the sample areas had been affected by a huge number of landslides following exceptional rainfall between 16 and 17 May 2023. The results show that the model can capture both spatially and temporally the observed shallow landslides, based on available data on precipitation, soil type, and land use at regional scale.

Keywords: shallow landslides; distributed modeling; soil hydrological balance; vegetation life; crop development

1 INTRODUCTION

In the interaction between soil and atmosphere on a natural slope, root systems play a decisive role, contributing on the one hand to mechanical stabilisation of shallow soil and on the other to modifying the volumetric water content and suction of the partially saturated soil. Only in recent years the scientific literature on the modeling of shallow landslides at the territorial scale included appropriate vegetation modeling (Murgia et al., 2022). Moreover, many "dynamic" aspects, i.e. those related to plant life, are still normally neglected. In fact, in most models, including those that consider non-stationary hydrological processes, vegetation is often considered an unchanged factor over time (Li and Duan, 2023).

The proposed CRITERIA-3D model allows for the evolution of roots and vegetation cover over time to be considered and can also consider the different phenological phases based on actual hourly meteorological data. The structure of the model also allows different cropping solutions to be tested to assess which ones could be most effective in counteracting shallow landslides on natural slopes. The model can simultaneously consider soil stratigraphy and related hydrological parameters, possible lithological contact, root distribution at depth and the evolution of the Leaf Area Index (LAI) over time. Based on hourly meteorological input data, the model returns the water content and suction at selected depths. These hydrological parameters consider the effect induced by evapotranspiration, including the transpiration activity of plants. Regarding slope stability, the model calculates the safety factor at different depths, based on a limit state equilibrium model (Lu and Godt, 2010) that considers the conditions of partial saturation induced by plants. Preliminarily, the model was validated by reproducing the hydrological conditions of a natural slope, equipped with a weather station and sensors for measuring suction and water content at different depths, located in Montué, in the Oltrepò Pavese area (Sannino et al., 2024). Furthermore, the model was applied to the same experimental site to assess its predictive potential in space and time for an observed shallow landslide (Sannino et al., 2025).

In this work, CRITERIA-3D was applied to a sample area in Monteleone, in the municipality of Roncofreddo (FC), which was affected by several landslides on 16 and 17 May 2023. CRITERIA-3D allows different land uses to be considered, including different types of vegetation, each with its own characteristics in terms of root systems and evapotranspiration properties. The results obtained highlight the importance of modeling plants in detail and the hydrological effects of vegetation on slope stability, as well as the effectiveness of the model in predicting the triggering of shallow landslides from both a spatial and temporal point of view.

2 MATERIALS AND METHODS

2.1 *Hydrological modeling*

The version of CRITERIA-3D presented in this note incorporates a stability model, based on the limit equilibrium method, as an improvement on a previously developed agro-hydrological model (Bittelli et al., 2010). It is a freely accessible model set-up by the Hydro-Meteorological Climate Service of Arpae of the Emilia-Romagna Region (SIMC) (https://github.com/ARPA-SIMC/CRITERIA3D). Specifically, CRITERIA-3D solves soil water flows according to the Richards equation using a finite element scheme, in which the calculation domain is approximated by a grid of points.

In addition to calculating infiltration and the resulting non-stationary vertical percolation on an hourly basis, the model includes in the water balance the infiltration and redistribution of water in directions other than vertical (according to the gradient), soil evaporation, capillary rise, surface runoff and root absorption by plants, based on the typical transpiration requirements of the crop, as well as a reduction in evaporation caused by the presence of vegetation. The model is able to consider different layers, each characterised by its own water retention curve, its own hydrological parameters and its own thickness. Partial saturation conditions are modelled using the water retention curve, based on the Van Genuchten-Mualem model in the version proposed by Ippisch et al. (2006) for calculating the degree of saturation and by the model proposed by Mualem (1976) for the hydraulic conductivity curve.

2.2 *Vegetation modeling*

CRITERIA-3D considers the presence of vegetation and its life stages by means of 'growing degree days' (GDD), an index that expresses the relationship between temperatures and the phenological development of crops. When the temperature exceeds a certain threshold, the plant can accumulate heat in the form of degree days, which will constitute a certain hourly Leaf Area Index (LAI) (Bittelli et al., 2010). The various phenological phases are modelled using the LAI curve throughout the year, as the leaf area grows and shrinks in different seasons. The vegetation also affects the evaporation rate of the shallow soil layers.

CRITERIA-3D considers a root system that varies with depth, expressed as the volumetric percentage of soil occupied by roots, which varies for each layer. Root distributions take on a geometric shape, which can be, for example, cylindrical or cardioid. By changing the parameters of these distributions, it is possible to approximate the geometry of the actual root system of the specific crop (Bittelli et al. 2010). Each layer occupied by roots corresponds to a certain rate of root water uptake (RWU), which depends on the actual air temperature and soil moisture status: when the soil is dry or saturated, the plant blocks its transpiration activity because it is under water stress. In fact, when the soil is dry, the plant closes its stomata so as not to lose cellular water; when the soil is saturated, the environment is anoxic and the roots suffocate. Evapotranspiration is calculated on an hourly basis using the Penman-Monteith method, as reviewed by Allen et al. (1994), considering data on net solar radiation, net heat flow from the soil, average air temperature, wind speed and vapour pressure.

2.3 *Slope stability analysis*

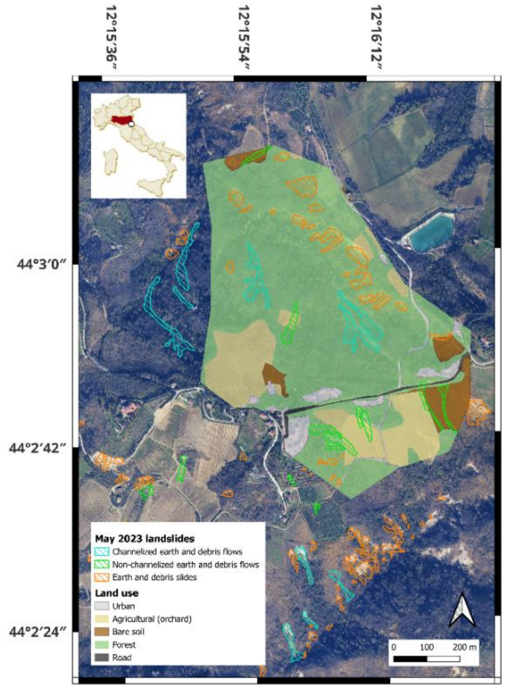
Since rainfall-induced shallow landslides involve layers of soil that are generally thin in relation to the landslide area, the calculation method traditionally used to model these landslide events is that of limit equilibrium applied to an infinitely extended slope. The scientific community agrees that this method is consistent with translational phenomena, since it uses a planar sliding surface. When the landslide occurs, the block of soil that is assumed to translate along the sliding surface is considered rigid, consistent with the CRITERIA-3D hydrological model, which is based on the same assumption to simulate water flows.

The method allows the factor of safety (FoS) to be calculated as a quantitative index of slope stability. The critical state of equilibrium is identified when FoS = 1, and below this value it is considered that the slope is subject to landslide.

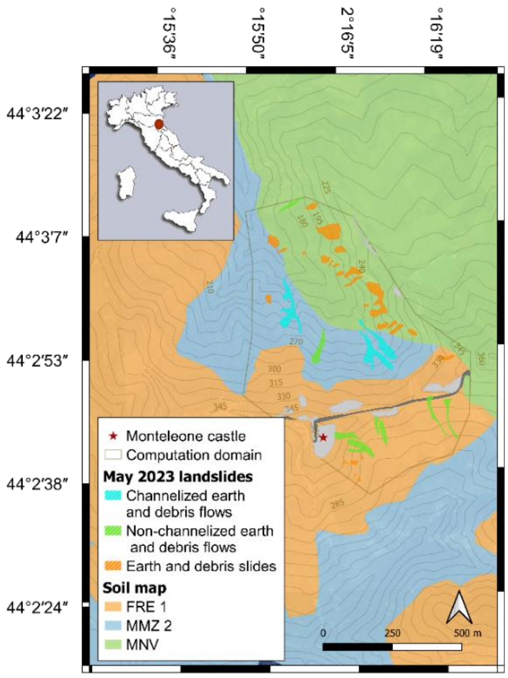
The factor of safety is calculated based on the Lu and Godt (2008) equation, which allows the onset of instability to be detected even in conditions of partial saturation, i.e. when suction is at negative values, even if close to zero. This is possible thanks to the use of a variable that quantifies the hydrological effects of instability due to capillarity and the physical-chemical forces acting in the soil, the so called "suction stress" (Lu and Godt, 2008).

2.4 *Application to a case study*

CRITERIA-3D was applied to a sample area of 5.65 km^2 in Monteleone (municipality of Roncofreddo, FC), within the Romagna area, which was affected by numerous landslides following heavy rainfall between 16 and 17 May 2023, with daily cumulative peaks of 205.6 mm on 16 May at the Trebbio station. The input data were acquired using the digital cartography available for the Emilia-Romagna Region, using a DEM (Digital Elevation Model) with a 5mx5m grid. Based on the land use map, the selected area includes different uses, such as urbanised areas, agricultural crops, woodland (forest), bare soil and roads (Figure 1a). With reference to the regional soil map, the area contains different types of shallow soil, which are identified based on texture, according to the USDA classification (Figure 1b).



(a)



(b)

Figure 1. Test area in Monteleone, Roncofreddo (FC): (a) land use map; (b) map of soils and landslides observed following the event of 16 and 17 May 2023

Table 1 shows the parameters used for the soil types, distinguished by different layers. The shear strength parameters were assigned with reference to García-Gaines and Frankenstein (2015). The soil hydraulic conductivity (K_s) is assumed according to the scheme reported in the Soil Survey Manual (1993). In the absence of experimental data, the root mechanical reinforcement action of the roots was conservatively considered to be zero.

As regards the agricultural and forest areas, the parameters related to vegetation were assumed as follows: a maximum root depth of 1.5 m for cultivated soils and 2 m for forests, LAI ranging from a minimum of 0 in winter to a maximum of 2.5 in late spring-summer for cultivated soils, and LAI ranging from 1 to 4 for forests. Root distribution is assumed to be “cardioid”, with the maximum percentage of roots in the first 50 cm for both types of vegetation. The period of vegetation cover, which runs from March to late October, was assumed as in Sannino et al. (2024). The simulation of landslide triggering was carried out by introducing hourly meteorological data from 1 January to 17 May 2023. This time was enough to assure the soil had reached a state of equilibrium and results were not affected by initial conditions.

Table 1. Input parameters for Monteleone test site

Soil	Layer	Depth (cm)	USDA text*	γ (kN/m³)	K_s (m/s)	c' (kPa)	ϕ' (kPa)
FRE1	I	0-60	SL	15.0	$3.3 \cdot 10^{-7}$	0	33
FRE1	II	60-87	L	15.0	$8.9 \cdot 10^{-7}$	0	28
FRE1	III	87-107	SL	14.9	$3.9 \cdot 10^{-7}$	0	28
FRE1	IV	107-120	SL	17.6	$5.8 \cdot 10^{-8}$	0	28
MMZ2	I	0-20	L	13.5	$1.1 \cdot 10^{-6}$	0	28
MMZ2	II	20-50	L	14.7	$1.1 \cdot 10^{-6}$	0	34
MMZ2	III	50-60	L	15.7	$6.0 \cdot 10^{-7}$	0	28
MNV	I	0-45	SCL	15.5	$5.9 \cdot 10^{-7}$	0	33
MNV	II	45-65	SCL	14.7	$1.6 \cdot 10^{-6}$	0	33
MNV	III	65-105	SCL	15.4	$1.1 \cdot 10^{-6}$	0	33
MNV	IV	105-120	SCL	15.6	$9.0 \cdot 10^{-7}$	0	32
MNV	V	120-130	C	16.7	$7.6 \cdot 10^{-8}$	20	27

*SL= Silt Loam; L=Loam; SCL=Sandy Clay Loam; CL=Clay Loam; K_s= hydraulic conductivity.

3 RESULTS

The results obtained by modeling landslides that occurred between 16 and 17 May 2023 are shown in Figure 2, which includes two FoS maps in the study area. The first map (Figure 2a) refers to 16 May 2023, while the second (Figure 2b) refers to the following day. The sequence demonstrates the model's ability to capture the temporal evolution of the phenomena. Although the areas with FoS lower than unity do not always correspond to the actual landslide areas and, in some cases, are overestimated, the results obtained can still be considered satisfactory, considering the method of input data acquisition and the estimation of the model parameters.

4 CONCLUSIONS

The effectiveness of using CRITERIA-3D as a tool for the spatial-temporal analysis of rainfall-induced shallow landslides has been demonstrated. The results obtained in terms of FoS maps show that CRITERIA-3D can model the evolution over time of rainfall-induced landslides, also considering the evapo-transpirative activity of different types of vegetation. While the previous applications had shown that considering the life stages of vegetation increased the efficiency of the model compared to bare soil (Sannino et al., 2024), in the present application, the results obtained with vegetated soil are not different from those obtained by simulating bare soil (not shown here for the sake of brevity), since the triggering rainfall event is of extraordinary intensity and the effect of vegetation is completely lost. In this perspective, even considering the mechanical contribution to be null seems an appropriate choice.

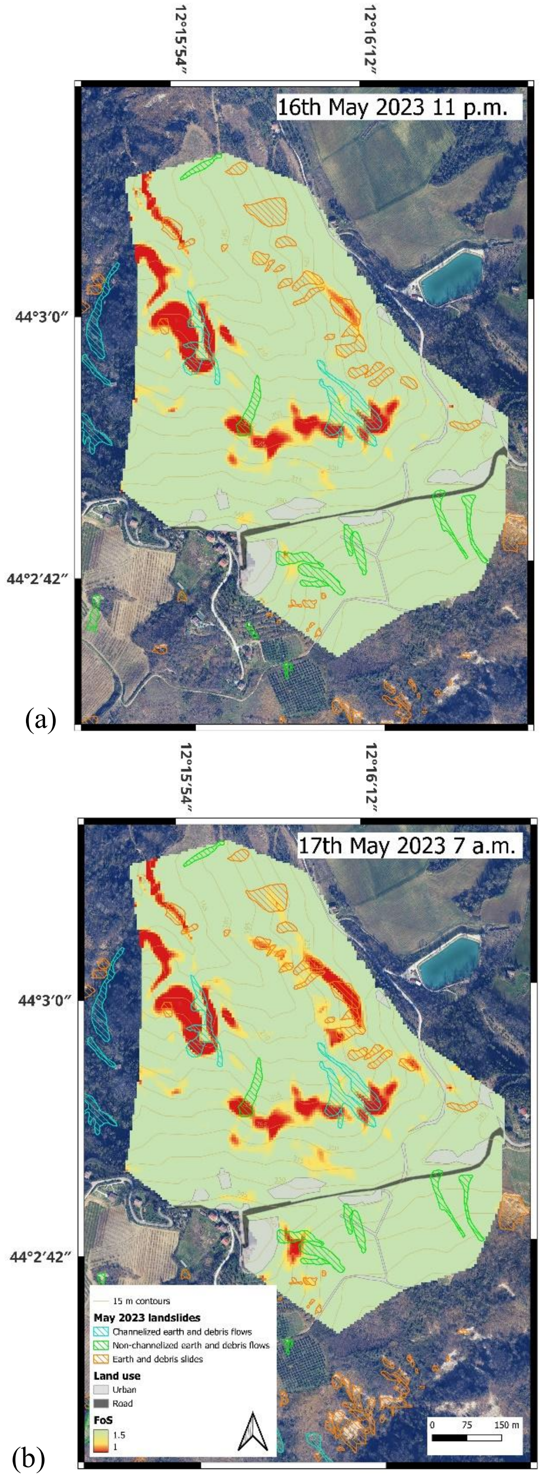


Figure 2. FoS maps in Monteleone test area: (a) 16 May 2023 at 11:00 p.m.; (b) 17 May 2023 at 7:00 a.m.

However, the comparison between observed and simulated landslides can be considered satisfactory, especially when considering the methodology adopted for estimating the input parameters based on the available regional digital large-scale data. The main limitation of the model in the present form is represented by the lack of detailed geotechnical input parameters and on the significant computational effort, that restricts the choice of the DEM resolution. Future research should focus on improving these key aspects.

5 ACKNOWLEDGEMENTS

This research was co-funded by the Ministry of University and Research (MUR) as part of the European Union's REACT-EU programme. Additional funding came from the European Union under the HORIZON-MISS-2022-CLIMA-01 call (Grant Agreement n. 101112737).

6 REFERENCES

Allen, R.G., Smith, M., Pereira, L.S., Perrier, A. 1994. An update for the calculation of reference evaporation, *ICID bulletin* **43**(2), 35-92.

Bittelli, M., Tomei, F., Pistocchi, A., Flury, M., Boll, J., Brooks, E. S., Antolini, G. 2010. Development and testing of a physically based, three-dimensional model of surface and subsurface hydrology, *Advances in Water Resources* **33**(1), 106-122.

García-Gaines, R.A., and Frankenstein, S. 2015. USCS and the USDA soil classification system: Development of a mapping scheme. U.S. Army Engineer Research and Development Center, *Cold Regions Research and Engineering Laboratory*, Report number 15-4, Report series ERDC/CRREL TR.

Ippisch, O., Vogel, H. J., Bastian, P. 2006. Validity limits for the van Genuchten–Mualem model and implications for parameter estimation and numerical simulation, *Advances in Water Resources* **29**(12), 1780-1789.

Li, Y., Duan, W. 2023. Decoding vegetation's role in landslide susceptibility mapping: An inte-grated review of techniques and future directions, *Biogeotechnics,* 100056.

Lu, N., Godt, J. 2008. Infinite slope stability under steady unsaturated seepage conditions, *Water Resources Research* **44**(11).

Murgia, I., Giadrossich, F., Mao, Z., Cohen, D., Capra, G.F., Schwarz, M. 2022. Modeling shallow landslides and root reinforcement: A review, *Ecological Engineering* **181**, 106671.

Sannino, G., Tomei, F., Bittelli, M., Bordoni, M., Meisina, C., Valentino, R. (2024). Implementation of a slope stability method in the CRITERIA-1D agro-hydrological modeling scheme, *Landslides* **21**(11), 2597-2616.

Sannino, G., Tomei, F., Bittelli, M., Meisina, C., Bordoni, M., Valentino, R. 2025. A three-dimensional agro-hydrological model for predictive analysis of shallow landslides: CRITERIA-3D, *Engineering Geology* **352**, 108073.

Soil Survey Manual, Issue 18 of Agriculture handbook. United States. Division of Soil Survey. U.S. Department of Agriculture, 1993.