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Review

Deterministic Physically Based Distributed Models for Rainfall-Induced Shallow Landslides

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Abstract: Facing global warming's consequences is a major issue in the present times. Regarding the climate, projections say that heavy rainfalls are going to increase with high probability together with temperature rise; thus, the hazard related to rainfall-induced shallow landslides will likely increase in density over susceptible territories. Different modeling approaches exist, and many of them are forced to make simplifications in order to reproduce landslide occurrences over space and time. Process-based models can help in quantifying the consequences of heavy rainfall in terms of slope instability at a territory scale. In this study, a narrative review of physically based deterministic distributed models (PBDDMs) is presented. Models were selected based on the adoption of the infinite slope scheme (ISS), the use of a deterministic approach (i.e., input and output are treated as absolute values), and the inclusion of new approaches in modeling slope stability through the ISS. The models are presented in chronological order with the aim of drawing a timeline of the evolution of PBDDMs and providing researchers and practitioners with basic knowledge of what scholars have proposed so far. The results indicate that including vegetation's effects on slope stability has raised in importance over time but that there is still a need to find an efficient way to include them. In recent years, the literature production seems to be more focused on probabilistic approaches.

Keywords: physical modeling; shallow landslides; infinite slope scheme; slope stability

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1. Introduction

Among landslides, those involving shallow soil (up to a 2–3 m depth) are most frequently induced by rainfall and are highly dangerous, as no premonitory signs are present over territories [1]. The landslide occurrence is the final step of a chain of processes that starts with rainfall infiltration and leads to slope collapse [2]. Therefore, a tool including process quantification to prepare for potential landslide hazards is necessary, especially under climate change conditions; in fact, the temperature rise will allow the atmosphere to hold more moisture so that a greater magnitude of heavy rainfall will likely occur [3]. However, little is known about the effects of climate and its variation on slope stability, landslides, landslide hazards, and the related risk of climate change [4].

Rainfall is recognized as the major shallow landslide triggering factor [5], and over time, different techniques have been employed to predict rainfall-induced shallow landslides in order to constitute Landslide Early Warning System (LEWS) tools [6]. To model landslide occurrences, two main approaches are recognized: physically based modeling and statistical modeling. These models can help in assessing not only the landslide susceptibility of large areas but also the related hazard, which is defined as the detection of the triggering time of a landslide (i.e., “when” or “how frequently” will occur) [7]. Physically based models are also referred to as process-based models, while statistical approaches are further named “data-driven models” as they use past events data based on the assumption that environmental conditions leading to landslides in the past are likely to provoke new instability phenomena in the future [8]. Although they represent interesting techniques for large scale susceptibility analysis, they highly depend on the resolution of past landslides inventories, which can propagate high levels of uncertainty to the outputs if they are not sufficiently detailed. Moreover, under climate change conditions, data-driven approaches have to be undertaken carefully since new environmental and meteorological conditions may not be represented by the past [9].

The use of physical–mathematical models has recently gained large consensus among engineers and the scientific community, not only for applications at the local or slope scale but also at larger extensions, as they can take into account the dynamic variability of the system [10]. Physically based model applications over large areas are also supported by remote sensing, which allows extensive observation of landslides, especially where it would not be possible with ground-based techniques, thus providing robust landslide inventories upon which model output accuracy can be assessed [11–14]. Whether the aim is to design emergency plans to warn people or inform policy makers about the consequences of extreme climatic events, physically based distributed models represent valid tools as they can detect landslide occurrences in advance. When dealing with future landslide prediction and climate change impacts on slope stability, this modeling approach is considerably noteworthy, especially when vegetation presence is considered [15], thanks to the possibility of assessing single aspects’ contribution to the overall stability.

Physically based deterministic distributed models (PBDDMs) adopt deterministic approaches for both input and output and can be used to back-analyze real landslides in order to derive soil hydraulic and geotechnical parameters. Deterministic models can be highly sensitive to the input parameters’ variability. To reduce uncertainty in assigning unknown soil parameters, some physical models include probabilistic treatments of input data or are coupled with other approaches to obtain probability maps of failure as outputs, e.g., [16].

When developing new models for shallow landslide detection, the processes to consider must be decided. Normally, PBDDMs for shallow landslide prediction are composed of a hydrological module interfaced with a geotechnical module, typically based on the estimation of the slope safety factor through the limit equilibrium method, as it is less computationally demanding than finite element numerical methods, which are often not practically useable over large areas [17]. At the same time, the hydrological processes involved in landslide initiation are many, and including all of them in a single model would make it impossible to run in a reasonable computational time. Because of this complexity, the majority of the existing models that consider hydrological aspects in detail tend to simplify the mechanical aspects. The simplified approach based on the infinite slope scheme (ISS) is adopted in the majority of PBBDMs for rainfall-induced shallow landslides. In this approach, the assumption of a planar failure geometry is considered consistent with the shape, size, and failure mechanisms of rainfall-induced shallow landslides, although this assumption has some applicability limitations [18].

In recent years, models including antecedent hydrological information have raised importance in landslide hazard assessment [19], and including vegetation-related processes has become fundamental in shallow landslides’ prediction. This is because canopies and roots modify the stability condition of slopes under both hydrological and mechanical viewpoints [20–22]. The rooted portion of soil has peculiar characteristics, and its behavior, together with proper consideration of unsaturated soil mechanics, should be taken into account in shallow landslide prediction. Furthermore, the interest in nature-based solutions (NBSs) and bioengineering techniques has raised the importance of preventing landslides over territories, not only because of environmental purposes but also because of economic aspects [23–25]. Quantitatively assessing the role of vegetation on slope stability is of importance, although a comprehensive methodology is still lacking [26].

In this work, a non-systematic narrative review of the main physically based deterministic distributed models developed over time is presented, highlighting which aspects or techniques were used and introduced over time by the different models. The review is restricted to the models that adopt the infinite slope scheme and are based on the limit equilibrium method. The aim is to draw a chronological memory of rainfall-induced shallow landslides deterministic modeling and also to address new research efforts in directions that have not yet been explored. This paper is organized as follows. In the second section, a brief discussion of shallow landslide modeling methods is presented, stretching some conceptual aspects of hydrology and plants' contribution. The third section presents the materials and methods adopted for this work, while the fourth section describes the selected models in detail. It was chosen to include only models that do not use any kind of probabilistic approach. This choice is meant to be helpful for practitioners and non-academic, but also for new researchers, in order to classify physically based models for rainfall-induced shallow landslides into two different groups: "purely" physically based deterministic distributed models (PBDDMs), i.e., the specific topic of this review, and hybrid forms. In the end, a conclusive section considers aspects that still have to be properly explored in PBDDMs. Some suggestions are also provided.

2. Shallow Landslide Modeling Methods

2.1. Hydrology

As already mentioned, the majority of the existing PBDDMs for rainfall-induced shallow landslides prediction are composed of two interfaced modules: one computes the hydrological phenomena, and the other computes the slope stability.

A recognized mechanism for shallow landslide activation is the rapid formation of nil or positive pore water pressure because of soil saturation [27–29]. Saturated lenses develop in response to rainfall events because of infiltration and seepage processes, and they can trigger landslides when enlarged enough. Water can accumulate in the soil because of the presence of an impermeable or low-permeability layer, either during vertical downward seepage or upward movements [30]. Some landslides can then completely or partially mobilize into destructive earth flows because of liquefaction [31–34], while others only translate the detached material up to a certain distance.

Because of these observations, the first slope stability models were developed based on saturated soil conditions [35]. Under saturation conditions, soil properties and hydrological parameters can be assumed as constant, and the role of matric suction (i.e., negative pore water pressure) is neglected. Real meteorological conditions can even be ignored in models based on saturated soil mechanics. In the most simplified cases where the soil is considered to be partially saturated, real rainfall amounts are considered as contributing to the uprising of a pre-existing groundwater table.

Some limitations of these simplified approaches have been recognized, and practical applications related to slope stability problems also involve unsaturated soil mechanics [36]. In fact, since shallow landslides have been observed to occur even under negative pore water pressure, i.e., when the soil is in partially saturated condition [37,38], it is important to consider the evolution in time of pore-water pressures and unsaturated soil mechanics in PBDDMs.

Unsaturated soil mechanics are normally based on non-linear soil property functions, including the constitutive relationship between soil water content and soil suction (also defined as the water potential or hydraulic head), namely, the Soil Water Retention Curve (SWRC, or Soil Water Characteristic Curve, SWCC), and the one that relates soil suction or soil water content to soil hydraulic conductivity, namely, the Hydraulic Conductivity Function (HCF) [39,40]. The relationships are unique for a certain pore size distribution of soil and are empirically defined. However, because of hysteretic behavior, these properties follow different patterns during wetting or drying phases [41]. Also, the presence of vegetation was demonstrated to alter the pore size distribution because of root growth, leading to an evolution of the SWRC and of the soil permeability over time with respect to SWRC or HCF of bare soil [42].

When considering unsaturated conditions, transient or stationary input rainfall can be assumed for hydrological balance computation, and water movements can be assessed through a transient analysis. The most commonly used approach to determine the transient values of soil water content is the use of partial differential equations—in particular, numerical solutions of Richards' equation for unsaturated seepage process [43,44] at different spatial domains (i.e., 1-D, 2-D, or 3-D). This approach allows to consideration of different hydrological processes into a single balance equation, although in the 3-D domain, its computation over large areas can be consuming both in terms of energy and time [45].

When dealing with rainfall-induced landslide hydrology, several processes should be quantified. In any case, the major water input is represented by rainfall infiltration, which enters the soil matrix and undergoes gradient and gravity-driven movements. Then, subsurface flows and redistribution processes take place, and soil hydraulic conductivity anisotropy should be considered [46]. In most cases, different hydraulic behaviors are only considered along soil vertical directions [47].

When a numerical problem is involved, it is essential to properly define boundary conditions, that is, defining how the considered physical system acts at the borders of its spatial and temporal domains [48].

As already mentioned, defining the antecedent condition of soil moisture prior to rainfall is fundamental to correctly simulate water movements during a precipitation event [49]. The global soil water balance equation should be solved for a certain time span, which should be antecedent with respect to the period of interest, in order to assess consistent soil moisture as an initial condition. In this sense, as a key hydrological process, plant growth and evapotranspiration activity should not be neglected [50]. In fact, vegetation alters the soil water content through different mechanisms, including the absorption of water over the rooted portion of the soil; the modification of SWRC; and parameters such as the saturated hydraulic conductivity, canopy rainfall interception, and the creation of preferential flow patterns through roots and stems. This latter aspect is very difficult to consider simultaneously with matrix flow equations if the model allows the consideration of two different domains at the same time [51]. Although preferential flow paths can have different natures and can originate in different ways, any of them is replicable by models based on matrix flow equations only if approaches such as dual-permeability (or double porosity) are adopted [52,53].

Notwithstanding the effectiveness of Richards' equation in soil water balance computation, this approach may not be the most efficient in specific cases. For example, when a landslide is triggered because of an in-depth wetting front propagation, the hydrological mechanisms can be approximated through simplified approaches for infiltration (e.g., [54,55]).

2.2. Slope Stability

With regard to the geotechnical modules of PBDDMs, the most commonly used approach for slope stability is the computation of a Factor of Safety (FoS). This approach is based on the limit equilibrium method and considers the relation between stabilizing and destabilizing actions on a slope. When the FoS is equal to 1, the slope is in a critical equilibrium state; as the FoS drops below 1, the entire slope is estimated as unstable.

Several methods to compute FoS exist [56]. In a general sense, FoS is computed over one or more potential failure surfaces in order to detect under which conditions and/or at which depth the landslide is triggered. PBDDMs should adopt an automatic procedure for analyzing different slip surfaces, especially when the soil strength and pressure profiles differ along with depth and the model can consider multi-layered soils with different parametrization.

Since shallow landslides are normally translational and their length/depth ratio is generally low, the infinite slope method (ISM), which assumes a ground-parallel planar failure surface, represents the most commonly used approach, although it has limitations [18]. Among others, Lu and Godt developed an equation for FoS that allows the classic saturated soil mechanics theory based on the effective stress concept to be easily extended to the unsaturated regime [57]. However, models that aim to simulate rotational movement also exist, as well as models that can approximate the landslide runout [58].

It is known that vegetation contributes to soil reinforcement in different ways and at different spatial scales [59,60]. With regard to plant roots, it is known that the rooting system can extend the soil shear strength either through water absorption or mechanical reinforcement, normally quantified as an additional cohesive term extending the soil's effective cohesion [61] and normally applied on the sliding surface. The mechanical reinforcement seems to be more effective in the shallower portion of the soil with respect to the hydrological reinforcement, which is effective down to a 1–2 m depth [62]. More in detail, the mechanical improvement in soil shear strength is exerted through the root network tensile strength and its interaction with soil and bedrock anchoring, as well as the ability of roots to cross the slip surface [63]. Both large and fine roots contribute to the global exerted reinforcement [64]. The overall root cohesion can be derived through different methods, namely, the Wu and Waldron model (WWM), the Fiber Bundle Model (FBM), the Analytical Fiber Bundle Model (AFBM), the Root Bundle Model (RBM), and the root bundle model with root-failure Weibull survival function (RBMw) [25,65–70]. The root reinforcement can be either basal or lateral when applied at the base of a failure plane or on the lateral sides of the landslide body, respectively. Nevertheless, in soil conditions close to saturation, it is not totally clear if these effects are still present or not [59,60]. Few of the existing models consider the real spatial variability of root distribution to assess the root reinforcement [71], even if the vegetation stand characteristics affect the magnitude of stabilization effects, especially if gaps are present [72].

PBDDMs can be applied at the slope scale, basin scale, or regional scale. In the first case, it may be possible to carry on field campaigns to obtain specific soil hydraulic and geotechnical parameters. In the second case, especially when the analyzed area is larger than a single slope or a small catchment, field work can become very expensive, and assigning reliable soil parameters can be challenging. For models that do not involve probabilistic approaches, parameters can be assigned based on texture or pedotransfer functions applied to geological units if extended field campaign data are not available [73].

3. Materials and Methods

This study builds upon previous review papers such as [20,25,74] and follows a non-systematic approach, mainly focusing on chronology and some specific aspects of different models. The flow chart of the methodology is represented in Figure 1.

A total of 43 models considered by other reviews were screened, and only 18 were detected as "purely deterministic". A total of 11 duplicates considered by more than one review were removed, while other 13 models presented some probabilistic approaches, and then they were removed. The resulting 18 deterministic models were analyzed, and 4 of them were discarded as they do not use the infinite slope scheme (ISS) as geotechnical model. In the last screening step, 2 models were removed because they were originally presented as non-distributed models, and 2 models considered by other reviews were an extension of a pre-existing model. The models which constitute extension of their previous version were, however, cited in the following section.

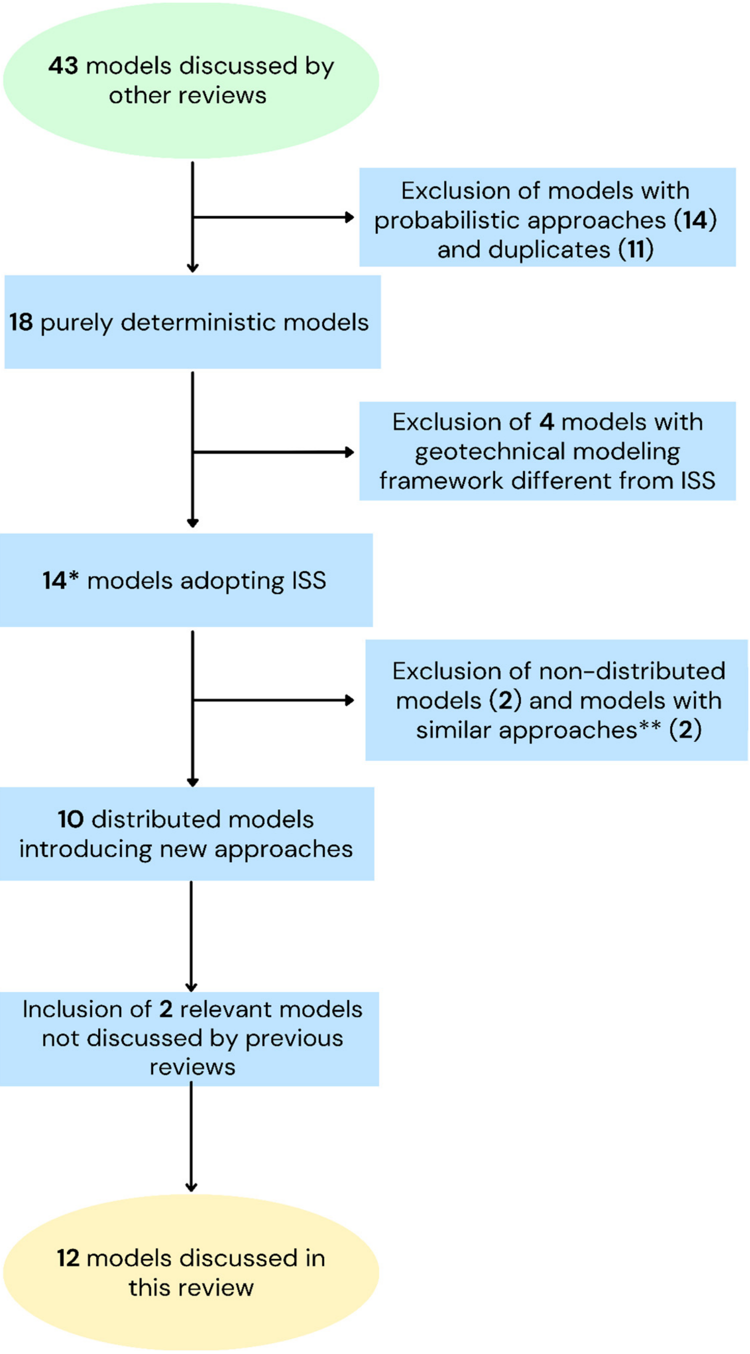

Figure 1. Flow chart of the methodology. * One of the reviewed models, SOSlope, uses the Discrete Element Method, but the ISS was adopted for the geometry definition. ** With "similar approaches", it is intended that the model was extending its previous version.

4. Discussion on Models

The 12 selected models are discussed in detail.

SHALSTAB [75] is one of the first GIS-based PBDMs published in 1994. It computes slope stability for cohesionless soils over an infinite slope under a steady-state flow condition, and it is intended to be used with ESRI-ArcGIS. By assuming a steady saturated flow, the model is able to calculate the rainfall amount that is necessary to trigger a landslide over a specified area using a contour-based Digital Elevation Model (DEM) methodology. Its output is an estimation of the critical saturated soil height computed through a hydrological model called TOPOG [76]. The model neglects the effects of the degree of saturation in the vadose zone. Because of its structure and mathematical formulations, SHALSTAB is not suitable to forecast the timing of landslide triggering.

In 1995, the dSLAM model was published [77]. The model aims to quantify the slope instability in steep and forested areas. With dSLAM, the mechanical root reinforcement is introduced in PBDDMs for shallow landslides, while hydraulic vegetation effects are ignored. The model is designed for translational slide overlying a lithic contact. dSLAM is a contour-based model and does not account for rainfall spatial distribution. The mechanical root reinforcement is considered a constant additive term to the overall soil cohesion. Hydrology is based on a kinematic wave groundwater model [78], and it can be run either with actual hyetographs or long-term sequences of precipitation. The authors demonstrate that the spatial distribution of slope instability is controlled by topography and forest harvesting. During major rainstorms, groundwater flow greately affects the factor of safety.

In 1998, the SHETRAN model was extended with a shallow landslide erosion and sediment yield component [79,80]. It is a basin-scale model that considers spatial variability of rainfall input and hydrological responses. It considers snowmelt as a triggering factor as well. The model computes the landslides' impact on sediment yields at the basin outlet, deriving the volume of dislocated material. Two levels of resolution are comprised: first, a finer spatial assessment of shallow landslide susceptibility is carried out, and a critical soil saturation condition is obtained through GISLIP, a GIS analysis tool; subsequently, a time-varying simulation based on the hydrological grid-based physical SHE model [81] is conducted at a coarser resolution, at which the geotechnical stability analysis also is conducted Therefore, the model can be computationally sustainable for basin-scale simulations (areas around 500 km^2). The SHE model comprises evapotranspiration activity and canopy interception.

In 2000, Iverson proposed a model intending to assess the effects of transient rainfall on the timing, rates, and locations of landslides [82]. The hydrology is computed considering the soil infiltration capacity equal to the saturated hydraulic conductivity in order to derive analytical values of the pressure head, assuming a pre-existing steady-state pore pressure. The aim of the model is to derive rainfall thresholds for triggering shallow landslides, corresponding to the peak value of pore pressure, by deriving transient pore pressure distributions that are added to the pre-existing one. Although a simplified transient analysis is included, Iverson's model is better suitable for shallow landslides related to short-duration rainfall (from approximately 1 h to 70 h), as the model neglects lateral water flow [83]. The model also derives post-failure motion.

TRIGRS [84] is a grid-based PBDDM that aims at locating the timing and size of landslides. At the time, most of the landslide prediction models were producing only susceptibility maps, not involving a complete transient and distributed analysis. In its first version, TRIGRS solves on a pixel-by-pixel basis the one-dimensional vertical version of Richards' equation by [85], assuming differentiated bare soil areas, which are characterized by a unique homogeneous isotropic layer. In general, TRIGRS is the most commonly used PBDDM for shallow landslides at the regional scale, even if no graphical interface is provided. Its use is linked to a Geographical Information System (GIS), where input data can be prepared and outputs can be visualized. Many versions of TRIGRS have been developed over time, including the unsaturated version, the accounting of a vegetation effect [86], and a parallelized version [87]. TRIGRS provides the minimum Factor of Safety (FoS) calculated at selected time steps of a rainstorm, the pore water pressures, and the depth of the minimum FoS at a certain time step. The soil is described by a SWRC. The unique consideration of 1-D water movements, although accurate under certain conditions, is not appropriate when complex topography is present over a large area. Moreover, the input DEM spatial resolution seems to strongly affect the results [88].

In the same year, 2008, the SLIP model was developed [89,90]. It is a PBDDM that adopts a simplified hydrological approach to simulate soil water balance, assuming that the saturated portion of the soil increases because of infiltrating rainfall. At the same time, the soil desaturates through a percolation process. To be quickly applied to large areas with low computational effort, the model avoids the need to be provided with complex hydrological formulation and approximates a transient seepage computation. In its recent version, the SLIP model also includes a simplified approach for plant interception and root cohesion, changing the model into G-SLIP [91]. SLIP represents a valid example of a simplified although effective solution for Early Warning Systems over large areas, which is an urgent need due to climate change.

In 2011, the SUSHI model was proposed by Capparelli and Versace [92]. It describes water movements in a bi-dimensional domain, allowing the consideration of irregular soil stratigraphy and different soil parameters. A 2-D Richards' equation is involved in the model, following the assumption of isotropic soil through the adoption of a specific "capillarity coefficient". This coefficient represents the rate at which water is absorbed or released because of pressure head changes in the soil. A fully implicit method and the finite difference method are employed for hydrology computation in the SUSHI model. Evapotranspiration is accounted for by adopting a uniform root distribution and deriving a sink transpiration term. The vegetation is modeled considering a fixed Leaf Area Index value (LAI) throughout the year.

In 2013, Lepore et al. [93] published a model called tRIBS-VEGGIE-Landslide, then modified by Arnone et al. [94] in 2016 to include probabilistic treatment of uncertainties. The methodology is based on a Triangular Irregular Network (TIN) mesh and accounts for post-failure movement by considering selected slope angles as thresholds for determining whether the landslide body will move down to a run-out distance. Landslide movement is assumed to follow the same flow directions evaluated by the tRIBS hydrological component (the deepest descend), which is based on a transient computation of infiltration and redistribution processes. The basin morphology can be modified by landslide deposits, with consequent impact on most of the simulated processes. Concerning vegetation, the model considers root mechanical reinforcement together with general soil cohesion, while the transpiration is estimated through the methodology provided by [95], which is based on vapor pressure deficit, soil moisture levels, rooting profile, leaf area, and available energy.

In 2014, Milledge et al. [96] pointed out that the existing models were highly computationally demanding and were not practically applicable across landscapes. The proposed model, called MD-STAB, simulates lateral resistances acting on landslide margins using earth pressure theory and the lateral root distribution, which is modeled as an exponential function of soil depth in a three-dimensional limit equilibrium force balance. This assumption allows the model to consider roots that laterally cross the shearing surfaces. The possibility of considering forces that act on the lateral sides of rigid blocks contradicts the infinite slope assumption, for which the inter-slice interactions are ignored. This model has also been extended, including the derivation of root reinforcement from field-measured forest stand characteristics [97]. The model ignores infiltration, soil suction, and capillary rises, and the groundwater level is steady and parallel to the slope surface.

In 2017, SOSlope was published by Cohen and Schwarz [98]. The model focuses on the effect of root and soil strength on slope stability in forests, accounting for single-tree contribution. The hydrological aspects are considered through a simplified and empirical dual-porosity model. Through this approach, SOSlope can approximate the water dynamics in both the soil matrix and the preferential flow domains. The model is suitable for assessing fundamental aspects such as the role of the forest structure (e.g., tree size, tree spacing), root distribution, and root mechanical properties on the triggering mechanisms of shallow landslides. SOSlope considers both lateral and basal root reinforcement and is able to reproduce the self-organized redistribution of forces on a slope during rainfall-triggered shallow landslides. The model is particularly suitable for highly detailed forest management purposes, and outputs can be used in GIS environments.

Lizàrraga and Buscarnera, in 2018, developed a model that uses suction-dependent plasticity and limit equilibrium theories to derive the slope Factor of Safety (FoS) in unsaturated soils [99,100]. The model considers mechanical aspects usually not included in other models, such as suction-hardening and liquefaction potential [101]. The aim is to simultaneously quantify the susceptibility to frictional slips and liquefaction-induced flow slides of shallow soil slopes in order to incorporate these considerations in regional-scale landslide hazard mapping. The underlying hydrology is a transient computation based on Richards' equation. Laboratory data are used to determine input parameters. The model application points out the strong interplay between infiltration mechanisms (i.e., slow or fast) and the mode and depth of slope instability. Vegetation effects are neglected.

In 2023, Abdollhai et al. [102] proposed a model specifically designed for the estimation of hillslope post-wildfire stability against rainfall-induced landslides. The proposed model constitutes a physically based yet practical slope stability framework capable of capturing the interplay of key driving factors and wildfire-induced alterations. The aim is to derive post-wildfire temporal changes in the Factor of Safety in response to rainfall. The transient hydrological analysis is conducted through an analytical approximation of 1D Richards' equation. The soil is considered isotropic and homogeneous. Changes in saturated soil water content are determined as a function of the soil elastic modulus, and the method proposed by [103] is then used to derive saturated water content in deformable soils. The post-wildfire effects on vegetation are quantified as a reduction in the transpiration rate due to the decrease in the number of roots. The infiltration capacity is also affected by wildfire, although in the first application, the authors decided not to account for it.

Figure 2 reports the normalized number of citations of the different considered models. The normalized number of citations is calculated as the ratio between the total number of citations (as derived by Google Scholar) and the number of years since publication (i.e., the difference between the current year—2024—and the year of publication). It can be seen that the most cited models are the Iverson model, SHALSTAB, and TRIGRS. Out of them, only the dSLAM model has a normalized citation number higher than 25. These four models can thus be considered as milestones of PBDDM knowledge and development over time.

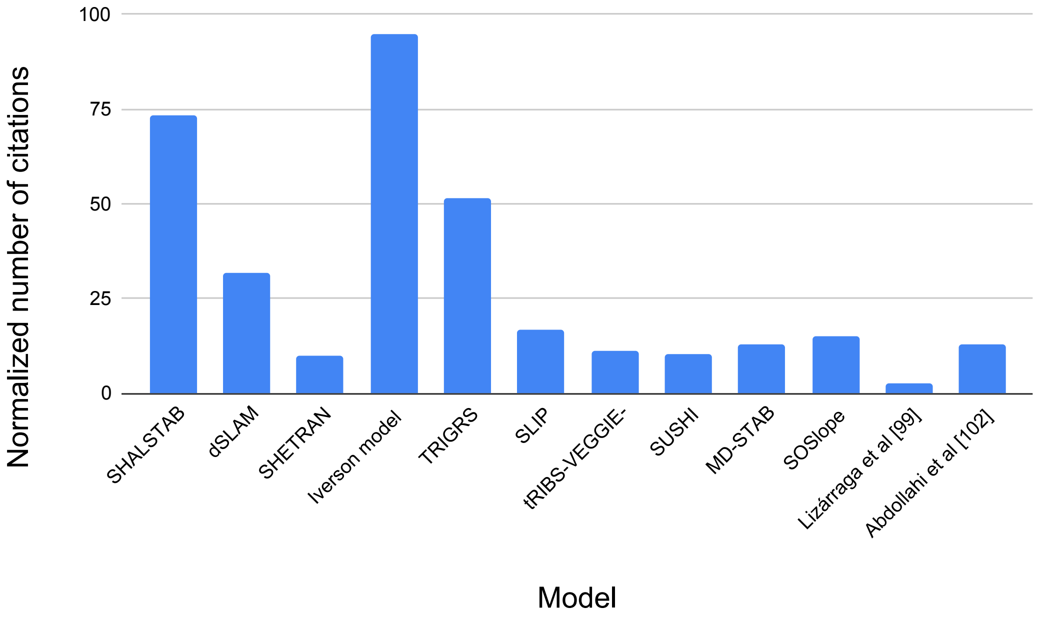

Figure 2. PBDDMs' normalized number of citations obtained (derived by Google Scholar). Models are in chronological order [99,102].

Table 1 summarizes some features of the 12 analyzed models. Notwithstanding the adoption of the infinite slope scheme, the hydrology modules, as highlighted, show that the use of the 1D Richards equation in deterministic models for shallow landslides is the most commonly used method.

Table 1. A summary of the 12 selected models. * The columns "Country of application" and "Real case study" refer to the related cited paper in this review. "WWM" stands for "Wu and Waldron root reinforcement model"; "AFBM" stands for "Analytical Fiber Bundle Model" for root reinforcement.

Model	**Country of Application ***	**Real Case Study**	**Hydrology**	**Vegetation**
SHALSTAB [75]	United States	Tennessee Valley (colluvial soils), Mettman Ridge (colluvial soils), and Split Creek (silty sands)	Derivation of the critical saturated soil height through TOPOG [76]	-
dSLAM [77]	United States	Cedar Creek basin, Oregon Coast Range—real landslides not well documented	Kinematic wave groundwater model [78]	Mechanical basal root reinforcement (WWM) as constant C_r
SHETRAN [79]	United Kingdom of Great Britain and Northern Ireland	Kirkton research catchment in Balquhidder, Scotland—real landslides not well documented	Lateral flow: Boussinesq equation; vertical flow: 1D Richards' equation; snowmelt	ET, interception, spatially variable land use
Iverson [82]	-	-	Reduced form of Richards' equation	-
TRIGRS [84]	-	-	Richards' equation per [85]	Extension by [86] comprises root cohesion and tree surcharge
SLIP [90]	Italy	Different areas of Italy	Increase in the saturated portion of the soil with rainfall	Extension by [91] comprises interception and root cohesion
SUSHI [92]	Italy	May 1998 Sarno landslides on pyroclastic soils from Campania (Italy)	1D Richards' equation (Hydro-SUSHI module)	ET as function of LAI, interception
tRIBS-VEGGIE-Landslide [93]	Puerto Rico	Luquillo forest (Puerto Rico)—no real landslides	1D Richards' equation	Hydrological effects: transpiration [95], evaporation reduction by canopies; vegetation variable with time, space, and depth (root distribution and root water uptake); root cohesion
MD-STAB [96]	United States	November 1996, Coos Bay, Mettnam ridge debris flow (gravelly sand)	Hydrostatic condition	Only mechanical reinforcement: basal and lateral, variable with depth
SOSlope [98]	-	-	Macropore water pressure and matrix suction	Mechanical lateral root reinforcement (RBM)
Lizárraga et al. [99]	Italy	May 1998 landslides on pyroclastic soils from Campania (Italy)	Authors used TRIGRS to compute hydrology	-
Abdollahi et al. [102]	United States	2019 Las Lomas watershed (California) shallow landslide (sandy loam and loam soils)	1D Richards' equation	ET Mechanical basal root reinforcement (AFBM)

5. Discussion and Conclusions

Based on the publishing date, several models were described in this narrative review, trying to draw a comprehensive overview of physically based deterministic models for shallow landslides.

By analyzing the literature, purely deterministic approaches appear to have recently become less explored than they were in recent decades. However, it appears clear that the attention given to the stabilizing effects of vegetation has grown over the years, as testified by the rising complexity involved when trying to assess these effects in a consistent way. Big challenges are still open about this topic since most of the root reinforcement models are based on variables and parameters not easily derivable such as root architecture or root diameters. Most of the root reinforcement models have a strong empirical basis that is not easily applicable at large scale, particularly when different kinds of plant species cohabit [104]. New paradigms and expedients should be explored for root effect quantification over large areas, and purely deterministic models can help in this task, as the processes and the related parameters can be quantified and studied singularly in a specific way. An example is provided by [105], where root-induced modifications of soil hydraulic properties (namely, the saturated hydraulic conductivity and the Soil Water Retention Curve) are included in a physically based model. From this point of view, involving vegetation as a dynamic variable, accounting for growing over time and the space of roots and canopy, based on real meteorological data and intraseasonal dynamic variability, can improve the performance of slope stability models [106,107].

More studies based on remote sensing linking canopy development with root architectures, rooting depth, and root spatial extensions could help in applying root development and reinforcement models over large areas, as vegetation parameters can be more easily derived when related to aboveground biomass [61]. On the contrary, non-invasive techniques for estimating roots' morphometric characteristics are still difficult to use.

An important aspect that constitutes a strong point since the first PBDMs were published is the interoperability with GIS environments. This aspect can help decision makers to cross different sources of information about territories. As it is difficult to have a unique, comprehensive PBDDM for all the processes that should be accounted for in landslide hazard assessment, overlaying different model outputs or different spatial information can provide more insights on a large scale. In fact, it should not be overlooked that PBDDMs pretend to give a single, specific output based on single, selected input parameters that may not represent reality, especially when large periods are considered. Comparing different sources of information through pre- or post-processing techniques and procedures may help raise the reliability of landslide risk assessment analyses, maintaining an acceptable operational time.

In distributed models, sensitivity analysis to different DEM (or mesh) spatial resolutions should be included. It is known that accuracy changes according to the considered spatial resolution, either when computing hydrological phenomena or slope stability, especially when this latter is based on the infinite slope method. This aspect appears not properly considered when new models are developed, although the problem is crucial for proper application of the model itself. In fact, spatial discretization of the domain can lead to different results.

Although rarely discussed when new models are developed, an important aspect for practical applications is the required running time of the different algorithms at the scale of interest. This problem is crucial, especially if the model should be used in early warning systems for civil protection purposes at the regional scale.

It is worth remembering that a very important expedient to overcome the spatial uncertainty of parameters is including probabilistic approaches in PBDMs, thus leading to hybrid solutions. There are several valid examples in the literature, such as SINMAP [108], GEOTOP-Fs [109], HIRESSS [110], SlideForMap [111], and FSLAM [112] These models include probabilistic assessments at different complexity rates, but in this paper, it was preferred to focus on physically based distributed models characterized by only deterministic input parameters and deterministic output results.

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