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Implementation of a slope stability method in the CRITERIA-1D agro-hydrological modeling scheme

Abstract This paper presents the implementation of a slope stability method for rainfall-induced shallow landslides in CRITERIA-1D, which is an agro-hydrological model based on Richards' equation for transient infiltration and redistribution processes. CRITERIA-1D can simulate the presence and development of roots and canopies over space and time, the regulation of transpiration activity based on real meteorological data, and the evaporation reduction caused by canopies. The slope can be considered composed of a multi-layered soil, leading to the possibility of simulating the bedrock and of setting an initial water table level. CRITERIA-1D can consider different soil horizons characterized by different hydraulic conductivities and soil water retention curves, thus allowing the simulation of capillarity barriers. The validation of the proposed physically based slope stability model was conducted through the simulation of the collected water content and water potential data of an experimental slope. The monitored slope is located close to Montuè, in the north-eastern sector of Oltrepò Pavese (northern Apennines—Italy). Just close to the monitoring station, a shallow landslide occurred in 2014 at a depth of around 100 cm. The results show the utility of agro-hydrological modeling schemes in modeling the antecedent soil moisture condition and in reducing the overestimation of landslides events detection, which is an issue for early warning systems and slope management related to rainfall-induced shallow landslides. The presented model can be used also to test different bioengineering solutions for slope stabilization, especially when data about rooting systems and plant physiology are known.

Keywords Rainfall-induced shallow landslides · Vegetation · Slope · 1D · Evapotranspiration · LAI · Roots

Introduction

The characterization of the mechanisms that trigger landslides is a complex although necessary task for civil protection purposes. A difficult aspect is the choice of the criteria and methods for identifying a triggering event, as these can change the amount of landslides detected (Iadanza et al. 2016). Among dangerous landslides, rainfall-induced ones are by far the most frequent, triggered during or following periods of intense and persistent rainfall (Greco et al. 2023). In particular, rainfall-induced shallow landslides represent one of the most catastrophic natural hazards because they occur suddenly and can potentially travel a long distance and at high velocity (Tufano et al. 2021). The hydrological processes in and around a shallow landslide area are fundamental to assess changes in the soil water potential. Decreasing the water potential (in absolute value) reduces the soil shear strength (Bogaard and Greco 2016) and thus the slope stability. Moreover, including antecedent hydrological information in landslide hazard assessment is still a challenging issue for landslide hydrology research (Greco et al. 2023).

The prediction of landslide occurrence has been conducted in many different ways over the years, including data-driven and process-based approaches. Data-driven approaches have been widely utilized in the last decades to derive landslide susceptibility maps, especially in large areas where hydrological and geotechnical data are limited (Kavzoglu et al. 2019; Lima et al. 2022). These models, which include machine learning techniques, are based on the treatment of past landslide data. Statistical, data-driven approaches assume that, if conditions remain the same, landslides will be triggered again (Bordoni et al. 2021a). However, under climate change, past conditions may not represent valid predictors, and these methods need to be used with care.

On the other hand, physically based models are appropriate tools not only for susceptibility mapping but also for hazard and risk assessment of rainfall-induced shallow landslides because they can appropriately quantify the processes that trigger failures (Durmaz et al. 2023). These kinds of models have the advantage of taking directly measurable quantities as input parameters, and, although they provide more accurate results the more data are measured, they can nevertheless be used even where the data on geotechnical and hydraulic properties, as well as temporal changes in topography or subsurface conditions, are relatively scarce (Pardeshi et al. 2013; Gioia et al. 2016). Moreover, physically based models appear rather suitable for use also under climate change conditions (Li and Duan 2023), especially at the local/slope or small catchment scale, as they are not based on past landslide events.

Conducting a quantitative landslide assessment analysis can have different purposes. In the literature, a distinction is made between landslide "susceptibility" and landslide "hazard" (Reichenbach et al. 2018): susceptibility mapping aims at detecting only the spatial potential occurrence of landslides, and it is based on physical, geological, and slope conditions such as the land use, referred to a specific moment. Instead, hazard assessments analyses involve evaluating also the temporal occurrence of a landslide. To achieve this goal, a time-dependent soil water balance (SWB) computation is useful to assess the soil condition at, and prior to, the moment of landslide occurrence in response to rainfall events. At the slope scale, physically based models that involve transient hydrological analyses are an advanced solution for determining soil water content and soil water potential, especially on vegetated areas, where the water content computation should be coupled with a proper modeling of the vegetation.

It is well-known that plants contribute to the water dynamics on slopes. The action of plants on the overall water budget and specifically on unsaturated soil properties is rather strong (Masi et al. 2023). Among other parameters, the saturated hydraulic conductivity and the soil water retention curve are modified by the activity of vegetation (Ni et al. 2019a, b; Lu et al. 2020). Quantifying these aspects is of particular interest when evaluating the soil condition prior to precipitation in rainfall-induced shallow landslide hazard assessment.

Two families of physically based models for rainfall-induced shallow landslides exist, namely probabilistic and deterministic models (Murgia et al. 2022). The first category involves statistical techniques for treating uncertainty of the input parameters. Slope stability outputs are given as a probability of failure. The second category adopts specific values of parameters that can be either field-measured or literature-derived, making these models suitable to be used also for future rainfall scenarios, permitting an adequate quantification of several processes, especially at the slope scale.

Over time, many different hydrological physically based deterministic models have been developed to solve the soil water quantification problem in the vadose zone, accounting for the activity and development of plants for agronomic applications (e.g., Bronstert and Plate 1997; Minacapilli et al. 2008; van Dam et al. 2008). These models are named agro-hydrological as they are mainly designed for crop irrigation control and water use efficiency purposes. These models can account for the growth over time of both the aboveground and belowground mass of vegetation, considering the phenology, the harvesting period, and seeding time for crops, based on the thermal time, which drives roots and canopies development. In agro-hydrological models, the presence of roots can be considered variable with depth, and the transpiration activity can be dynamically assessed. These models accept meteorological data as a dynamic input, at different temporal resolutions.

A well-established method to conduct landslide hazard assessment is by adopting stability models coupled with water balance analyses in different spatial domains (e.g., Baum et al. 2008; Montrasio and Valentino 2008, 2016). However, these investigations largely consider that vegetation improves the accuracy of slope stability analyses (Simoni et al. 2008; Bathurst et al. 2010; Capparelli and Versace 2011; Lepore et al. 2013; Montrasio et al. 2023; Guo et al. 2024a, 2024b; Ng et al. 2019, 2021, 2022). Traditionally, the effects of vegetation on slope stability are classified as hydraulic and mechanical effects: the first comprising the transpiration-induced increase of suction, modification of soil hydraulic properties (i.e., changes in pore distributions, the soil water retention curve, and saturated hydraulic conductivity), the effect of canopy evaporation reduction, and preferential roots channel flow; the second comprising processes such as the mechanical reinforcement by roots, both basal and lateral, and the root soil anchoring. Few of the current widely used models account for the impact of vegetation on soil hydraulic properties (Ni et al. 2019a, b; Murgia et al. 2022), while the mechanical stabilizing effect of vegetation is more easily included in slope stability as a unique additive term for the whole soil profile, especially in those models that adopt the factor of safety computation within the infinite slope method framework. However, the major mechanical reinforcement effect has been observed to be effective only over the shallowest portion of the soil; conversely, hydrological reinforcement effects seem to be more significant at major depths (Ni et al. 2018). In general, vegetation effects are considered static input data, rarely taken into account as transient and depth-variable amounts (Li and Duan 2023), although considering the vertical variability of both soil properties and the distribution of roots better represents the reality.

Even though the soil depth involved in shallow landslides is relatively small (i.e., normally less than 2–3 m), in this shallow layer, water can encounter lenses of different permeability, both while infiltrating and during upward capillarity movements. Thus, the proper characterization of soil horizons, including the rooted portions of soils, is important to detect events such as the formation of nil or positive pore pressures, which are recognized as the main factor triggering shallow landslides.

In this paper, a slope stability model is implemented into a physically based, deterministic agro-hydrological model named CRITERIA-1D (Campi et al. 2015; Tomei et al. 2024). The model was developed by the Hydrometeorological and Climate Service (SIMC) of the Public Agency for Environmental Prevention and Energy of the Emilia-Romagna Region (ARPAE) and is freely available online. CRITERIA-1D computes the daily soil water balance by solving a unidimensional version of Richards' equation for the transient infiltration process. The equation accounts for the following hydrological processes: water infiltration, deep and lateral drainage, capillary rise, surface runoff, soil evaporation, plant transpiration, canopy evaporation reduction, water irrigation inputs, and water table oscillations. As an agro-hydrological model, CRITERIA-1D is coupled with conceptual models that simulate the development over time of both aboveground (through the leaf area index) and belowground (through root depth and density) vegetation biomass. The model accounts for a multi-layered soil, including the hydrological and geotechnical characterization of each horizon, a depth- and time-variable root density distribution, and root mechanical reinforcement. The soil water content, water potential, and slope stability can be computed at any selected depth. The novelty of the proposed model is that it simultaneously accounts for all the abovementioned aspects and that it considers both canopies and roots as daily dynamic inputs based on real meteorological data. The model is then suitable for testing slope stability even under future meteorological conditions and climate scenarios, because of its physically based simulation of plant evolution. Moreover, the model assumes the initial vegetation condition and a portion of meteorological input data for the spin-up process, deriving the soil water balance on a daily basis. In this way, a consistent suction initial boundary condition for the complete hydrology–stability simulation is provided. Although the direct effect of vegetation on the soil water retention curve and saturated conductivity over time are not directly assessed in CRITERIA-1D like in other models (e.g., Ng et al. 2020; Ni et al. 2019a, b, 2020), the model considers the evapotranspiration-induced water potential besides the pre-wetting suction condition induced by root water uptake. The water uptake is modeled through a macroscopic approach, considering the water removed by the rooted portion of the soil as a term in the general soil water balance equation. Few of the existing physically based models for landslide hazard assessment involving transient hydrology computation comprise all of the cited aspects simultaneously (Murgia et al. 2022; Meena et al. 2022; Li and Duan 2023). Based on field hydrological and geotechnical data, the model is applied and validated at the Montuè test site, where a shallow landslide occurred in 2014. The model results showed good agreement with field water content and water potential data with low input parameter

calibration when the hydrological effects of vegetation on the soil water content are included. In fact, the results were obtained for two different scenarios: the first considers a bare soil, and the second assumes the presence of developed vegetation. The comparison of the two scenarios' results shows that an agro-hydrological model such as CRITERIA-1D is a reliable tool for the quantitative assessment of hydrological aspects in a landslide phenomenon and also in natural environments. In fact, when the transpiration-induced suction increase, derived from rooted layers and the leaf area index (LAI) development over time, is considered, the field data are better approximated and landslide occurrence is not overestimated.

The model

Hydrological computation

CRITERIA-1D is an open-source numerical code that simulates the main hydrological processes in the soil–plant system. The code comprises a numerical solution based on a one-dimensional restriction of the agro-hydrological model CRITERIA-3D (Bittelli et al. 2010), which implements Richards' equation. CRITERIA-1D and CRITERIA-3D were developed by the Hydro-Meteorological Service of the Emilia-Romagna Region (ARPAE SIMC, Italy) to model the main phenomena related to soil water balance. These phenomena are described through the coupling of surface and subsurface flows and the coupling of soil water fluxes computation with conceptual models for crop development, solar radiation, evapotranspiration, and snowmelt (Bittelli et al. 2010).

The mono-dimensional CRITERIA-1D model solves a general soil water balance by accounting for processes related to infiltration, plant water uptake, capillarity, and evaporation, while the surface runoff is considered through a simplified approach (Fig. 1). The surface and subsurface flows are coupled, and an approximation of lateral drainage is included. As concerns the delaying effect of vegetation on the infiltration rate, a pond depth can be assigned to the soil surface depending on the land use. When this pond is full of water and new water inputs are added at a rate higher than the infiltration rate of the shallowest layer, the surplus exits the soil water balance. The input data are represented by the daily air temperature (minimum and maximum), daily total precipitation, crop, and soil parameters. The main computed outputs are the soil water content (SWC), the water potential, the leaf area index (LAI), the daily evapotranspiration (ET), and its components (crop transpiration and soil evaporation). CRITERIA-1D comprises a detailed description of the root density with depth, which is one of the main key factors in soil water balance computation and also in slope stability analysis (Masi et al. 2021). The most important hydrological properties in CRITERIA-1D are as follows: the soil saturation (SAT), which indicates the volume of the fraction of voids that can be occupied by water; the field capacity (FC), which is the presumed water content at which internal drainage stops; and the wilting point (WP), which is considered the residual amount of water that plants are not able to take up due to the high water potential. These three properties depend on the soil texture, as the soil particle size and voids influence the soil behavior in retaining water under a certain water potential rate. The infiltration process of rainfall in the soil is controlled by the surface conditions and the hydraulic conductivity (K) of the different soil layers. The numerical model in CRITERIA-1D solves a global continuity equation through an integrated finite difference formulation for a homogeneous reference volume:

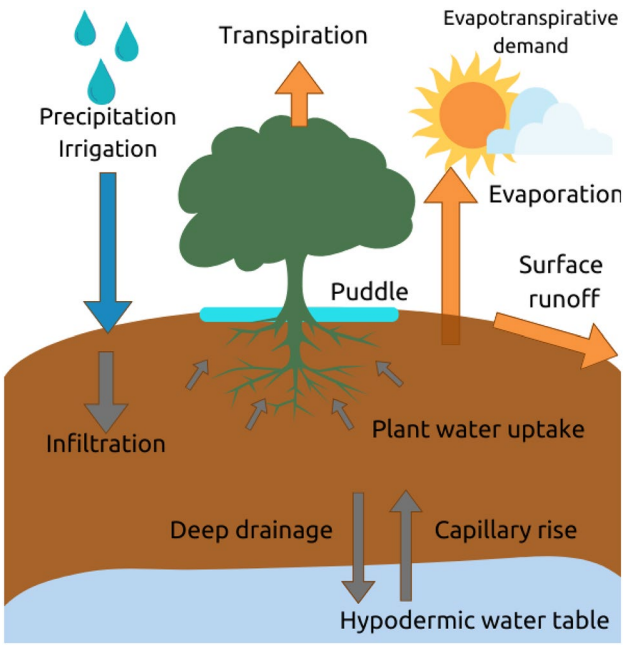

Fig. 1 CRITERIA soil water balance general scheme (adapted from Tomei et al. 2024)

$$\int div(u)dz + \int \frac{\partial(W\theta)}{\partial t}dz = \int qdz \quad (1)$$

where:

u is the flux density,
W is the total available volume at a point,
θ is the fraction of W occupied by water (volumetric water content),
q is the water input or output, and
z is the computation depth.

In CRITERIA-1D, the domain is approximated by a one-dimensional grid of nodes. Thus, the equation is equivalent to the mass balance equation for the volume surrounding each node:

$$\frac{\partial V_i}{\partial t} = \sum_{j=1}^{n} Q_{ij} + q_i \forall i \neq j \quad (2)$$

where:

V_i is the amount of stored water in the volume surrounding the node i;
Q_{ij} is the flux between the i-th and the j-th node;
q_i is the input flux at the i-th node.

The flux Q_{ij} is described by Darcy's Law in the finite difference form:

$$Q_{ij} = -K_{ij}S_{ij}\frac{(H_i - H_j)}{L_{ij}} \quad (3)$$

where S_{ij} is the interfacial area between nodes i and j; L_{ij} is the distance between the two nodes; H_i and H_j are the hydraulic potentials at the nodes i and j, respectively; and K_{ij} is the internode conductivity, derived as a geometric mean of nodal conductivities $K_i(H_i)$

and $K_j(H_j)$. The water balance is solved assuming that each soil layer is homogeneous and that the soil skeleton is not deformable. Each soil layer is represented by a single node, characterized by hydrological and soil texture parameters derived from the field soil horizons. Outputs can be obtained at any selected depth between the surface and the bottom soil boundary. The model comprises an automatic time step quantification algorithm, and the mass balance error is computed with reference to the results of the previous time step through a tolerance threshold. In order to get values of water potential and hydraulic conductivities at each node, CRITERIA-1D uses the modified van Genuchten–Mualem formulation proposed by Ippisch et al. (2006) to calculate the equivalent degree of saturation (S_e) (Eq. 4). The hydraulic conductivity function (K) is calculated through the approach presented by Mualem (1976) (Eq. 5):

$$S_e = \begin{cases} \frac{1}{S_c}\left[1+(ah)^n\right]^{-m} & if(h > h_e) \\ 1 & if(h \le h_e) \end{cases} \quad (4)$$

$$K = \begin{cases} K_s\, S_e^t \left[\frac{1-\left(1-(S_e\, S_c)^{\frac{1}{m}}\right)^m}{1-\left(1-S_c^{\frac{1}{m}}\right)^m}\right]^2 & if(S_e < 1) \\ K_s & if(S_e \ge 1) \end{cases} \quad (5)$$

where:

h_e is the air-entry value (depending on the soil texture) [kPa];
$S_c = \left[1+(\alpha h_e)^n\right]^{-m}$ is the degree of saturation at air-entry value h_e;
S_e is the degree of saturation [−];
α, τ, n, and m are the fitting parameters;
K_s is the saturated hydraulic conductivity [m/s].

Experimental fitting parameters for both the van Genuchten curve and the saturated hydraulic conductivity curve can be used in the model. If there is a lack of experimental data, the model estimates the necessary parameters based on the soil texture through appropriate pedotransfer functions. This latter choice is useful in study cases where data collection may not be possible. More details and mathematical formulations about the hydrology of CRITERIA-3D can be found in Bittelli et al. (2010), while for technical details of CRITERIA-1D, refer to Tomei et al. (2024).

Boundary conditions

As concerns the initial hydraulic state, CRITERIA-1D adopts a Neumann boundary condition imposing that the water content at the surface is equal to zero, while at the bottom of the domain, a free drainage condition is imposed. The other layers are initially assigned with an available water (AW) of 0.8, close to field capacity (FC). The initial fluxes are set equal to zero for all the soil layers.

Generally, CRITERIA-1D starts with thermal summations equal to zero (corresponding to January 1st in the northern hemisphere and July 1st in the southern hemisphere) and uses a certain period of meteorological data for the spin-up process, in order to assess the soil water content and soil water potential condition prior to the target simulation period, comprising daily evapotranspiration and crop evolution.

If a water table is present, CRITERIA-1D automatically sets the corresponding prescribed water potential and water content as the initial state, and these data are used to assess the capillary rise process. If the water table is not considered in the numerical simulation, the only bottom boundary condition is free drainage.

As concerns the upper spatial boundary, the hydraulic condition is modeled through a ponding depth based on the type of crop present. Initially, the surface flux is set to zero, and the pond is filled up with rainfall or irrigation until saturation. If the pond is completely full, runoff starts. Simultaneously with the filling, water infiltrates at a rate equal to the hydraulic conductivity of the first shallow layer.

Crop modeling

The presence of a crop is modeled in CRITERIA-1D through coupled conceptual models that contribute to soil water balance computation. From the hydrological point of view, plants modify the soil water balance in the root zone because of root water uptake (RWU). Water removed from rooted layers increases the slope stability (Arnone et al. 2016; Masi et al. 2021). Another action exerted by plants is the reduction of the evaporation rate in the shallow layers because of canopies, whose development is modeled in CRITERIA-1D through temperatures. In fact, according to the so-called thermal time, quantified in growing degree days (GDD), four life cycle stages (five for herbaceous crops) can be assessed in CRITERIA-1D. In more detail, with the above-specific GDD thresholds based on the considered species, plants can accumulate heat, and the heat accumulation will result in a certain number of growing degree days:

$$GDD = \frac{\left(T_{min} + T_{max}\right)}{2} - Threshold \quad (6)$$

The sum of the GDD, in turn, defines the time-variable leaf area index (LAI) over the year based on two functions. The first describes the growing phase of the vegetation, comprising (i) the sprouting phase (if the crop is herbaceous), (ii) the exponential growth of the LAI, and (iii) the linear growth of the LAI:

$$LAI = \frac{\left(LAI_{max} - LAI_{min}\right)}{1 + e^{(a+b\times GDD)}} + LAI_{min} \quad (7)$$

where:

LAI_{max} and LAI_{min} are the maximum and minimum LAI of the considered vegetation;
a and b are the coefficients of the linear regression between log(LAI) and GDD.

The second LAI function in CRITERIA-1D characterizes, for herbaceous and horticultural crops, the decreasing phase of the LAI, thus comprising (i) the decreasing growth rate of the LAI and (ii) the decrease of the LAI:

$$LAI = \frac{\left(LAI_{max} - LAI_{min}\right)}{1 + \frac{10\times\left(GDD-GDD_3\right)}{GDD_4\times C_4 LAI}^{N_4 LAI}} + LAI_{min} \quad (8)$$

where:

GDD_3 is the sum of the GDD of the first 3 phases;
GDD_4 is the sum of the GDD of phase 3 and phase 4;
C_4LAI and N_4LAI are specific coefficients for the crop.

When the LAI exceeds GDD4, the herbaceous or horticultural crops undergo harvesting, and thus the LAI is automatically set equal to LAI_{min}. Instead, trees exponentially decrease, reaching a minimum value in the mid-autumn season. For grass crops, mowing cycles are also simulated. On the other hand, if the land cover is fallow, phenological stages are not considered. In this latter case, the LAI reaches its maximum through heat accumulation and then remains stable until November 1st of each year. After this date, the LAI starts to decrease linearly until the last day of the year, when LAI_{min} is reached. The parameters needed to compute the evolution of the LAI over time can be set manually through a user-friendly interface; otherwise, CRITERIA-1D provides them for an implemented set of crops. Depending on the type of soil and the actual development of the crop, the infiltrated water may be more or less available to the vegetation, affecting its transpiration rate. Transpiration acts until the wilting point, represented by leaves suction (Ψ_{leaf}), is attained (approximately 1500–1800 kPa, depending on the crop type). The potential evapotranspiration (ET_o) is modeled through the Hargreaves–Samani (1985) equation, which uses only extraterrestrial radiation, and the maximum and minimum daily temperature to obtain daily values of ET_o:

$$ET_0 = 0.0023 \frac{R_a}{2.456} \left(\frac{T_{max} + T_{min}}{2} + 17.78 \right) \left(T_{max} - T_{min} \right)^{\frac{1}{2}} \quad (9)$$

where:

R_a is the mean extraterrestrial radiation depending on latitude [mm/day];
T_{max} is the maximum daily temperature;
T_{min} is the minimum daily temperature;
17.78 is the conversion factor for 0 degrees Fahrenheit;
0.0023 is an empirical coefficient, derived from 0.0135 × KT. The constant 0.0135 was originally proposed by Hargreaves and Samani (1985), while KT depends on the geographical area. For this application, KT = 0.17 is assumed.

The reference evapotranspiration ET_o obtained through Eq. 9 is divided into maximum soil evaporation and maximum crop transpiration in CRITERIA-1D on the basis of a crop coefficient, kc, defined as a function of the LAI. The vegetation is involved also in the soil evaporation reduction. Then, the model estimates the actual soil evaporation and crop transpiration based on the soil water availability, and transpiration is computed only for the rooted layers of the soil, defined by a selected maximum root depth, driven by the wilting point of the crop. More detailed information about CRITERIA-1D vegetation modeling can be found in the manuals freely provided by Antolini et al. (2016) and Tomei et al. (2024).

Slope stability

Rainfall-induced shallow landslides involve a soil mantle that is much less thick than the slope failure length (Lu and Godt 2008). For this reason, the failure plane is assumed parallel to the slope surface and a planar infinite slope scheme has been implemented in CRITERIA-1D to analyze the slope stability. This choice is consistent with the hydrological computation, since the soil layers are considered rigid and homogeneous. Thus, the CRITERIA-1D model is suitable to predict planar slip surfaces (Varnes 1978) at different depths. The slope stability is estimated by the computation of a factor of safety (FoS) for each soil layer through the equation proposed by Lu and Godt (2008), which is based on the suction stress concept (σ^s):

$$FoS = \frac{tan\varphi'}{tan\beta} + \frac{2c_{tot}}{\gamma H_{ss} sin2\beta} - \frac{\sigma^s}{\gamma H_{ss}} (tan\beta + cot\beta) tan\varphi' \quad (10)$$

where:

$\sigma^s = -\frac{\theta - \theta_r}{\theta_s - \theta_r}(u_a - u_w)$;
$C_{tot} = c' + c_r$;
c' is the effective soil cohesion [kPa];
c_r is the root mechanical contribution [kPa];
θ is the actual soil water content [m^3/m^3];
θ_r is the residual water content at the wilting point [m^3/m^3];
θ_s is the saturated water content [m^3/m^3];
φ' is the friction angle [°];
β is the slope angle [°];
H_{ss} is the depth of interest [m];
γ is the unit weight of the soil [kN/m^3].

In CRITERIA-1D, the contribution of the rooting system to the global soil shear strength is quantified as an additional cohesion (c_r), which can be added to c', obtaining a total cohesive term (c_{tot}). The mechanical contribution can be either field-measured or derived through different models that are present in the scientific literature. The most used root reinforcement models are the Wu and Waldron model (WWM), the Fiber Bundle Model (FBM), and the Root Bundle Model (RBM). All three models make it possible to calculate the maximum force that can be sustained by a root bundle (Cronkite-Ratcliff et al. 2022). The value derived from literature cases can be considered a maximum root strength contribution that will be assigned to the layer with the highest root density in CRITERIA-1D. The maximum value will be reduced for the effective root density at each layer of the soil profile. Through this approach, a variable root strength contribution with depth is assumed by CRITERIA-1D in the root zone.

Test site

The experimental slope is located in Montuè village, Oltrepò Pavese, a hilly region in the northern Apennines, Italy (Fig. 2). A monitoring station installed on the slope has acquired meteorological and soil measurements data since 2012 (Fig. 3).

The area is prone to rainfall-induced shallow landslides, most of which are caused by intense or prolonged rainfall events. Since around 1950, the first documented rainfall-induced landslides in the north-eastern sector of Oltrepò Pavese occurred in 2009 as represented in Fig. 2. These landslides were caused by an extreme rainfall event of 620 mm in 62 h (Bordoni et al. 2015). Between February 28 and March 2, 2014, a new landslide occurred a few meters from the monitoring station (Figs. 2 and 4) due to an amount of 68.9 mm of rainfall in 42 h, registered at the monitoring station. The sensors installed at Montuè test site allow the acquisition of measurements of meteorological variables, such as precipitation, temperature, solar radiation, relative humidity, wind intensity, and direction, as well as soil variables, such as soil water content and pore water pressures (or water potential) at different depths (Fig. 3). More precisely, the integrated monitoring station at Montuè comprises a rain gauge (Model 52,203, Young Comp., Traverse City, MI),

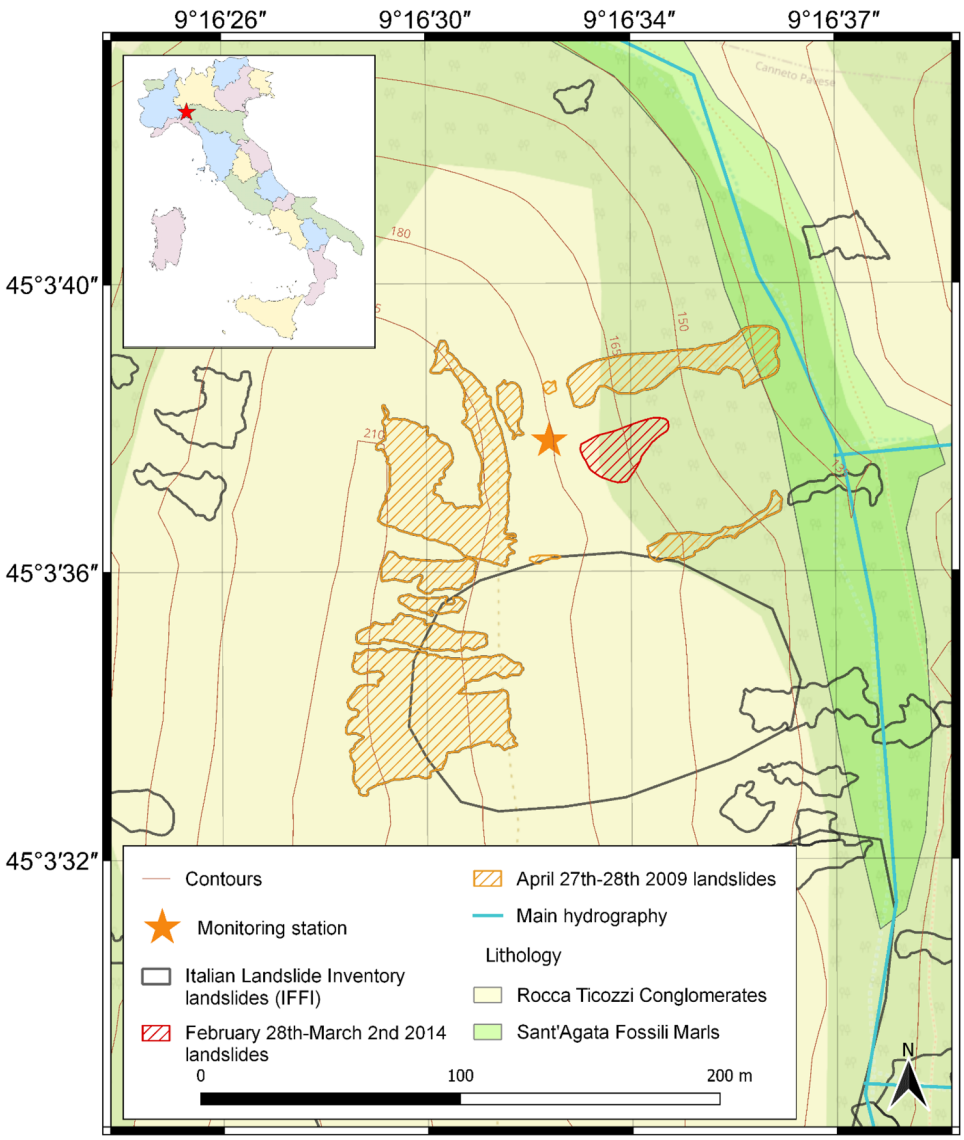

Fig. 2 Study area

a thermo-hygrometer (Model HMP155A, Campbell Sci. Inc., Logan, UT), a barometer (Model CS100, Campbell Sci. Inc., Logan, UT), an anemometer (Model WINDSONIC, Campbell Sci. Inc., Logan, UT), and a net radiometer (Model NR-LITE 2, Kipp & Zonen, Delft, Netherlands) as meteorological sensors. Moreover, six time-domain reflectometer (TDR) probes (Model CS610, Campbell Sci. Inc., Logan, UT) equipped with a multiplexer (SDMX50, Campbell Sci. Inc., Logan, UT), installed at 20, 40, 60, 100, 120, and 140 cm from the ground level, measure the soil water content (Fig. 3). A combination of three tensiometers (Model Jet-Fill 2725, SoilMoisture Equipment Corp., Santa Barbara, CA) and three heat dissipation (HD) sensors (Model HD229, Campbell Sci., Logan, UT) are installed at 20, 60, and 120 cm from the ground level and measure the pore water pressure. The tensiometers measure the pore water pressure directly, while the HD sensors get the pore water pressure values through the use of the conversion equation from Flint et al. (2002). HD sensors can only acquire values lower than −10 kPa (Bittelli et al. 2012), so the tensiometers are necessary to measure values higher than −10 kPa (Bordoni et al. 2015). Table 1 summarizes the different sensors' characteristics, while in the Appendix, the calibration curve used for the heat dissipation sensors is provided (Fig. 13).

From previous studies by Bordoni et al. (2015), it is known that the slip surface depth for the 2014 landslide was around 100 cm, and the most likely triggering condition was the formation of a perched water table above the calcic horizon, located at a depth of 120 cm.

The soil at Montuè is a calcic Gleysol (IUSS 2007). A detailed description of the site pedology, not discussed here, is presented in the work of Bordoni et al. (2015). The horizons represented in Fig. 3 are classified as silt loam (I and V) and silty clay loam (II, III, and IV). The underlying lithology is constituted by Rocca Ticozzi conglomerates, a bedrock made up of gravel, sand, and poorly cemented conglomerates with a low percentage of marls. At a depth of 130 cm, contact between the soil and the weathered bedrock has been observed. The soil coverage in 2014 was

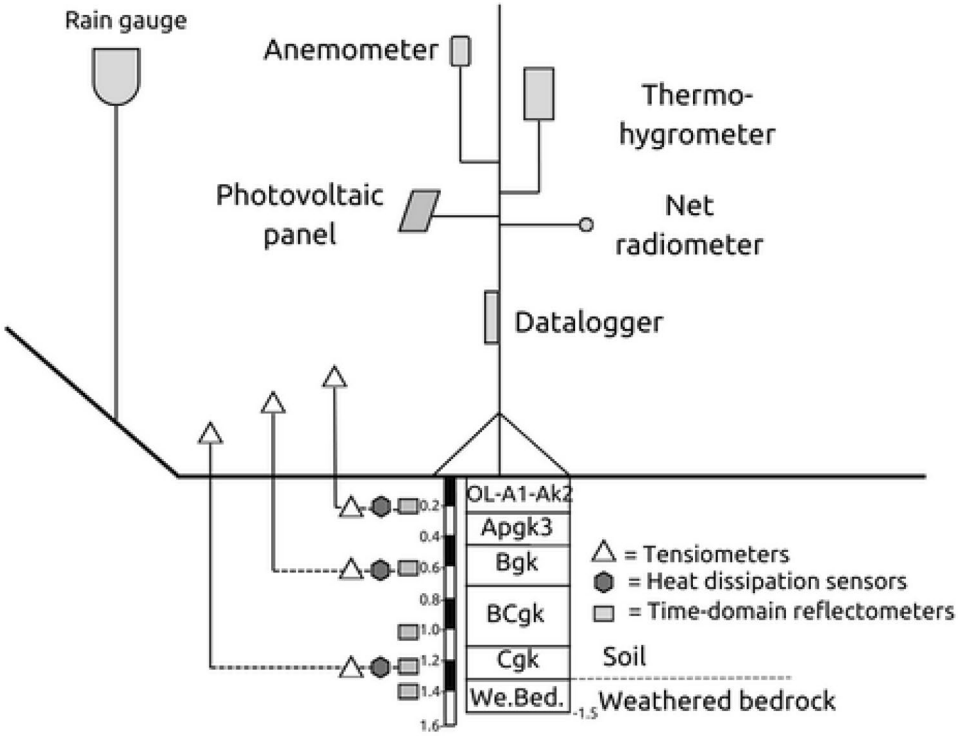

Fig. 3 The monitoring station

constituted by grass and shrubs with rooting at a maximum depth of 40 cm (Bordoni et al. 2015), while woodlands were present all around the monitoring station and the landslide area. The soil coverage on the landslide body was constituted by sparse, young woodland (Fig. 4). Since 2012, hysteretic processes and variability of the field-measured saturated hydraulic conductivity (K_{sat}) in different periods of the year have also been observed (Bordoni et al. 2015, 2017, 2021b), but in the present application, no hysteretic behavior was directly considered.

Model application

To apply CRITERIA-1D at the test site, soil horizons with similar properties were grouped together on the basis of the research by Bordoni et al. (2015). The soil stratigraphy and relative horizon parameters listed in Tables 2 and 3 were used in this application. Values of the texture, effective cohesion, friction angle, and bulk density were obtained from field measurements and from the previous research by Bordoni et al. (2015). Values for the saturated and residual water content were derived from field-measured time series for the period of interest

Fig. 4 The 2014 landslide (location and size are reported in Fig. 2)

Table 1 Montuè field equipment

	Device	Accuracy	Model	Range of measure
Soil water content, soil temperature, soil water electrical conductivity	TDR probes	0.01–0.02 m^3/m^3	CS610, Campbell Sci. Inc., Logan, UT	0–1 m^3/m^3
Soil water potential (< −10 J/kg)	Heat dissipation (HD) sensors	1.5–2.0 J/kg	HD229, Campbell Sci., Logan, UT	−10,000/−10 J/kg
Soil water potential (> −10 J/kg)	Tensiometer	1.5–2.0 J/kg	Jet-Fill 2725, SoilMoisture Equipment Corp., Santa Barbara, CA	−80/15 J/kg
Rainfall	Rain gauge	0.01 mm	52,203, Young Comp., Traverse City, MI	0 mm
Air temperature, air humidity	Thermo-hygrometer	0.2 °C, 1%	HMP155A, Campbell Sci. Inc., Logan, UT	−80/60° C, 0–100%
Atmospheric pressure	Barometer	0.1 hPa	CS100, Campbell Sci. Inc., Logan, UT	600–1100 hPa
Wind speed, wind direction	Anemometer	0.01 m/s, 3°	WINDSONIC, Campbell Sci. Inc., Logan, UT	0–60 m/s, 0–359°
Net solar radiation	Net radiometer	3 W/m^2	NR-LITE 2, Kipp & Zonen, Delft, Netherlands	-
Datalogger: No. 1 CR1000X (Campbell Scientific, Inc.)				

(Bordoni et al. 2021a, b). It must be specified that the root mechanical contribution (c_r) has been assumed equal to zero, differently from what has been done in recent research for similar sites (Bordoni et al. 2024). The reason for this choice is that in a condition at or close to saturation, the bond between roots and soil may become very weak, eliminating additional cohesion (Stokes et al. 2014). Moreover, when the vegetation composition and the roots' distribution are unknown, values of additive cohesion taken from the literature may lead to non-precautionary values of FoS in saturated conditions.

For this application, the simulation period spans from January 1 2012 to December 31 2015, in order to model two years of weather data to reproduce the soil moisture condition prior to the 2014 landslide (Fig. 5). Parameters for the van Genuchten soil water retention curve and hydraulic conductivity function were estimated based on the field water content and water potential time series; values were thus provided for the saturation (SAT), field capacity (FC), and permanent wilting point (WP), considered for the fine-grained horizons as the water content measured at a water potential of 0.1, 30, and 1600 kPa, respectively. For the last layer, namely the weathered bedrock, the SWRC was fitted adopting 10 kPa instead of 30 kPa as the field capacity value. However, as already mentioned, if no values are provided, the CRITERIA-1D model can derive them, assigning fitting parameters for the van Genuchten–Mualem model based on the horizon's texture.

The soil permeability, which has been determined through field measurements of saturated hydraulic conductivity (K_{sat}), showed

Table 2 CRITERIA-1D soil parameters for Montuè application

Horizon	Depth range (cm)	Coarse fraction (%)	Organic matter (%)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	c' (kPa)	ϕ' (°)
I	0–22	0	1.44	16.6	58.0	25.4	1.733	0	31
II	22–42	0	1.36	11.9	59.9	28.2	1.703	0	31
III	42–70	0	1.03	16.0	53.9	30.1	1.703	0	33
IV	70–110	0	0.88	12.6	57.9	29.5	1.897	0	33
V	110–130	0	0.62	7.70	65.8	26.5	1.861	29	26
We. Bedr	130–150	50	0.30	75.0	25.0	0.00	1.841	29	26

Table 3 CRITERIA-1D hydrological parameters for Montuè application

Horizon	Θ_s (m^3/m^3)	Θ_r (m^3/m^3)	h_e (kPa)	n (–)	m (–)	α (kPa^{-1})	K_{sat} (m/s)	Available water (m^3/m^3)
I	0.39	0.12	2.6	1.412	0.292	0.011	7.00E−06	0.263
II	0.40	0.13	3.1	1.392	0.282	0.011	2.00E−06	0.261
III	0.44	0.15	3.1	1.385	0.278	0.010	2.00E−06	0.280
IV	0.41	0.10	3.1	1.388	0.280	0.024	2.00E−06	0.284
V	0.48	0.16	2.6	1.326	0.246	0.018	7.00E−06	0.303
We. Bedr	0.41	0.12	1.0	1.361	0.265	0.019	1.00E−07	0.280

great variability over the years and in different seasons. As testified by previous research by Bordoni et al. (2015, 2017, 2021b), the Montuè test site is constituted by a soil with hysteretic behavior. This hysteretic behavior is a typical phenomenon observed in the majority of soils. It consists in a difference between the wetting and drying phases of soils, resulting in a different observed water content–water potential relationship. At Montuè, field observation revealed that the soil presents a hysteretic behavior, and also a variable K_{sat} over time was measured. The K_{sat} variability can be induced by plants as well (Ni et al. 2019a). Through CRITERIA-1D, different simulations were carried out using the different measured values of hydraulic conductivity at saturation. Meanwhile, a reference value for each horizon, based on its texture, was used in this application (Table 3), according to field data that suggested an average value of the measured range of K_{sat} as the most consistent. This choice is also sustained by the fact that, for the years of interest, no values of K_{sat} were directly measured in the field. The different simulations showed that for water content values close to saturation, the results were similar even if K_{sat} differed by up to two orders of magnitude, while maintaining the other parameters. As the aim of this research is testing the use of CRITERIA-1D for landslide prediction and the condition of interest is in most cases represented by near saturation or complete saturation, the results were considered satisfactory, and the average K_{sat} value based on soil texture (Driessen 1986; Tomei et al. 2024) was selected for simulations.

At Montuè, the bottom layer, whose depth ranges from 130 to 150 cm, is classified as weathered bedrock. Its permeability was never measured, and in CRITERIA-1D, it was arbitrarily set in

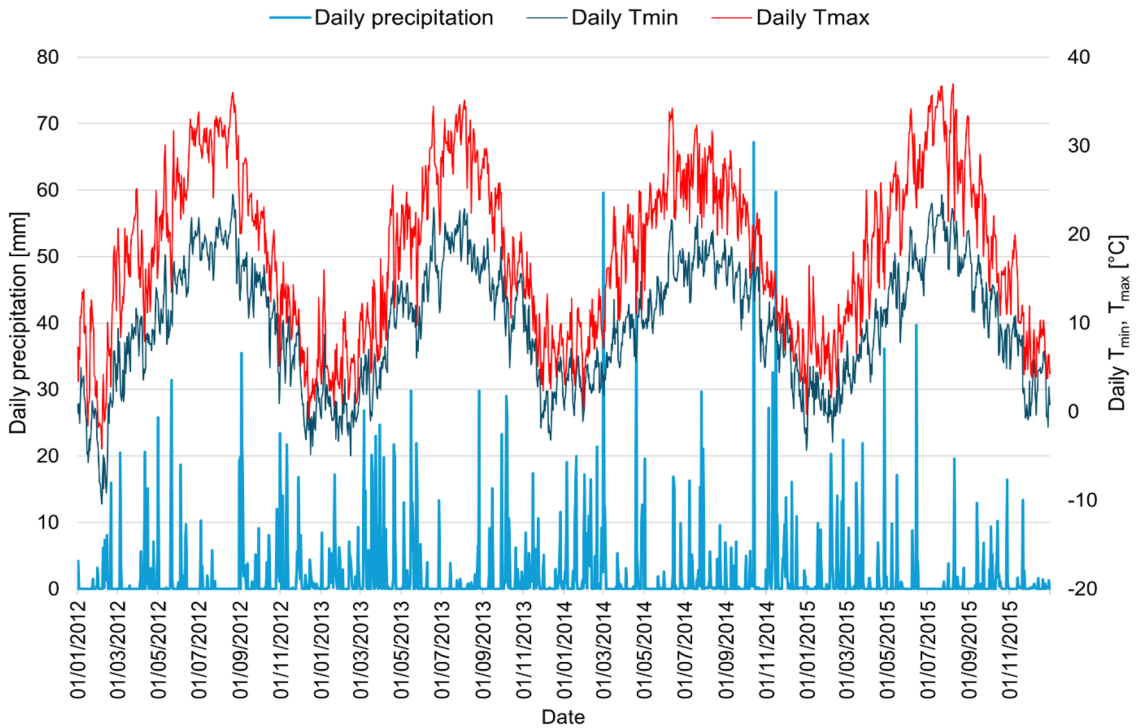

Fig. 5 Input weather data for the simulation (dates are provided in dd/mm/yyyy format)

Table 4 CRITERIA-1D vegetation parameters for Montuè application

LAI[m²/m²]	min	0.5
	max	2.5
Thermal thresholds (°C)	Lower	0
	Upper	35
GDD (°C)	Phase 1	3500
	Phase 2	1000
LAI curve factors (–)	*a*	4.1
	b	-0.0014
Root depth (RD) (cm)	RD_0	5
	RD_{max}	130
$k_c$max (–)	1	
Root shape distribution	Cardioid	
Root shape deformation factor (–)	0	
Irrigation (mm)	0	
Ψ_{leaf} (kPa)	1569.02*	
c_r (kPa)	0	

*CRITERIA-1D accepts this value expressed as water depth in cm

order to reproduce a less permeable layer with respect to the overlaid ones. As the only possible bottom boundary condition is free drainage, this artifact is necessary to reproduce the field case of the Montuè test site. In fact, the formation of a perched water table at a depth between 80 and 120 cm seems to have provoked the 2014 landslide (Bordoni et al. 2015). A slope angle of 0.5 m/m was considered a representative of the whole slope in this application.

Table 4 summarizes the vegetation parameters used by CRITERIA-1D for the Montuè case study. As already mentioned, for some kinds of crops, specific sets of parameters are provided with the model; however, in this application, the specific composition of the vegetation in each season at Montuè is unknown. Nevertheless, it is known that mainly herbaceous plants and some shrubs were covering the station when the landslide occurred. In the absence of more detailed data, the yearly vegetation coverage was simulated as fallow as concerns the LAI behavior, assigning a minimum LAI of 0.5 for the coldest months, passing rapidly (simulated through the GDD of the two phases) to a maximum LAI of 2.5, maintained from late March to late October (Fig. 6). The coverage periods were derived by satellite photographs that show live vegetation covering the test site in 2014 (Fig. 7). The root density was considered static for the 4-year simulation period, because the transpiration-induced hydrological reinforcement effect is controlled in CRITERIA-1D by the leaf area index. The maximum root depth (RD_{max}) is set at the contact between the soil and the weathered bedrock (130 cm), because of the presence of shrubs and of *Robinia pseudoacacia L.* trees at the landslide site (Fig. 4), which is located a few meters from the monitoring station (Fig. 7). Roots are assumed to start at a depth of 5 cm to simulate a root collar ($RD_o = 5$ cm). The root distribution is set as a standard cardioid with no shape deformation (Fig. 6e). The minimum LAI was set as diverse from zero to reproduce the evaporation reduction caused by vegetation also in the winter months; as in this site, the soil remains covered with dead vegetation.

CRITERIA-1D was originally designed for agronomic applications, and this work represents the first attempt to apply it in more naturally vegetated environments; thus, in the absence of detailed measurements, vegetation parameters were calibrated according to the field water content and water potential data.

The other model application shown in this work considers a bare soil covering the slope. The intention is to compare the results with those obtained by assuming the presence of vegetation.

With regard to meteorological input data, precipitation and air temperature daily records were derived from the monitoring station at Montuè (Fig. 5). Missing temperature records were linearly interpolated. Missing precipitation records were replaced with data derived from a spatialization algorithm using neighboring monitoring stations.

It is worth noting that the landslide of Fig. 4 is suitable for modeling with the infinite slope method because of the planar slip surface shape observed. Moreover, the soil volume involved had a thickness of around 1 m over a slope more than 110 m long. As the length was much larger than the height of the soil volume, the assumption of the infinite slope appears consistent with reality.

Results and discussion

Hydrology

The water budget was computed at different depths. In particular, outputs at 20, 40, 60, 100, 120, and 140 cm related to the two applications were derived. As already discussed, one case considers the presence of vegetation, while the other considers a bare soil. The soil and weather data are the same in both applications and are derived from a monitoring station located a few meters away from the landslide scarp (Fig. 2).

The results show that, in the upper layers (Fig. 8), plant transpiration and root water uptake allowed for a better description of the minimum water content values observed in the dry seasons than the bare soil. With regard to the maximum water content values observed in the wet seasons, the first two layers are better simulated through a bare soil assumption. However, with regard to the minimum water content amounts, a simulation that accounts for plant transpiration and root water uptake, even when a small portion of shallow soils is occupied by roots (i.e., a maximum of around 2% in the first 40 cm, see Fig. 6e), better describes the measured data. Moreover, it should be considered that CRITERIA-1D assumes only horizontal ground surface and soil horizons, while at the Montuè test site, the monitoring station is located on a slope, and it is surrounded by vegetation. Since both the lateral water movements and the water taken up by neighboring plants are neglected, a bare soil does not approximate the actual decrease in soil water content, which is indeed better approximated in a simulation considering a vegetated slope. It can be noted that the fast water infiltration movements due to high daily rainfall amounts (see as an example the rainfall events of 01 September 2012 and 01 November 2014 in Fig. 8) are correctly simulated by CRITERIA-1D for both vegetated and bare soil. However, the consequent minimum water content, due to the combined effect of gravity movements, lateral flows, and the water uptake by roots, is better modeled by the simulation that assumes the presence of vegetation, at 20 cm, 40 cm, and 60 cm of depth.

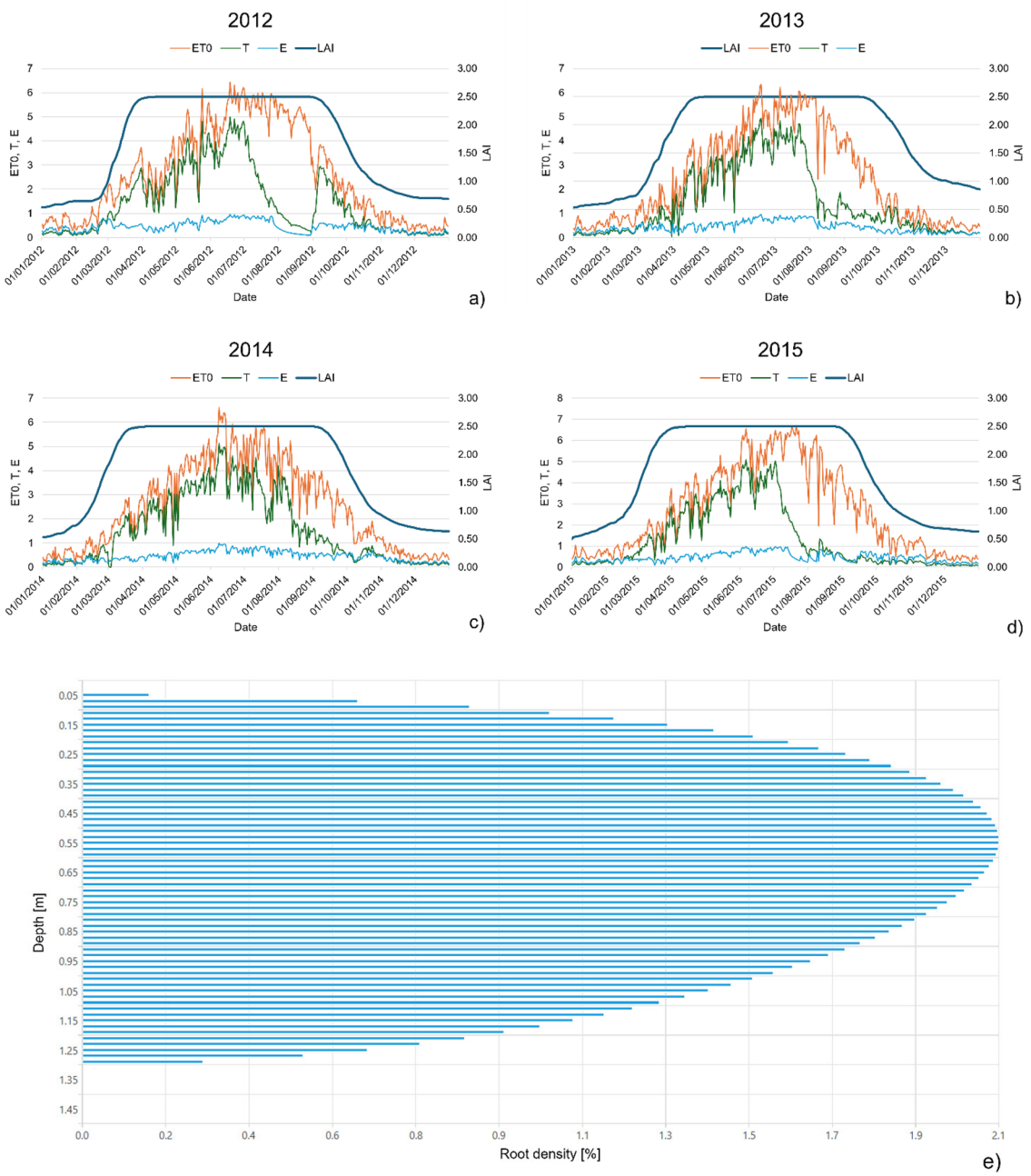

Fig. 6 Vegetation development over the simulation periods: LAI, potential evapotranspiration (ET0), actual evaporation (E), actual transpiration (T) in 2012 (**a**), 2013 (**b**), 2014 (**c**), 2015 (**d**), and the static root density with depth (**e**) (dates are provided in dd/mm/yyyy format)

A further aspect that needs to be emphasized is that the simulation covers a 4-year period, spanning from January 2012 to December 2015. It has been observed that throughout this period, the vegetation has grown, especially after the 2012 excavation works connected to the installation of the monitoring station. For this reason, the computed water content appears to be overestimated with respect to the field measurements in 2015, even around the maximum values, when bare soil is considered. The overestimation becomes larger moving down in depth (see Fig. 8) for values around the minimum water content.

The results obtained at depths of 100 cm and 120 cm (Fig. 9a, b) show a different situation with respect to the upper layers. In fact, the field data are better approximated for both the maximum and minimum values if vegetation is included in the model (green curves). It appears clear that considering rooted deep layers allows a better modeling of the real hydrological phenomena occurring in this soil.

At a depth of 140 cm (Fig. 9c), the field data suggest a different behavior. This layer, which was classified as weathered bedrock based on field observations, shows longer periods with water

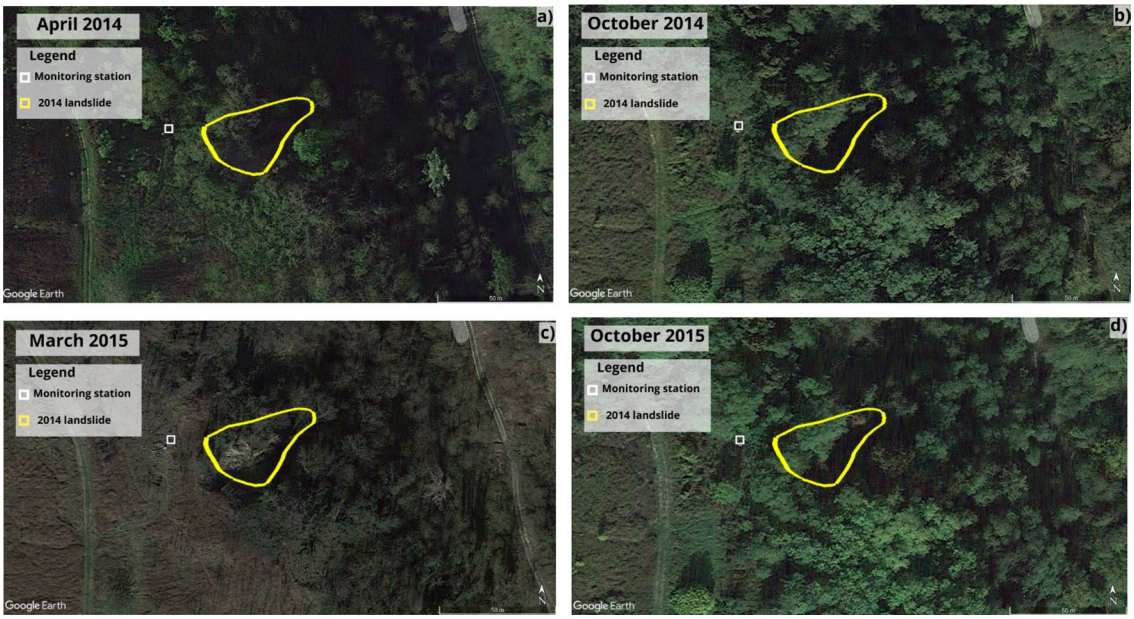

Fig. 7 Vegetation cover condition derived from satellite photographs: April 2014 (**a**), October 2014 (**b**), March 2015 (**c**), and October 2015 (**d**)

content values close to saturation compared with all the other depths. However, although roots are not present in this layer, the case of vegetated soil performs better than the bare soil. It has to be highlighted that the results for this layer refer solely to the soil matrix, while the presence of gravel and thus the related water movements are not simulated.

Figure 10 shows the results obtained by calculating the average of both the measured and simulated water contents between the ground level and a depth of 150 cm. It can be seen that the overall hydrological behavior is better simulated if the presence of vegetation is considered. The root mean square error (RMSE) (Table 5) confirms a better performance for the vegetated slope simulation for all the considered depths. These results highlight the importance of including a detailed description of the vegetation dynamics and root development (in both space and time) to properly quantify the soil hydrological processes leading to shallow landslides.

Water potential

The difference in soil water potential between adjacent computational nodes is the leading physical variable for all water transport processes, storage, infiltration, and redistribution in CRITERIA-1D. Based on soil texture and field water potential data, if available, each homogeneous soil layer is characterized by its own soil water retention curve (SWRC), and water movement is driven by the water potential gradients. The water potential was computed at depths of 20, 60, and 120 cm corresponding to the sensor's installation depths at the Montuè site (Fig. 3). CRITERIA-1D can indicate some water content levels at chosen points of the SWRC. For this application, values for the saturation, field capacity, and wilting point were derived from field data for the different horizons. The modified Ippisch–van Genuchten model is employed as the SWRC in both CRITERIA-1D and CRITERIA-3D (Bittelli et al. 2012). The results represented in Fig. 11 show that the condition close to saturation or at complete saturation for prolonged periods starts at a depth of 60 cm, being more stable at 120 cm. This suggests the formation of a perched water table, probably at an intermediate depth. From field data, it is found that, between February 28th and March 2nd, i.e., when the landslide occurred, positive water potentials developed. These values were correctly detected for both the vegetated and bare soil simulations in CRITERIA-1D. The difference between the two scenarios is evident by observing the low values of the water potentials, similarly to the water content simulations.

Considering the presence of vegetation (green lines in Fig. 11a–c) returns higher values of negative water potential during summer dry periods compared with the bare soil simulation, especially at the shallowest depth considered (Fig. 11a). However, at deeper layers, the vegetated scenario outperforms that with bare soil (Fig. 11b, c). The water potential values appear to be simulated well with the vegetated soil especially in summer 2014, up to a depth of 60 cm (Fig. 11b). Actually, this was the only summer in the considered period in which the transpiration activity did not drop because of a high rainfall rate (Fig. 6c).

The effect of considering evapotranspiration is evident at deeper layers. The water potential patterns are better captured particularly as concerns the minimum values and the rapid drying movements. An example is represented by the simulation at the depth of 60 cm, where the maximum root density occurs (Fig. 6e). At this layer, the simulated descending water potential trend in time is accurate in July, when the transpiration is still present (Fig. 11b).

It is worth highlighting the effect of evapotranspiration-induced suction on the soil water potential in September 2012 (Fig. 11b), when the transpiration starts again because of a high amount of rainfall. Only the vegetated simulation simulates the subsequent drying phase.

Generally, the wetting curve branches are better captured by the vegetated simulation over the whole of the considered time

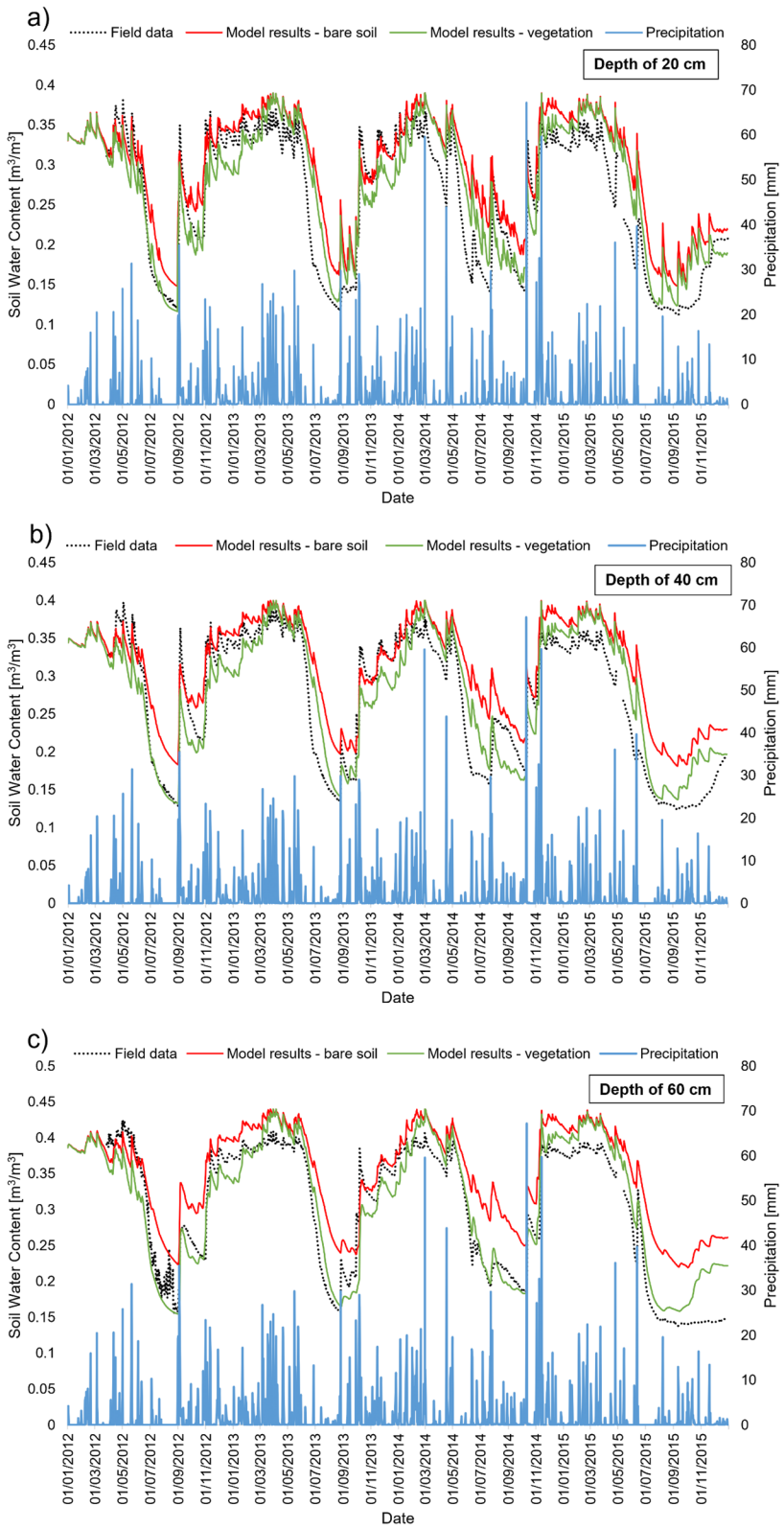

Fig. 8 Water content simulation at depths of 20 (**a**), 40 (**b**), and 60 cm (**c**) (dates are provided in dd/mm/yyyy format)

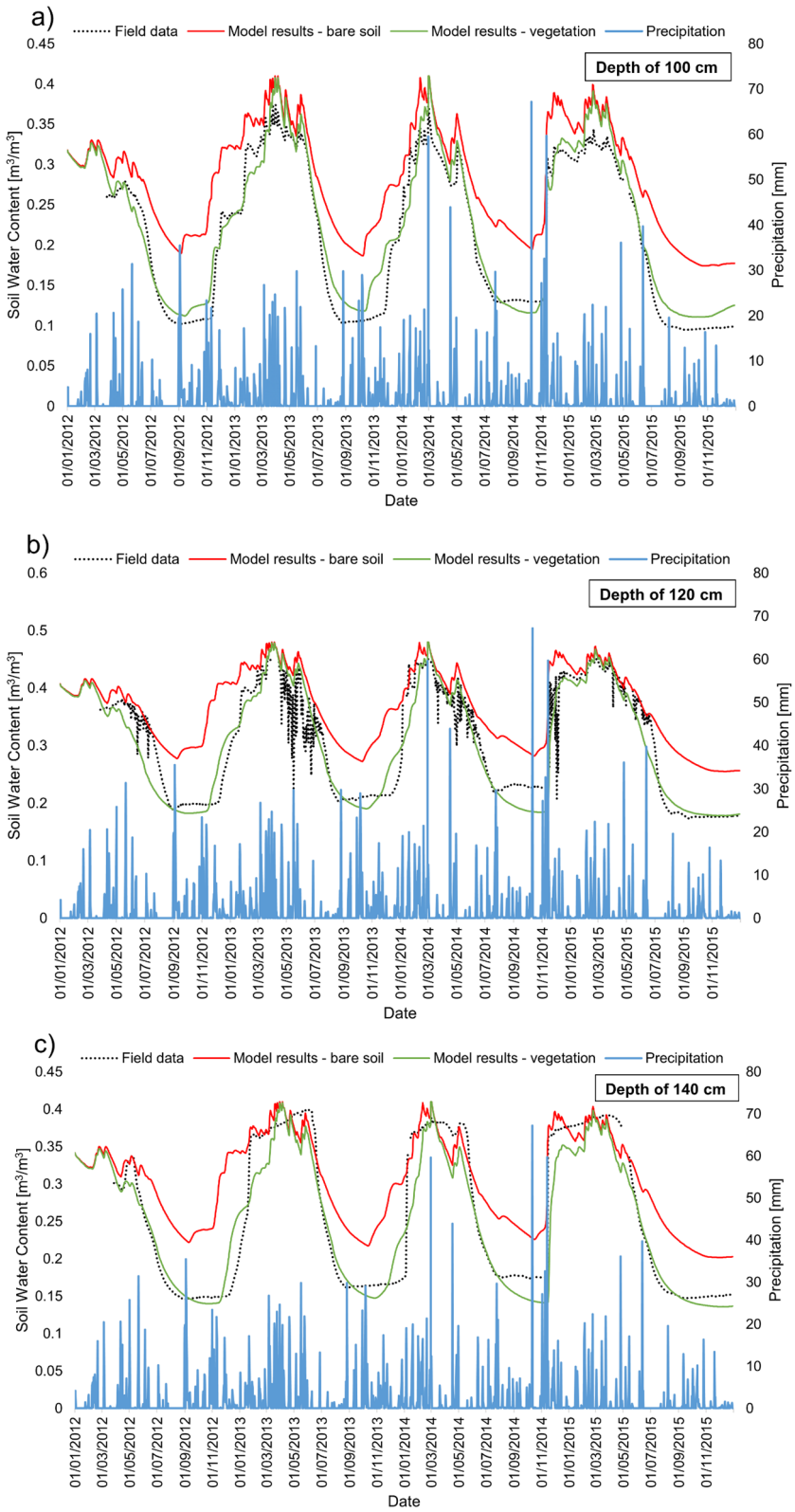

Fig. 9 Water content simulation at depths of 100 (**a**), 120 (**b**), and 140 cm (**c**) (dates are provided in dd/mm/yyyy format)

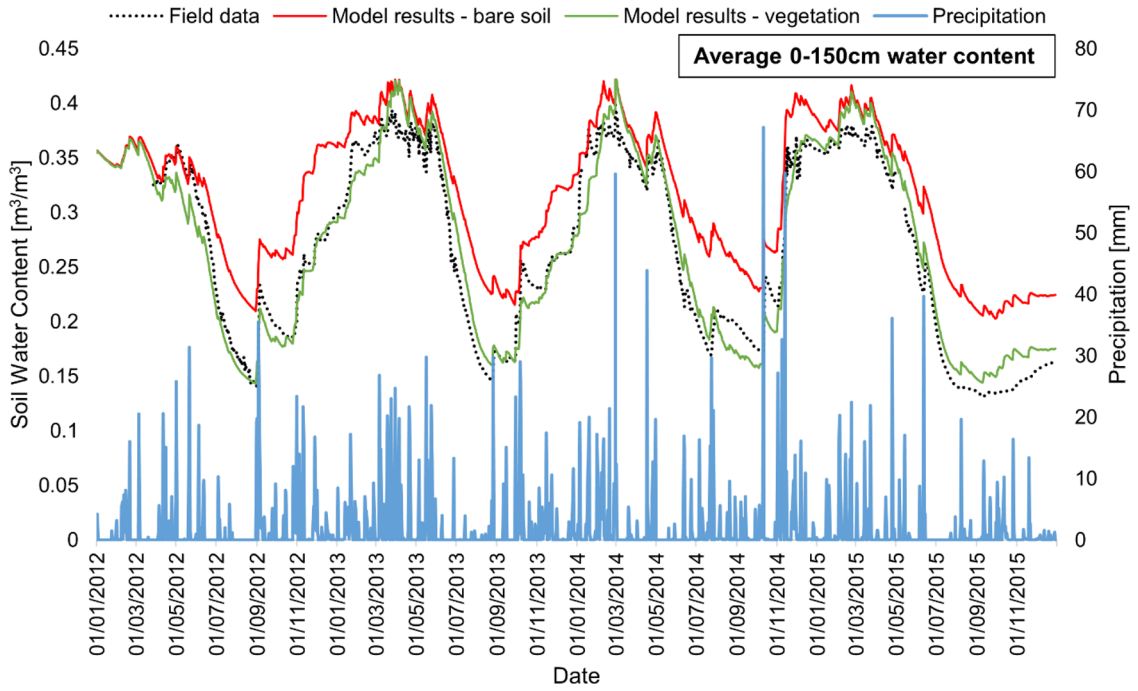

Fig. 10 Average water content simulation for the whole profile from 0 to 150 cm (dates are provided in dd/mm/yyyy format)

span, suggesting the importance of simulating the pre-wetting water potential due to evapotranspiration activity, as well as the evaporation reduction because of canopies.

Slope stability analysis

Figure 12 shows the results of the slope stability analysis carried out through CRITERIA-1D in terms of variation of the factor of safety (FoS) in time at different depths. The trend of the FoS showed that considering a bare soil can lead to overestimations of landslide events detection (Fig. 12a). In fact, during the simulation period, the FoS assumes a value lower than one, indicating instability, several times if no vegetation and evapotranspiration-induced stability effect is considered. This aspect must not be neglected when a tool is to be used for early warning purposes. When considering the presence and the hydrological effect of vegetation, the situation is different, and the unique landslide of 2014 is correctly predicted at a depth of 100 cm, i.e., the real depth of occurrence, as already detected by Bordoni et al. (2015) (Fig. 12b).

In CRITERIA-1D, the root water uptake activity is related to the leaf area index at every time step (Fig. 6). The LAI changes from its minimum to its maximum based on real meteorological data throughout the year, and from 1 year to another, together with evapotranspiration (see Fig. 6). Thus, the hydrological effect on the soil shear strength caused by plants modeled in CRITERIA-1D has a reliable physical basis, although a standard root distribution was used in this application. Furthermore, the transpiration activity in CRITERIA-1D is stopped when the soil is dry or saturated, on the basis of a water tolerance threshold that can be manually set.

The year 2013 was characterized by a prolonged wet period with respect to the other considered years (Fig. 5), and many subsequent rainfall events occurred. Despite this, as the LAI was growing to its maximum level (the false detected landslide for the bare soil is between April and May 2013, see Figs. 6b and 12a), the transpiration activity continued, such that the factor of safety did not drop below one. On the contrary, in 2014, very high rainfall (approximately 70 mm in 42 h) occurred during a wet period, and the transpiration dropped to zero because of the stress condition due to soil saturation (Fig. 6c). These results suggest that the cause of the landslide occurrence was the interruption of the root water uptake and thus the hydraulic reinforcement effect.

Like other physically based deterministic models, CRITERIA-1D does not comprise any statistical treatment of input parameters uncertainties. If parameters are not directly measured in the field, it is possible to calibrate the soil and crop

Table 5 Root mean square errors for the hydrological simulations

Depth —(m)	RMSE—bare soil (m^3/m^3)	RMSE—vegetation (m^3/m^3)
0.2	0.06	0.05
0.4	0.07	0.05
0.6	0.08	0.06
1	0.08	0.04
1.2	0.10	0.08
1.4	0.08	0.05
0–1.5	0.07	0.04

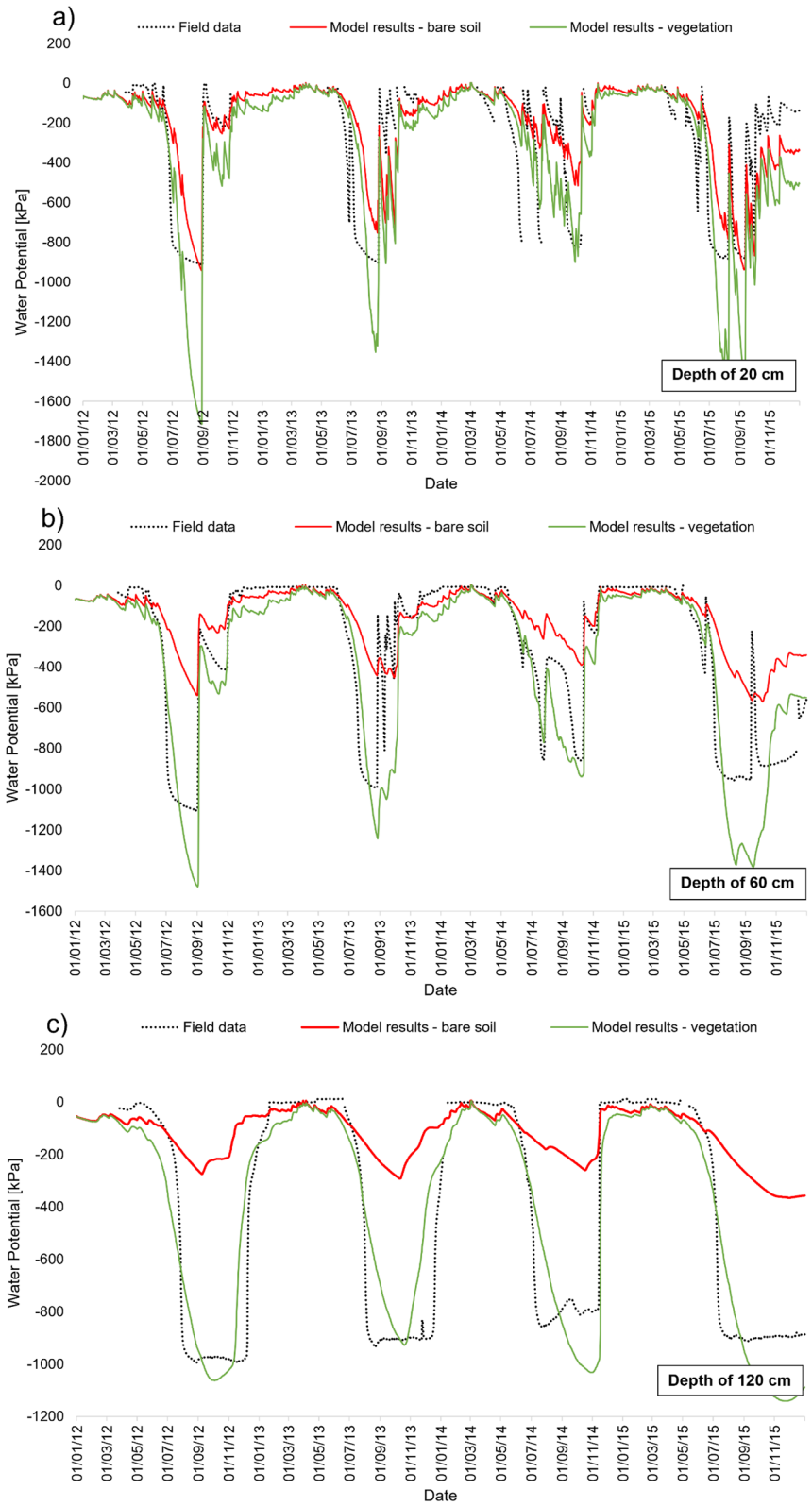

Fig. 11 Water potential simulation at depths of 20 (**a**), 60 (**b**), and 120 cm (**c**) (dates are provided in dd/mm/yy format)

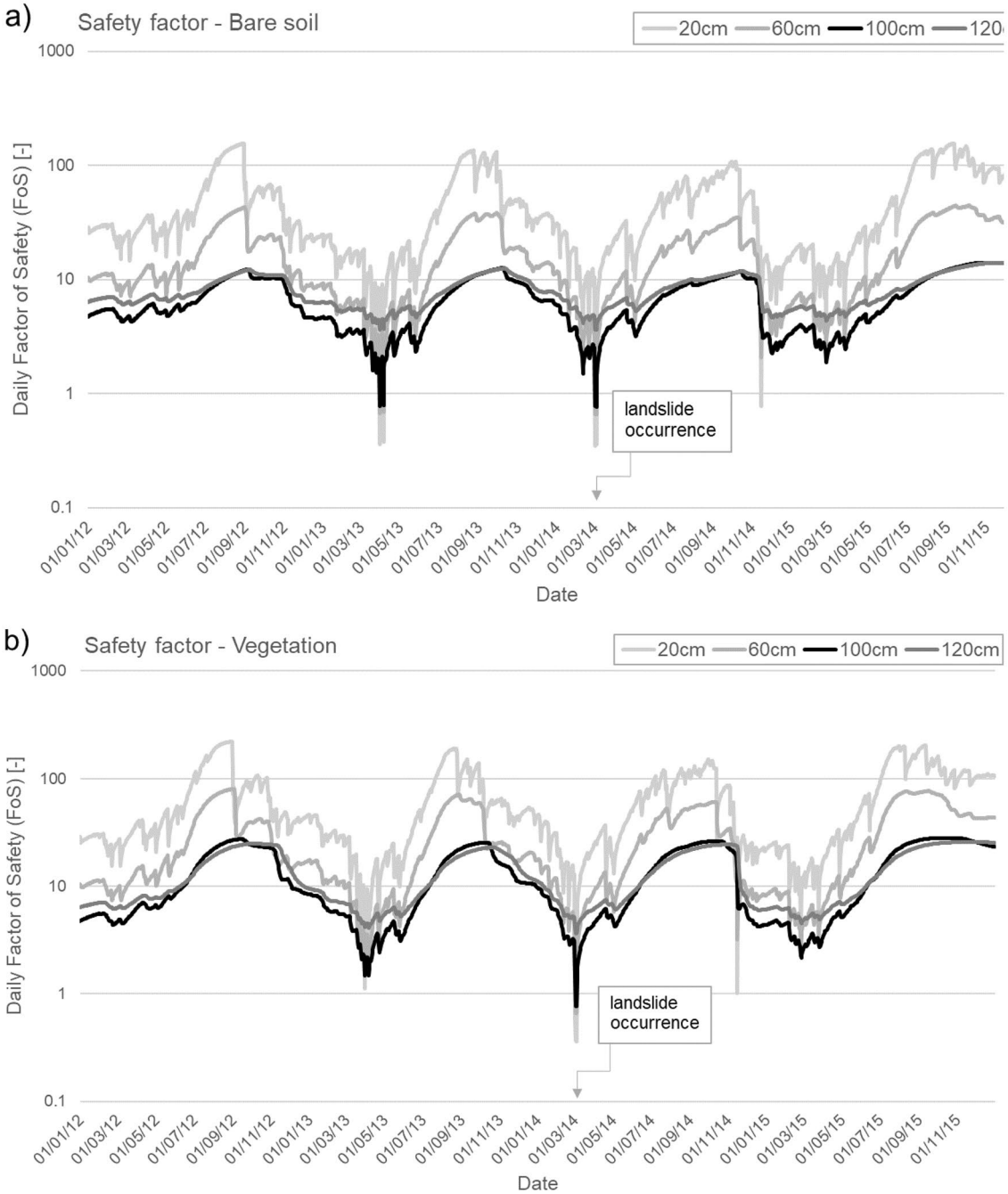

Fig. 12 Simulation of daily factor of safety at different depths considering a bare soil (**a**) and the presence of vegetation (**b**) (dates are provided in dd/mm/yy format)

parameters for a certain slope through the back analysis of past landslides and measured time series of soil water content and water potential. Moreover, although CRITERIA-1D cannot reproduce the volumetric changes due to the shrinking–swelling cycles and the consequent formation of macro-voids and preferential flows, it appears suitable for fine-grained silty soils even if texture-based parameters are used. The proper modeling of vegetation, enlarging the soil water balance components, helps the model to be consistent even when using calibrated values of the soil parameters.

Conclusions

The aim of this research was to implement a slope stability method into the agro-hydrological CRITERIA-1D model, due to its ability to consider the presence of vegetation as a dynamic, spatially, and time-variable input. Another objective was to test the reliability of the proposed approach for the implementation of the same slope stability method in the three-dimensional CRITERIA-3D, which is an ongoing research activity. Modeling the root zone and the presence of canopies is recognized as an important aspect for landslide prediction, especially when computation of the soil water balance

transient is included in the model. The main findings obtained by employing the CRITERIA-1D model can be summarized as follows:

- The implementation of a slope stability method in an agro-hydrological modeling scheme is a valid tool for rainfall-induced shallow landslide prediction. In particular, the possibility of dynamically modeling the transpiration-induced hydrological effects is of importance; although it is not the unique hydrological vegetation effect on unsaturated soil properties (Ni et al. 2018), it is rarely considered by the current widely adopted models.
- On soils with hysteretic behavior, the use of a unique soil water retention curve (SWRC) and the underlying assumption of homogeneous soil layers sometimes may not be appropriate. However, at the Montuè test site, thanks to the possibility of modeling vegetation dynamically, the choice of using texture-based values of K_{sat} showed its efficacy.
- With regard to slope stability analysis, the root density distribution and the presence of plants affect water movements and the water potential in soils, and this research underlined the importance of including this component in physically based deterministic models to avoid the overestimation of landslide event detection. Although designed for agronomical contexts, CRITERIA-1D shows good suitability also for a natural environment case.
- The pre-wetting condition due to the evapotranspiration-induced hydrological effect has an important impact on slope stability transient evaluation; moreover, in shallow landslide models, account should be taken of the fact that transpiration can become null when the soil undergoes saturated conditions. Accounting for this mechanism can improve the accuracy of models.

Further developments will include the implementation and validation of the slope stability model in the three-dimensional CRITERIA-3D code (Bittelli et al. 2010) on the same test site and the validation of CRITERIA-1D in other natural environments. Another research focus will be the possibility of implementing different soil hydrological parameters depending on the season. Also, the presence of any differences between considering only the hydrological or both the hydrological and mechanical root effect in shallow landslide prediction through CRITERIA-1D where field data are available will be investigated. The possibility of simulating plants growing from 1 year to another when the simulations cover more than 1 year through the LAI will be also explored.

As an open-source tool, CRITERIA-1D can help the design of nature-based solutions for slope instability mitigation purposes, as different scenarios can be designed and tested on past landslides events, especially if the mechanical contributions of roots are also properly considered (Tosi 2007; Bordoni et al. 2024).

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Data availability

Data used during the current study are available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

Model availability CRITERIA-1D is an open-source model available at the following GitHub page https://github.com/ARPA-SIMC/CRITERIA1D where manuals are also available.

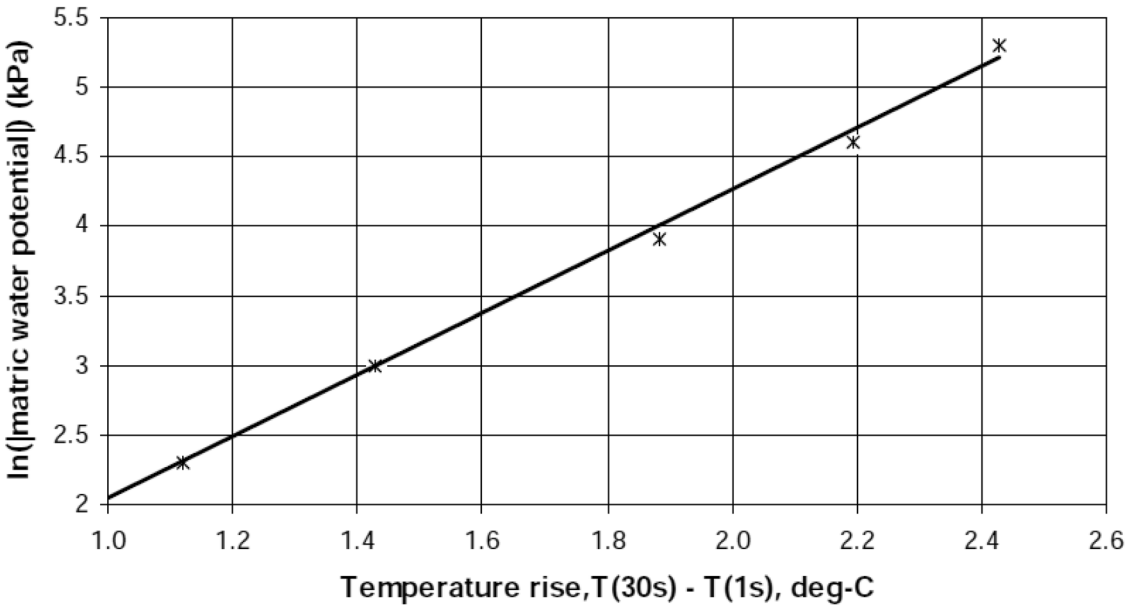

Fig. 13 Calibration curve of heat dissipation sensors showing the matric water potential vs temperature rise

Appendix

Figure 13 shows the calibration curve of heat dissipation (HD) sensors used at the Montuè test site. The curve was derived from the sensor's instruction manual (Campbell Scientific, Inc. (2006). 229 Heat dissipation matric water potential sensor: Instruction manual. Campbell Scientific Inc.: Logan, Utah, USA).

References

Antolini G, Tomei F, Dottori F, Marletto V, Van Soetendael M, Bittelli M (2016) CRITERIA technical manual. Arpae Emilia-Romagna - Hydro-Meteo-Climate Service. https://www.arpae.it/it/temi-ambientali/meteo/scopri-di-piu/strumenti-di-modellistica/criteria/criteria_2016_technical-manual.pdf. Accessed 20 Jan 2024

Arnone E, Caracciolo D, Noto LV, Preti F, Bras RL (2016) Modeling the hydrological and mechanical effect of roots on shallow landslides. Water Resour Res 52:8590–8612. https://doi.org/10.1002/2015WR018227

Bathurst JC, Bovolo CI, Cisneros F (2010) Modelling the effect of forest cover on shallow landslides at the river basin scale. Ecol Eng 36:317–327. https://doi.org/10.1016/j.ecoleng.2009.05.001

Baum RL, Savage WZ, Godt JW (2008) TRIGRS: a Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis, Version 2.0. US Geological Survey, Reston, VA, USA, p 75. https://pubs.usgs.gov/of/2008/1159/downloads/pdf/OF08-1159.pdf. Accessed 11 Jan 2024

Bittelli M, Tomei F, Pistocchi A, Flury M, Boll J, Brooks ES, Antolini G (2010) Development and testing of a physically based, three-dimensional model of surface and subsurface hydrology. Adv Water Resour 33:106–122. https://doi.org/10.1016/j.advwatres.2009.10.013

Bittelli M, Valentino R, Salvatorelli F, Rossi Pisa P (2012) Monitoring soil–water and displacement conditions leading to landslide occurrence in partially saturated clays. Geomorphology 173–174:161–173. https://doi.org/10.1016/j.geomorph.2012.06.006

Bogaard TA, Greco R (2016) Landslide hydrology: from hydrology to pore pressure. Wiley Interdiscip Rev Water 3:439–459

Bordoni M, Meisina C, Valentino R, Lu N, Bittelli M, Chersich S (2015) Hydrological factors affecting rainfall-induced shallow landslides: from the field monitoring to a simplified slope stability analysis. Eng Geol 193:19–37. https://doi.org/10.1016/j.enggeo.2015.04.006

Bordoni M, Bittelli M, Valentino R, Chersich S, Meisina C (2017) Improving the estimation of complete field soil water characteristic curves through field monitoring data. J Hydrol 552:283–305. https://doi.org/10.1016/j.jhydrol.2017.07.004

Bordoni M, Vivaldi V, Lucchelli L, Ciabatta L, Brocca L, Galve JP, Meisina C (2021a) Development of a data-driven model for spatial and temporal shallow landslide probability of occurrence at catchment scale. Landslides 18:1209–1229

Bordoni M, Bittelli M, Valentino R, Vivaldi V, Meisina C (2021b) Observations on soil atmosphere interactions after long term monitoring at two sample sites subjected to shallow landslides. Bull Eng Geol Environ 80:7467–7491

Bordoni M, Vivaldi V, Giarola A, Valentino R, Bittelli M, Meisina C (2024) Comparison between mechanical and hydrological reinforcement effects of cultivated plants on shallow slope stability. Sci Total Environ 912:168999. https://doi.org/10.1016/j.scitotenv.2023.168999

Bronstert A, Plate EJ (1997) Modelling of runoff generation and soil moisture dynamics for hillslopes and micro-catchments. J Hydrol (amst) 198:177–195

Campi P, Modugno F, Navarro A, Tomei F, Villani G, Mastrorilli M (2015) Evapotranspiration simulated by CRITERIA and AquaCrop models in stony soils. Ital J Agron 10:67–73. https://doi.org/10.4081/ija.2015.658

Capparelli G, Versace P (2011) FLaIR and SUSHI: two mathematical models for early warning of landslides induced by rainfall. Landslides 8:67–79. https://doi.org/10.1007/s10346-010-0228-6

Cronkite-Ratcliff C, Schmidt KM, Wirion C (2022) Comparing root cohesion estimates from three models at a shallow landslide in the Oregon Coast Range. GeoHazards 3:428–451. https://doi.org/10.3390/geohazards3030022

Driessen PM (1986) The water balance of the soil. In: van Keulen H, Wolf J (eds) Modelling of agricultural production: weather, soils and crops. Pudoc, pp 76–116. https://edepot.wur.nl/172091 (9022008584)

Durmaz M, Hürlimann M, Huvaj N, Medina V (2023) Comparison of different hydrological and stability assumptions for physically-based modeling of shallow landslides. Eng Geol 323:107237. https://doi.org/10.1016/j.enggeo.2023.107237

Flint AL, Campbell GS, Ellett KM, Calissendorf C (2002) Calibration and temperature correction of heat dissipation matric potential sensors. Soil Sci Soc Am J 66:1439–1445. https://doi.org/10.2136/sssaj2002.1439

Gioia E, Speranza G, Ferretti M, Godt JW, Baum RL, Marincioni F (2016) Application of a process-based shallow landslide hazard model over a broad area in Central Italy. Landslides 13:1197–1214. https://doi.org/10.1007/s10346-015-0670-6

Greco R, Marino P, Bogaard TA (2023) Recent advancements of landslide hydrology. Wiley Interdiscipl Rev Water 10(6):e1675. https://doi.org/10.1002/wat2.1675

Guo H, Qu C, Liu L, Zhang Q, Liu Y (2024a) Reliability analysis of vegetated slope considering spatial variability of soil and root properties. Comput Geotech 169:106257. https://doi.org/10.1016/j.compgeo.2024.106257

Guo H, Ng CWW, Zhang Q (2024b) Three-dimensional numerical analysis of plant-soil hydraulic interactions on pore water pressure of vegetated slope under different rainfall patterns. Journal of Rock Mechanics and Geotechnical Engineering. https://doi.org/10.1016/j.jrmge.2023.09.032

Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. Appl Eng Agric 1:96–99. https://doi.org/10.13031/2013.26773

Iadanza C, Trigila A, Napolitano F (2016) Identification and characterization of rainfall events responsible for triggering of debris flows and shallow landslides. J Hydrol (amst) 541:230–245. https://doi.org/10.1016/j.jhydrol.2016.01.018

Ippisch O, Vogel HJ, Bastian P (2006) Validity limits for the van Genuchten-Mualem model and implications for parameter estimation and numerical simulation. Adv Water Resour 29:1780–1789. https://doi.org/10.1016/j.advwatres.2005.12.011

IUSS Working Group WRB (2007) World reference base for soil resources 2006, first update 2007. World Soil Resources Reports No. 103. FAO, Rome. https://www.fao.org/fileadmin/templates/nr/images/resources/pdf_documents/wrb2007_red.pdf

Kavzoglu T, Colkesen I, Sahin EK (2019) Machine learning techniques in landslide susceptibility mapping: a survey and a case study. In: Pradhan S, Vishal V, Singh T (eds) Landslides: theory, practice and

modelling. Advances in natural and technological hazards research, vol 50. Springer, Cham. https://doi.org/10.1007/978-3-319-77377-3_13
Lepore C, Arnone E, Noto LV, Sivandran G, Bras RL (2013) Physically based modeling of rainfall-triggered landslides: a case study in the Luquillo forest, Puerto Rico. Hydrol Earth Syst Sci 17:3371–3387. https://doi.org/10.5194/hess-17-3371-2013
Li Y, Duan W (2023) Decoding vegetation's role in landslide susceptibility mapping: an integrated review of techniques and future directions. Biogeotechnics 2(1):100056. https://doi.org/10.1016/j.bgtech.2023.100056
Lima P, Steger S, Glade T, Murillo-García FG (2022) Literature review and bibliometric analysis on data-driven assessment of landslide susceptibility. J Mt Sci 19(6):1670–1698
Lu N, Godt J (2008) Infinite slope stability under steady unsaturated seepage conditions. Water Resour Res 44(11). https://doi.org/10.1029/2008WR006976
Lu J, Zhang Q, Werner AD, Li Y, Jiang S, Tan Z (2020) Root-induced changes of soil hydraulic properties–a review. J Hydrol 589:125203
Masi EB, Segoni S, Tofani V (2021) Root reinforcement in slope stability models: a review. Geosciences 11(5). https://doi.org/10.3390/geosciences11050212
Masi EB, Tofani V, Rossi G, Cuomo S, Wu W, Salciarini D, Caporali E, Catani F (2023) Effects of roots cohesion on regional distributed slope stability modelling. Catena 222:106853. https://doi.org/10.1016/j.catena.2022.106853
Meena V, Kumari S, Shankar V (2022) Physically based modelling techniques for landslide susceptibility analysis: a comparison. IOP Conf Ser Earth Environ Sci 1032(012033):1
Minacapilli M, Iovino M, D'Urso G (2008) A distributed agro-hydrological model for irrigation water demand assessment. Agric Water Manag 95:123–132. https://doi.org/10.1016/j.agwat.2007.09.008
Montrasio L, Valentino R (2008) A model for triggering mechanisms of shallow landslides. Hazards Earth Syst Sci 8:1149–1159
Montrasio L, Valentino R (2016) Modelling rainfall-induced shallow landslides at different scales using SLIP - Part I, VI Italian Conference of Researchers in Geotechnical Engineering– Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, CNRIG2016. Procedia Engineering 158:476–481. https://doi.org/10.1016/j.proeng.2016.08.475
Montrasio L, Gatto MPA, Miodini C (2023) The role of plants in the prevention of soil-slip: the G-SLIP model and its application on territorial scale through G-XSLIP platform. Landslides. https://doi.org/10.1007/s10346-023-02031-9
Mualem Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour Res 12:513–522. https://doi.org/10.1029/WR012i003p00513
Murgia I, Giadrossich F, Mao Z, Cohen D, Capra JF, Schwarz M (2022) Modeling shallow landslides and root reinforcement: a review. Ecol Eng 181:106671
Ng CWW, Leung AK, Ni JJ (2019) Plant-soil slope interaction. CRC Press Taylor & Francis Group, Boca raton, FL, USA
Ng CWW, Ni JJ, Leung AK (2020) Effects of plant growth and spacing on soil hydrological changes: a field study. Géotechnique 70(10):867–881
Ng CWW, Zhang Q, Ni J, Li Z (2021) A new three-dimensional theoretical model for analysing the stability of vegetated slopes with different root architectures and planting patterns. Comput Geotech 130:103912. https://doi.org/10.1016/j.compgeo.2020.103912
Ng CWW, Guo H, Ni G, Zhang Q, Chen Z (2022) Effects of soil–plantbiochar interactions on water retention and slope stability under various rainfall patterns. Landslides 19:1379–1390. https://doi.org/10.1007/s10346-022-01874-y
Ni JJ, Leung AK, Ng CWW, Shao W (2018) Modelling hydro-mechanical reinforcements of plants to slope stability. Comput Geotech 95:99–109
Ni JJ, Leung AK, Ng CWW (2019a) Modelling effects of root growth and decay on soil water retention and permeability. Can Geotech J 56(7):1049–1055. https://doi.org/10.1139/cgj-2018-0402
Ni JJ, Leung AK, Ng CWW (2019b) Unsaturated hydraulic properties of vegetated soil under single and mixed planting conditions. Géotechnique 69(6):554–559
Ni JJ, Bordoloi S, Shao W, Garg A, Xu G, Sarmah AK (2020) Two-year evaluation of hydraulic properties of biochar-amended vegetated soil for application in landfill cover system. Sci Total Environ 712:136486
Pardeshi SD, Autade SE, Pardeshi SS (2013) Landslide hazard assessment: recent trends and techniques. SpringerPlus 2:523. https://doi.org/10.1186/2193-1801-2-523
Reichenbach P, Rossi M, Malamud BD, Mihir M, Guzzetti F (2018) A review of statistically-based landslide susceptibility models. Earth Sci Rev 180:60–91
Simoni S, Zanotti F, Bertoldi G, Rigon R (2008) Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS. Hydrol Process 22:532–545. https://doi.org/10.1002/hyp.6886
Stokes A, Douglas GB, Fourcaud T et al (2014) Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. Plant Soil 377:1–23
Tomei F, Antolini G, Villani G, Bittelli M, Sannino G (2024) CRITERIA-1D technical manual. https://github.com/ARPA-SIMC/CRITERIA1D/blob/master/DOC/CRITERIA1D_technical_manual.pdf. Accessed 29 Jan 2024
Tosi M (2007) Root tensile strength relationships and their slope stability implications of three shrub species in the northern Apennines (Italy). Geomorphology 87:268–283. https://doi.org/10.1016/j.geomorph.2006.09.019
Tufano R, Formetta G, Calcaterra D, De Vita P (2021) Hydrological control of soil thickness spatial variability on the initiation of rainfall-induced shallow landslides using a three-dimensional model. Landslides 18:3367–3380. https://doi.org/10.1007/s10346-021-01681-x
van Dam JC, Groenendijk P, Hendriks RFA, Kroes JG (2008) Advances of modeling water flow in variably saturated soils with SWAP. Vadose Zone Journal 7:640–653. https://doi.org/10.2136/vzj2007.0060
Varnes DJ (1978) Slope movement types and processes. In: Schuster RL, Krizek RJ (eds) Landslides, analysis and control, special report 176: transportation research board. National Academy of Sciences, Washington, DC., pp 11–33

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