An advanced process-based distributed model for the investigation of rainfall-induced landslides: The effect of process representation and boundary conditions

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Abstract

Extreme rainfall events are the major driver of shallow landslide occurrences in mountainous and steep terrain regions around the world. Subsurface hydrology has a dominant role on the initiation of rainfall-induced shallow landslides, since changes in the soil water content affect significantly the soil shear strength. Rainfall infiltration produces an increase of soil water potential, which is followed by a rapid drop in apparent cohesion. Especially on steep slopes of shallow soils, this loss of shear strength can lead to failure even in unsaturated conditions before positive water pressures are developed. We present HYDROlis-thsis, a process-based model, fully distributed in space with fine time resolution, in order to investigate the interactions between surface and subsurface hydrology and shallow landslides initiation. Fundamental elements of the approach are the dependence of shear strength on the three-dimensional (3-D) field of soil water potential, as well as the temporal evolution of soil water potential during the wetting and drying phases. Specifically, 3-D variably saturated flow conditions, including soil hydraulic hysteresis and preferential flow phenomena, are simulated for the subsurface flow, coupled with a surface runoff routine based on the kinematic wave approximation. The geotechnical component of the model is based on a multidimensional limit equilibrium analysis, which takes into account the basic principles of unsaturated soil mechanics. A series of numerical simulations were carried out with various boundary conditions and using different hydrological and geotechnical components. Boundary conditions in terms of distributed soil depth were generated using both empirical and process-based models. The effect of including preferential flow and soil hydraulic hysteresis was tested together with the replacement of the infinite slope assumption with the multidimensional limit equilibrium analysis. The results show that boundary conditions play a crucial role in the model performance and that the introduced hydrological (preferential flow and soil hydraulic hysteresis) and geotechnical components (multidimensional limit equilibrium analysis) significantly improve predictive capabilities in the presented case study.

1. Introduction

Landslides pose a great threat to human life and can damage irreparably infrastructures and hamper the sustainable development of mountainous areas [Schuster and Highland, 2001; van Asch et al., 2007]. Infrequent meteorological or seismic events are the major triggering factors of many landslides, favoring destabilizing conditions on otherwise stable slopes or accelerating the failure of vulnerable slopes. Thus, external factors, such as rainstorms, snowmelt, earthquakes, and human disturbances tend to disrupt the equilibrium between soil strength, which keeps the slope stable, and gravitational forces, which tend to move the soil downslope.

Shallow landslides represent the major landform shaping process in steep terrain environments. These events are triggered mainly by the direct infiltration of intense rainfall or run-on (i.e., reinfiltration of excess runoff into downslope cells), which result in a decrease of the effective stress and apparent cohesion of the soil aggregate [Torres et al., 1998; Baum et al., 2005; Godt et al., 2009; Damiano and Olivares, 2009; Montgomery et al., 2009]. Key factors for a realistic prediction of rainfall-induced landslides are the capability to capture the interdependence of the soil shear strength with soil water potential and the time evolution of the soil water potential during infiltration and drying processes [Fredlund, 2000; Lu et al., 2010]. The nonunique relationship between soil water potential and water content, expressed by the soil water retention curves (SWRC),
results in different values of soil water potential and therefore of shear strength of soil for the same water content, depending on whether the soil is being wetted (during storms) or dried (during interstorm periods).

Assessment of landslide hazards has been carried out with a variety of modeling approaches, given the intrinsic limitations and costs connected with landslide monitoring. Models used for landslide hazard quantification and prediction can be grouped in two main categories: statistically based (probabilistic) models and process-based (mostly deterministic) models.

Statistically based models are mainly developed around the idea of multivariate correlations between mapped (observed) landslides and landscape attributes such as slope angle, curvature, aspect, soil, and bedrock properties. These models require a landslide inventory in order to determine the coefficients of mathematical expressions that relate a metric of landslide hazard to the aforementioned landscape attributes [Carrara et al., 1991; Guzzetti et al., 1999; van Westen et al., 2008; Nandi and Shakoor, 2010; von Ruette et al., 2011]. Multivariate correlation methods provide a concise summary of the numerous processes involved in shallow landslides and their complex interdependence and they are a very useful operational tool for mapping of regional landslide-prone areas. However, while they provide spatial distribution of landslide susceptibility to triggering phenomena, no information can be obtained about the time of occurrence and the temporal dynamics of landslide events. This approach is thus very sensitive to the data set used and only indirectly accounts for hydrological and soil mechanic processes.

Another approach, which ranks among the probabilistic methods, is the analysis of the intensity and duration of the rainfall events triggering landslides [Caine, 1980; Keefer et al., 1987; Guzzetti et al., 2007, 2008]. Critical rainfall threshold curves are built by taking into account all rainfall triggered landslide events of a given geographic area. These methods can be useful for assessment of regional landslide hazard and can be implemented in early warning systems. However, they cannot be used for the stability assessment of a particular slope because of their lack of any physical basis and they are unable to assess the return period of the landslide-triggering rainfall event, as done, for instance, by other studies [D’Odorico et al., 2005].

Differently from statistically based models, process-based models make use of the fundamental governing equations of subsurface hydrology and geotechnics. A detailed analysis requires the description of temporal evolution of the 3-D variably saturated water flow through soil combined with an analysis of stress distribution due to pore pressure spatiotemporal variability. Such an analysis would imply solving numerically the 3-D Richards’ equation [Richards, 1931; Hillel, 1998] for the subsurface water flow coupled with the equations of momentum and energy equilibrium for the soil skeleton and the use of a constitutive relation to represent the mechanical behavior of the soil [Fredlund and Rahardjo, 1993; Sheng et al., 2008]. The complexity and the excessive computational burden of such an analysis led many researchers to use simplified low-dimensional approaches. For instance, Montgomery and Dietrich [1994] used an approach which combines a steady state subsurface flow model [O’Loughlin, 1986] and a slope stability model based on the infinite slope equation [Lambe and Whitman, 1969]. Applications of their model [Montgomery and Sullivan, 1998; Dietrich and Bellugi, 2001; Gorsevski et al., 2006] show that it is quite efficient in reproducing the spatial variability of shallow landslide occurrences, when the topography has a dominant role on landslide initiation. Combination of the infinite slope equation with less simplified hydrological dynamics was also presented [Wu and Sidle, 1995; Casadei et al., 2003; Dhakal and Sidle, 2004; Rosso et al., 2006]. However, most of the aforementioned approaches rely on the restrictive assumption of a steady state subsurface flow, which can affect the predictive capability of the models both in terms of accuracy and timing of the prediction. In order to circumvent the steady state assumption, an approximated version of the Richards’ equation was presented [Iverson, 2000; Cordano and Rigon, 2008]. This approach has the shortcoming that saturated or nearly saturated conditions are assumed in order to derive the analytical solution of the Richards’ equation. For this reason, Crosta and Fratini [2003] coupled three different simplified hydrological components with the infinite slope equation and Baum et al. [2010] developed a model that combines a transient infiltration component with infinite slope analysis. The latter uses the method outlined by Iverson [2000] for saturated initial conditions and an analytical solution of the 1-D Richards’ equation [Srivastava and Yeh, 1991] for unsaturated initial conditions. Application of these models in catchments located in U.S. and Italy showed promising results [Salciarini et al., 2006; Godt et al., 2008; Salciarini et al., 2008; Sorbino et al., 2009; Liao et al., 2010]. However, all these models are sensitive to the choice of initial conditions, they solve the infiltration component only in one dimension and they assume infinite slope conditions. The issue of assuming
prescribed initial conditions was solved by running long-term simulations with hydrological models that together with profiles of soil water potential also compute factors of safety. This is the case of GEOtop-FS [Simoni et al., 2008], which combines the distributed hydrological model GEOtop [Rigon et al., 2006] with an infinite slope geotechnical model and of the model presented by Arnone et al. [2011], which combines infinite slope analysis with the hydrological model TRIBS [Ivanov et al., 2004a,b]. Alternative approaches to model landslides based on the fiber bundle concept were more recently presented [Cohen et al., 2009; Lehmann and Or, 2012; von Ruette et al., 2013]. According to their approach the soil columns, which constitute the discretized catchment, are connected with idealized bundles of fibers [Cohen et al., 2009]. During the wetting process, some of the fibers can exceed their strength and the remaining load is redistributed among the intact fibers, triggering possibly the failure of some other weak fibers. This gradual failure of the fibers can describe the progression of local failures which initiate a landslide. Although this approach succeeded in reproducing the size and frequency statistics of real landslide inventories, its simplistic hydrological component cannot capture the evolution of soil water potential history during infiltration and drying processes making realistic long-term simulations for landslide risk assessment difficult.

This study bridges gaps of the previous approaches presenting a process-based distributed model (HYDROlisthisis), characterized by high resolution in space and time, specifically aimed at the investigation of rainfall-induced landslides. The components of the model were chosen in such a way that an adequate level of detail is attained, while at the same time the computational burden is maintained acceptable for large-scale applications. Subsurface flows are calculated using a framework, which solves the 3-D variably saturated flow in a robust way, both in terms of accuracy and computational cost when compared to other state-of-the-art models [Anagnostopoulos and Burlando, 2012]. The most notable advantage of this framework is its suitability for massive parallel applications, which makes it efficient for the simulation of large catchments. A surface runoff routine, based on the kinematic wave approximation, is loosely coupled to the subsurface flow component. Special attention was given to the investigation of the role of the soil hydraulic hysteresis, a topic that was fundamentally neglected in previous landslide prediction research and that may play an important role in the hydrologic response of hillslopes [Ebel et al., 2010] and in the mechanics of shallow landslides [Ma et al., 2011]. A hysteresis module is incorporated in the subsurface flow computational framework allowing us to model the soil water potential changes and the subsequent modifications in soil shear strength between storm and interstorm periods with a more mechanistic approach. Preferential flow phenomena, which are attributed to the existence of macropores, fissures, cracks, and root holes, are taken into account in a simple way by incorporating a piecewise-continuous hydraulic conductivity function coupled with an approach for describing nonequilibrium flow, which characterizes nonmacroporous media. A root uptake function is specified in order to take into account the role of vegetation through the sink of soil moisture due to evapotranspiration at different depths. The geotechnical component is based on a multidimensional limit equilibrium analysis [Anagnostopoulos, 2014; Dietrich et al., 2007; Milledge et al., 2014], which takes into account the basic principles of unsaturated soil mechanics (supporting information, section 3). Such a method allows us to relax the very restrictive assumptions of infinite slope analysis, which is used by most of the approaches proposed in the literature. The following sections briefly describe the theoretical basis of the model and an application to a small catchment in Switzerland. The real-world case application allows to investigate the effect of the boundary conditions and of the different hydrological and geotechnical components on model performance. The proposed model (HYDROlisthisis) is implemented following a modular approach to increase incrementally the number of simulated processes. The main tools used for the assessment of model performance are accuracy statistics and Receiver Operating Characteristic (ROC) curve analysis [Begueria, 2006; Frattini et al., 2010].

2. Model Overview

HYDROlisthisis is a process-based fully distributed model designed for the investigation of the triggering mechanisms of shallow landslides based on long-term simulations. The model consists of coupled hydrological and geotechnical components. The hydrological component simulates 3-D variably saturated flow through soil, hysteretic behavior of the soil water retention curve (SWRC), surface runoff, evapotranspiration including topography-dependent solar radiation effects and a vertically distributed function of root water uptake. The geotechnical component, which is based on a multidimensional limit equilibrium analysis,
considers earth pressures acting on the lateral sides of the soil column. These forces are computed using the coefficients of active, passive, and at rest pressure derived for saturated and unsaturated conditions.

2.1. Spatial Representation

The model requires to represent catchment topography by a Digital Elevation Model (DEM) according to which the topographic surface is discretized with a regular square grid of cells with known elevation. Although a regular grid is not the most parsimonious computational choice its use has been common in many distributed hydrological simulations over the last two decades [Abbott et al., 1986; Quinn et al., 1991; Wigmosta et al., 1994; Fattichi et al., 2012] because of its simplicity and availability of algorithms to compute terrain related features such as slope, aspect, flow directions, and sky-view factor [Orlandini and Moretti, 2009; Schwanghart and Kuhn, 2010; Fattichi et al., 2012]. The DEM representation is used to define the surface of each element. For the computations of subsurface processes and slope stability, each soil column is subdivided into layers of variable thickness (Figure 1). A finer mesh resolution is adopted near the surface to better characterize infiltration/exfiltration zone dynamics, while a coarser mesh resolution is adopted at greater depths for computational efficiency.

2.2. Model Inputs

The model requires spatial distributed information of soil properties, soil depth, and land use types. Horizontal and vertical variability of soil properties can be specified to fully account for heterogeneities and anisotropy of soil. Distributed meteorological data, including precipitation, temperature, relative humidity, cloud transmissivity, and wind velocity are necessary inputs. Computation of slope stability requires the knowledge of soil friction angle, soil, and root cohesion and soil bulk density, which can be obtained by laboratory experiments or in situ measurements.

2.3. Boundary Conditions

The boundary condition at the bottom of the soil column, where the bedrock is located, can be either a no flow or a specified drainage condition, while fluxes at the soil surface can be either atmosphere or soil controlled. In the case of water flux into the soil, when the flux is lower than the infiltration capacity a Neumann-type (constant flux) boundary condition is imposed; when the flux is greater than the infiltration capacity a Dirichlet-type (constant head) boundary condition is imposed.

Soil depth and bedrock topography were found to be important factors driving hydrologic response and affecting slope stability [Lanni et al., 2013; Brönnimann et al., 2013]. The lack of reliable methodologies for...
Table 1. Parameters Used for the Computation of the Soil Depth Maps

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$ (m²/yr)</td>
<td>0.000268</td>
<td>Heimsath et al. [2001]</td>
</tr>
<tr>
<td>$z$ (m⁻¹)</td>
<td>3.0</td>
<td>Heimsath et al. [2001]</td>
</tr>
<tr>
<td>$\rho_s/\rho_r$</td>
<td>2.0</td>
<td>Dietrich et al. [1995]</td>
</tr>
<tr>
<td>$K_l$ (m²/yr)</td>
<td>0.0050</td>
<td>Dietrich et al. [1995]</td>
</tr>
<tr>
<td>$K_{sl}^{nl}$ (m²/yr)</td>
<td>0.0032</td>
<td>Roering et al. [1999]</td>
</tr>
<tr>
<td>$K_{sd}^{nl}$ (m²/yr)</td>
<td>$3.1 \times 10^{-6}$</td>
<td>Braun et al. [2001]</td>
</tr>
<tr>
<td>$S_c$</td>
<td>1.20</td>
<td>Roering et al. [1999]</td>
</tr>
</tbody>
</table>

* $P_0$ represents the soil production rate for exposed bedrock, $z$ the rate of soil production decay with depth, $\rho_s/\rho_r$ the bulk densities for soil and bedrock, $K_l$ the linear hillslope diffusivity for the linear diffusion case, $K_{sl}^{nl}$ the nonlinear hillslope diffusivity for the nonlinear slope dependent case and the nonlinear slope-depth-dependent case, $K_{sd}^{nl}$ the nonlinear hillslope diffusivity for the nonlinear slope-area-dependent case, and $S_c$ the tangent of the angle of stability.

In contrast to empirical models, process-based geomorphic modeling represents a more rigorous framework for the prediction of soil thickness. Most of these methods are based on the mass conservation equation for soil transport [Dietrich et al., 1995; Roering, 2008]. The magnitude of soil depth at a specific point within a basin depends on the dynamic equilibrium between the sediment transport rate and the weathering rate of the bedrock. Several equations were proposed for the sediment transport rate [Culling, 1960; Roering et al., 1999, 2001; Roering, 2008; Heimsath et al., 2005; Pelletier and Rasmussen, 2009] and the weathering rate of the bedrock [Heimsath et al., 1997; Dietrich et al., 1995; Furbish and Fagherazzi, 2001; Minasny and McBratney, 2006; Pelletier and Rasmussen, 2009]. Because these approaches provide a more realistic representation of soil formation processes we adopted them in this study. An extensive description of these methods is presented in the section 1 of the supporting information accompanying this article.

More specifically in this study, we produced several soil depth spatial distributed maps computed from four sediment transport laws (linear and nonlinear diffusion models, nonlinear slope dependent model, and nonlinear slope-dependent and area-dependent model) in the Napf catchment, for which a high-resolution (3 m × 3 m) DEM was available. The exponential soil production function by Heimsath et al. [1997] was finally selected because the catchment is situated in an alpine, humid environment. Since we do not have soil depth measurements to calibrate the parameters that the models require, they were assumed in a characteristic range from the literature (Table 1). Given the lack of direct observations, the suitability of the different soil depth models cannot be directly assessed and therefore the comparison among the four cases should be regarded only from a qualitative point of view.

The maps of soil depth distributions, obtained with the process-based geomorphic models, are presented in Figure 2. As expected, they consistently predict higher depths in the convergent valleys, where a thick colluvium tends to accumulate, while thinner soils occur at the narrow ridges. Linear and nonlinear models predict similar spatial patterns at gentle slopes. However, in steeper slopes soil thickness exhibits more spatial variability between the divide and the slope bottom when a nonlinear transport law is used. The area-dependent transport law creates a distinct spatial pattern of soil depth, which is heavily influenced by the rill and channel network of the catchment. This analysis highlights the importance that dominant soil production and erosion processes and relevant parameters have in reproducing plausible spatial distributions of soil depth in a given catchment.

### 3. Model Description

#### 3.1. Hydrological Component

This section describes briefly the various elements that build the hydrological component of HYDROlisthesis. The choice of each one of these elements is justified on the basis of conceptual arguments and computational efficiency. A full description of each component, including literature review and confirmation versus...
experimental and numerical data from the literature, can be found in section 2 of the supporting information and in Anagnostopoulos [2014].

3.1.1. Subsurface Flow
The subsurface variably saturated flow is simulated using a robust and computationally efficient numerical approach introduced by Anagnostopoulos and Burlando [2012]. This approach follows an object-oriented design that allows for a straightforward coding of the different processes thus leading to a flexible and reusable model structure. It is derived by taking into account the 3-D mass balance equation for each cell of the discretized space, considering both saturated and unsaturated conditions. For a rectangular spatial grid discretization, this formulation is similar to finite differences (FD) or finite volumes (FV) method schemes. But if an irregular grid is used there is a potential for modeling flow problems using a simple FD-like computational kernel based on a cell assembly similar to Finite Elements Method (FEM) analysis.

The model is flexible in the choice of soil water retention curves and internodal conductivity averaging schemes. The computational algorithm used to simulate the 3-D variably saturated flow was proved to be unconditionally stable and its accuracy and mass balance conservation was tested against well-established experimental data and analytical solutions of variably saturated flow problems [Anagnostopoulos and Burlando, 2012]. The most notable advantage of this approach is its massive parallel nature, which makes it very attractive for parallel computing. Along this direction, a parallel version of this algorithm was developed based on the CUDA™ prototype [NVIDIA, 2012], which is used in order to execute the algorithm over the numerous streaming multiprocessors of a NVIDIA™ graphics card.

3.1.2. Surface Flow and Coupling With the Subsurface Flow
Surface and subsurface flow components are inherently interconnected and their coupling is a numerical challenge [Sulis et al., 2010; Kollet and Maxwell, 2006; Camporese et al., 2010]. The component used to route water in the surface is based on the kinematic wave approximation and is loosely coupled (without an iterative procedure) to the subsurface flow component. The flow is conceptualized as sheet flow over a planar surface and the different flow characteristics of overland and channel flow are the result of the assignment.
of different Manning coefficients and different width for the channel rectangular cross section depending on the upslope contributing area of each cell [Montgomery and Foufoula-Georgiou, 1993; Orlandini, 2002]. The routing is done according to the topographic flow directions, which are computed from the Digital Elevation Model. A fine time step should be adopted in order to respect the Courant condition [Chanson, 2004; Hunter et al., 2005]. It should be noted that the time step of the surface routing is different from the adaptive-time step of the subsurface flow, which changes according to the convergence status of the subsurface flow solver [Anagnostopoulos and Burlando, 2012].

3.1.3. Soil Hydraulic Hysteresis
The nonunique relationship between pressure head and water content in the SWRC, known as hysteresis, is an important characteristic of unsaturated soils. The water content at a given time depends on the entire drying and wetting history of the soil [Haines, 1930]. Specifically, the water content at given soil water potential for a wetting curve is lower than that of a drying curve. Hysteresis can play a significant role in the dynamics of variably saturated regimes, influencing the hydrologic response of hillslopes [Montgomery et al., 1997; Torres et al., 1998; Montgomery et al., 2002; Ebel et al., 2010], soil shear strength, and the mechanics of shallow landslides [Ma et al., 2011], thus playing a role in the determination of the soil water content prior to the triggering of a landslide. Two main approaches are used for the description of hysteresis: conceptual and empirical models, since a fully physical-based representation is numerically unachievable. Conceptual models are based on the domain theory [Poulovassilis, 1962; Poulovassilis and Childs, 1971; Mualem, 1973, 1984] while empirical models [Scott et al., 1983; Kool and Parker, 1987; Parker and Lenhard, 1987; Huang et al., 2005] have simpler formulations and thus are more suitable for inclusion in numerical codes.

We implemented the empirical model of Huang et al. [2005] combined with the reversal point treatment of Werner and Lockington [2006] to deal with hysteresis in HYDROlisthesis (see supporting information, section 2.3). The use of an empirical model is imposed by the excessive amount of data (measurements of main wetting and drying curves) that conceptual models need for parameter estimation. These data are rarely available. Furthermore, more complex models require a computational effort that can represent a major limitation, especially for large-scale and long-term simulations.

3.1.4. Preferential Flow
Natural soils normally exhibit a high degree of heterogeneity due to macropores, fissures, cracks, and root holes, which are the result of soil forming processes and biological activity [Beven and Germann, 1982, 2013]. The existence of these structural heterogeneities result in the nonuniformity of the pressure potential making the infiltration front to move faster to greater depths using the macropore space without passing through the soil matrix. Flow in macropores is mainly driven by gravity in contrast to the flow in the soil matrix, which is also driven by capillary forces. Several studies showed that the contribution of preferential flow paths to hillslope water regime and catchment response can be substantial [Weiler and Naef, 2003a,b; Jones, 2010]. Shallow landsliding can be seriously affected by these preferential flow paths that can contribute to the buildup of pressure heads at highly risk soil zones, which would not otherwise develop through the normal infiltration process [Uchida et al., 2001; Uchida, 2004; Hencher, 2010; Krzeminska et al., 2013]. Hence, in order to better predict the timing and location of rainfall-induced soil slips, it can be important to account for preferential flow.

In HYDROlisthesis, preferential flow is assumed to occur only near saturation and is modeled by adopting a piecewise-continuous hydraulic conductivity function [Mohanty et al., 1997], which takes into account the sudden increase of hydraulic conductivity near saturation due to the activation of the macropores (see supporting information, section 2.4). Nonequilibrium flow that characterizes porous media with macropores is accounted for through the implementation of the simple approach presented by Ross and Smettem [2000].

3.1.5. Evapotranspiration and Root Water Uptake
Potential evapotranspiration is computed using the Priestley-Taylor equation [Priestley and Taylor, 1972], which does not require distributed wind speed and humidity data. Transpired water is taken up from the soil at different depths accounting for the root biomass distribution profile that defines the sink term in the mass balance equation [Collins and Bras, 2007; Ivanov et al., 2008].

3.2. Geotechnical Component: Multidimensional Limit Equilibrium Analysis
The geotechnical component of HYDROlisthesis is based on a multidimensional plastic limit equilibrium analysis [Anagnostopoulos, 2014; Dietrich et al., 2007; Milledge et al., 2014], which relies on the basic principles of saturated and unsaturated soil mechanics. The main advantage of such an approach is the relaxation
of several of the assumptions embedded in the infinite slope analysis. Infinite slope analysis is appropriate for long, continuous slopes, where the thickness of the unstable material is small compared to the overall length of the slope and the lateral boundary effects on the sliding material can be neglected. In a divergent or a convergent topography, where the soil depth may be heavily dependent on curvature, the previous assumptions do not generally hold.

The state of stress in unsaturated conditions is represented by the suction stress concept [Lu and Likos, 2004, 2006], which mimics the Terzaghi’s effective stress. All the faces of a given computational element are assumed to fail simultaneously with the shear strength of the material along the potential failure surfaces governed by the Mohr-Coulomb criterion. During failure, the assumption of HYDROlisthesis is that passive earth pressures develop at the downhill face of the cell, active earth pressures at the uphill face and earth pressures at rest at the lateral faces (Figure 3). The inclusion of these lateral, uphill, and downhill forces, including the additional cohesion due to roots, typically offers an extra resistance that increases the factor of safety in a given cell. Therefore, the multidimensional plastic limit equilibrium analysis allows to avoid the overestimation of landslide areas which is a typical problem of the infinite slope method. A complete description of the geotechnical component of the model can be found in section 3 of the supporting information and in Anagnostopoulos [2014].

3.3. Validation of the Model Components

Each model component was extensively tested along with their coupling against well-established test cases available in the literature. The subsurface flow component was tested against experimental data, analytical solutions, and numerical experiments. The results in terms of direct comparison with the experimental data and in terms of mass balance conservation can be found in Anagnostopoulos and Burlando [2012] and in Anagnostopoulos [2014], showing very good agreement in all cases. Furthermore, the coupling of surface and subsurface flow components was assessed using a sloping plane numerical experiment [Sulis et al., 2010], in which outputs of HYDROlisthesis were compared with the outputs of some well-known models in the literature. The results of this comparison can be found in section 5.1.1 of the supporting information as well as in Anagnostopoulos [2014]. The integration of the hysteresis and preferential flow in the subsurface flow component was tested using the experimental data of Indrawan et al. [2007] and the numerical results of Ross and Smettem [2000], respectively. The results of both tests confirm that the coupling of the subsurface flow component with the hysteresis and preferential flow components gives meaningful results. Finally, in the section 5 of this article and in section 5.3 of the supporting information we present the distributed hydrological and geotechnical results for the Napf catchment, which provide a validation of the model as a whole and show the potential of HYDROlisthesis to provide a series of distributed variables that can be used to better understand hydrological dynamics and landslide initiation in the catchment.
4. Case Study and Methodology

4.1. Description of the Study Area

HYDROlisthisis predictive ability was tested in an alpine catchment, located in the region near Napf mountain (1408 m asl) in central Switzerland at the border between canton Bern and Luzern (Figure 4). The area is highly vulnerable to shallow landslides and a serious rainfall event occurred on the 15–16 July 2002 destabilizing many slopes of the catchment. The Napf catchment covers an area of 2.48 km² with an elevation range of 900–1360 m. The main topographic characteristic is the presence of steep slopes, which favor the initiation of shallow landslides (Figure 5). In terms of land use 48% of the catchment is covered by forests, concentrated in the areas at high elevation, while the lower part of the catchment is covered by pastures (see supporting information, Figure S3). The vegetation parameters of the two dominant land use classes of the Napf catchment, used for the computation of transpiration, are shown in Table 3.

4.1.1. Geomorphology

The Napf catchment is located on the tectonic unit of the Molasse Basin, which consists of four different lithographic formations: Upper Freshwater Molasse, Upper Marine Molasse, Lower Freshwater Molasse, and Lower Marine Molasse. The main distinctive characteristic of the previous formations is the age of the deposited material. The two dominant formations in the catchment area are the Upper Freshwater Molasse and the Upper Marine Molasse having as main constituents interchanging layers of sandstone and marl. The area is characterized by narrow valleys and steep slopes, which are the result of fluvial and hillslope processes (e.g., erosion, landslides). The main soil types, which are the result of the degradation of the underlying bedrock, are classified as sandy loam and silty clay loam according to the USDA soil textural classification (see supporting information, Figure S3). The corresponding geotechnical (cohesion, friction angle) and soil hydraulic parameters (van Genuchten’s model parameters) are given in Table 2.

4.1.2. Meteorological Data

An extreme rainfall event occurred on the 15–16 July 2002 and caused a series of shallow landslides in the Napf catchment. It was characterized by a short duration (3 h) and high-rainfall depth (60 mm), which are estimated to correspond to a return period between 10 and 30 years [Rickli et al., 2004]. Meteorological data
were collected from the Napf weather station, which is located 5 km north-east from the catchment and is operated by MeteoSwiss (Swiss Federal Institute of Meteorology and Climate). The average value of precipitation of Napf station for the month of July is 236 mm while the average annual rainfall is 1736 mm (30 year period 1961–1990). Time series of other meteorological data such as air temperature and shortwave radiation were also accessible and were used for the computation of potential evapotranspiration.

Gridded daily precipitation at 2 × 2 km² resolution was also available as an elaborated product, RhiresD, of MeteoSwiss [Wüst et al., 2009]. Precipitation inputs to each computational element of the model were assigned based on the RhiresD product disaggregated from daily to hourly resolution. To this purpose, following Fatichi et al. [2015], the Napf station was used for defining the hourly partition of the daily aggregated precipitation contained in RhiresD grid cells that cover the Napf catchment (supporting information, Figure S4).

4.1.3. Landslide Inventory

The landslides induced by this event were documented by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) [Rickli et al., 2004]. Several criteria were used in order to identify shallow landslide occurrences. A minimum volume of 30 m³ and a maximum depth of 2 m was set as a threshold for the inclusion of a landslide in the inventory, while landslides near the stream network and man-made structures were excluded. The majority of the observed landslides were characterized as translational and only a small percentage of them were rotational. In all cases, the mobilized material was soil because of the limited depth of the failure surface, which did not pass through the bedrock. Several characteristics of the observed landslides, including position (measured by GPS), length, width, and topographic attributes (but not soil characteristics), were available from the landslide inventory.

4.2. Numerical Simulations

A DEM at high-spatial resolution (3 × 3 m², Figure 5) was used for the representation of the catchment topography. Each soil column was discretized using layers of variable thickness, which are finer near the soil surface and coarser at greater depths, whereas a no flow boundary condition was assumed at the bottom of each column. The total number of computational cells ranges between 2 × 10⁶ and 3 × 10⁶ depending on the soil depth map used. The soil type and land use map (supporting information, Figure S3), combined with the soil and land use properties of Tables 2 and 3, respectively, were used for all of
the simulations. The saturated hydraulic conductivity was assumed to decline with the soil depth, \( K_v(z) = K_v(0) e^{-0.0016z} \) (with \( z \) in mm) [Vertessy and Elsenbeer, 1999], and the soil anisotropy factor was assumed to be constant and equal to \( a = \frac{K_h}{K_v} = 100 \). No model calibration was sought in order to choose an optimal parameter set. We rather rely on the process-based nature of the model, the parameters of which represent physical quantities and/or properties of the system and, thus, tend to vary within narrower ranges. While we acknowledge that a precise characterization of soil hydraulic parameters at the appropriate scales still represents an important source of uncertainty, our main aim is to analyze in a comparative way the sensitivity of the model performance to the inclusion/exclusion of different processes and to the soil depth boundary conditions. Therefore, we believe that using a predefined realistic parameter set can be considered adequate.

Accordingly, in order to assess the performance of HYDROlisthisis, 11 numerical simulations were conducted using different boundary conditions and model components (Table 4). Specifically, the selection of the soil depth map designates the boundary conditions of the simulation. Three different soil depth maps were used (Simulations 1–8, Table 4). A constant depth throughout the catchment was also used for comparative purposes. The first soil depth map was computed with an empirical model, given by the equation \( \text{depth} = 5.0 \cdot e^{-1/40 \cdot \text{slope}} \). Then two process-based models with a linear and nonlinear diffusion sediment transport laws were used to compute the soil depth. The simulations with the different soil depth maps as boundary conditions were carried out using the 3-D variably saturated flow module (without hysteresis and preferential flow), while for the geotechnical component both infinite slope (Simulations 1–4) and multidimensional limit equilibrium analysis (Simulations 5–8) were used. The effect of including preferential flow and hysteresis components was tested with three additional simulations (Simulations 9–11, Table 4) using the multidimensional limit equilibrium analysis and the nonlinear diffusion soil depth map. In order to create realistic initial conditions for all of the aforementioned simulations, the model was run for one entire year prior to the event.

The decision to model preferential flow and hysteresis is based on the fact that the Napf catchment is mainly covered by forests and grassland, which suggests that there is an extensive root zone within the vadose zone, potentially creating a large network of preferential flow paths that can contribute to the buildup of pressure heads in specific areas [Weiler and Naef, 2003a; Uchida, 2004; Hencher, 2010; Jones, 2010]. Furthermore, experimental evidence from catchments with similar conditions [Montgomery et al., 1997; Torres et al., 1998; Montgomery et al., 2002; Ma et al., 2011] pointed at the control that soil hydraulic hysteresis phenomena can exert on pore water pressure development, thus suggesting the importance of investigating their potential influence on the numerical simulations of the Napf catchment.

### 4.3. Accuracy Statistics and ROC Curves

To assess the performance of the different model configurations, we used different types of metrics. The easiest way to assess the accuracy of a landslide model is a direct comparison of simulated and observed

| Table 3. Vegetation Parameters for the Two Land Use Classes, Which are Present at the Napf Catchment |
|---------------------------------|------------------|------------------|
| **Forest** | **Grass** |
| \( D_{50} \) (m) | \( D_{95} \) (m) | \( D_{95} \) (m) |
| 0.5 | 1.5 | 0.25 |
| \( D_{95} \) (m) | \( D_{95} \) (m) | \( D_{95} \) (m) |
| | | 0.55 |
| \( albedo \) | \( n \) (s m\(^{-1/3}\)) | \( p_{w} \) (MPa) |
| 0.23 | 0.015 | -3.0 |
| \( \rho_{w} \) (MPa) | \( \rho_{w} \) (MPa) | \( c_{\text{root}} \) (Pa) |
| -0.8 | -0.5 | 1000 |
| \( \rho_{w} \) (MPa) | \( \rho_{w} \) (MPa) | \( \rho_{w} \) (MPa) |
| | 5000 | |

| Table 4. Synopsis of the Numerical Simulations Used to Assess the Performance of HYDROlisthisis |
|---------------------------------|------------------|------------------|
| No. | Subsurface Flow | Geotechnics | Soil Depth Map |
| 1 | Simple 3-D variably saturated flow | Infinite slope analysis | Constant depth model |
| 2 | Simple 3-D variably saturated flow | Exponential model | Exponential model |
| 3 | Simple 3-D variably saturated flow | Linear diffusion model | Linear diffusion model |
| 4 | Simple 3-D variably saturated flow | Nonlinear diffusion model | Nonlinear diffusion model |
| 5 | Simple 3-D variably saturated flow | Multidimensional limit-equilibrium analysis | Constant depth model |
| 6 | Simple 3-D variably saturated flow | Exponential model | Exponential model |
| 7 | Simple 3-D variably saturated flow | Linear diffusion model | Linear diffusion model |
| 8 | Simple 3-D variably saturated flow | Nonlinear diffusion model | Nonlinear diffusion model |
| 9 | Preferential flow | Multidimensional limit-equilibrium analysis | Linear diffusion model |
| 10 | Preferential flow | Linear diffusion model | Linear diffusion model |
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5. Results

The performance of shallow landslide models is usually assessed according to their capability of reproducing the location and timing of past landslide occurrences. Obviously no model can achieve extremely accurate results due to the complex processes that are involved in landslide initiation and the imperfect knowledge of boundary conditions. Therefore, all the attempts are limited to achieve a certain degree of accuracy. As explained further above, the individual components of HYDROlisthisis were explicitly tested (see supporting information, section 5) using experimental and numerical case studies from the literature. In the following, the application of the model to the Napf catchment event is presented with the aim of better understand hydrological dynamics in the catchment. The distribution of the soil moisture averaged over the 1 year simulation period and the percentage of the time that cells are saturated are landslide maps. These indicate the presence/absence of landslide occurrences within a given area, which in model outputs are expressed by means of values of the factor of safety. This is, however, a continuous variable, which requires the definition of a preselected cutoff value for the classification of the model output in two distinct classes, stable and unstable cells. Cells with values of the factor of safety greater than the cutoff value, which in the limit equilibrium case takes the unitary value, are considered as stable, while values lower than the cutoff value are considered as unstable.

The comparison between observed data and models results leads to the construction of a confusion matrix (Table 5), which has four possible outcomes: (i) an observed landslide is modeled correctly (True Positive, TP), (ii) an observed landslide is not modeled at all (False Negative, FN), (iii) a modeled landslide does not coincide with an observed landslide (False Positive, FP), and (iv) a grid cell modeled as stable is correctly modeled outside an observed landslide (True Negative, TN). More in general, accuracy statistics involves the computation of various indices that are based on the metrics expressed by the confusion matrix [Begueria, 2006; Frattini et al., 2010]. The metrics computed in this study are indicated in Table 6.

These metrics are, however, strongly influenced by the arbitrary choice of the cutoff value. In order to circumvent this limitation, cutoff-independent methods have been developed. The Receiver Operating Characteristic curves, originally introduced for estimating the performance of radars during the Second World War, are the most popular cutoff-independent evaluation method used in the performance assessment of landslide models [Begueria, 2006; Fawcett, 2006; Frattini et al., 2008, 2010; Van Den Eeckhaut et al., 2006; Nefeslioglu et al., 2008]. A typical ROC curve consists of FP Rate (FPR) and TP Rate (TPR) pairs, which are computed from the respective confusion matrices for different cutoff values (Figure 6). A ROC curve shifted toward the upper-left corner indicates better model performance. The better the performance of the model the bigger is the Area Under the ROC Curve (AUC). The diagonal line in the ROC space represents a trivial model that randomly assigns safe and unsafe regions. A model is of practical interest only if it performs better than the trivial model.

5.1. Hydrology

HYDROlisthisis is structured to provide a series of distributed hydrological variables that can be used to better understand hydrological dynamics in the catchment. The distribution of the soil moisture averaged over the 1 year simulation period and the percentage of the time that cells are saturated are

<table>
<thead>
<tr>
<th>Table 5. Confusion Matrix Used for the Assessment of Model Performance</th>
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</thead>
<tbody>
<tr>
<td>Observed</td>
</tr>
<tr>
<td>Class 1 (+) Stable</td>
</tr>
<tr>
<td>Class 2 (–) Unstable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metric</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>True Positive Rate (TPR)</td>
<td>TP / (TP + FN)</td>
</tr>
<tr>
<td>False Positive Rate (FPR)</td>
<td>FP / (FP + TN)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>(TP + TN) / (P + N)</td>
</tr>
<tr>
<td>Precision</td>
<td>TP / (TP + FP)</td>
</tr>
<tr>
<td>True skill statistic</td>
<td>TPR – FPR</td>
</tr>
</tbody>
</table>

"TP, FP, TN, and FN represent true positives, false positives, true negatives, and false negatives, respectively."
shown in Figure 7. The major control of the spatial distribution of soil moisture is topography. The convergent parts of the catchment concentrate most of the soil moisture and the cells near the stream network are close to saturation or saturated for a large part of the year. Soil moisture redistribution toward the convergent parts of the catchment is the result of the relatively large simulated lateral fluxes (supporting information, Figure S15), which are draining the steep slopes. Note that the high-spatial resolution that we adopted emphasizes the sharp contrast between saturated areas near the river and the rest of the catchment.

Incoming shortwave radiation is computed as described in Anagnostopoulos [2014] and depends on the sky-view factor of each cell of the catchment. The spatial distribution of incoming shortwave radiation affects the distribution of potential evapotranspiration and simulated transpiration fluxes (see supporting information, Figure S16). Transpiration depends also on the vegetation type and water availability (see supporting information, Figure S17). Convergent areas of the catchment, which are close to saturation due to the water redistribution induced by the lateral fluxes, exhibit higher transpiration fluxes.

The spatial patterns of infiltration and runoff averaged over the 1 year simulation period are presented in Figure 8. Most of the precipitation is infiltrated except in the convergent parts of the catchment, the

Figure 6. A typical ROC curve. It consists of (FPR, TPR) pairs which are computed from the respective confusion matrices for different cutoff values and it indicates better model performance if it is shifted toward the top-left corner. The diagonal line represents a trivial model that randomly assigns safe and unsafe regions.

Figure 7. (a) Effective saturation averaged over the 1 year simulation period and (b) percentage of time that cells are saturated.
infiltration capacity of which is limited by the high soil moisture. In these areas, soil is near saturation for most of the year and the excess precipitation is routed as surface runoff to areas with greater infiltration capacity or to the streams. Most of the generated runoff reaches the streams and leaves the catchment in the form of streamflow, however areas where re-infiltration of run-on occurs can be identified throughout the catchment. These small areas are located in mild slopes and can be recognized because annual infiltration rate is greater than the annual precipitation. The cumulative annual discharge is 1372 mm (see supporting information, Figure S18). This value appears to be consistent with the climatology of the catchment but it cannot be confirmed by observations in the specific year because unfortunately there are no discharge measurements available at the outlet of the catchment.

5.2. Landslide Prediction

HYDROlithsis landslide prediction capability depends heavily on the used geotechnical and hydrological components as well as on the boundary conditions defined by the soil depth maps. The importance of the geotechnical component is highlighted in Figure 9, which shows the maps of the simulated and observed landslides for both infinite slope and multidimensional limit equilibrium analysis (MLEA) corresponding to simulations using the empirical exponential model for the soil depth map, and without using the preferential flow and the hysteresis component. The effect of the geotechnical component on model performance is very significant. The infinite slope analysis scheme tends to considerably overestimate the simulated cells with landslides. In contrast, the MLEA simulation tends to mobilize a significantly smaller area. The destabilized area is 20.27% of the total area for the infinite slope analysis case, whereas the MLEA destabilizes only 6.67% of the area exhibiting at the same time a better performance (Table 7). Maps of the critical pressure head and depth of the cells with the minimum factor of safety are presented in Figure 10. Landslides seem to occur both in saturated and unsaturated conditions and the critical depth ranges between 0.2 and 1.2 m, which is a very reasonable range for shallow landslides.

Accuracy statistics (Table 7) and ROC curve analysis (Figures 11 and 12) were used to evaluate the effect of the various boundary conditions and model components on model performance. ROC curves are shown for simulations with different boundary conditions (i.e., different soil depth maps) and geotechnical schemes (Figure 11), which were carried out to in order to highlight the influence of soil depth on model performance. The selection of the soil depth map affects clearly the model predictive ability (Figure 11). Having as a reference point the constant depth map, which yields the worse model performance, the predictive ability of the model is getting better using the empirical exponential soil depth map and substantially improves when the two process-based linear and nonlinear diffusion soil depth maps are used.

Figure 8. (a) Infiltration and (b) runoff averaged over the 1 year simulation period.
The simulations with the two different geotechnical components, the infinite slope and the MLEA analysis, respectively, yield two distinct sets of curves (Figure 11). It is clear that MLEA scheme outperforms the infinite slope one for all the boundary conditions scenarios we used. This is also depicted on the computation of the statistics of accuracy metrics (Table 7). Efficiency, precision, and true skill statistics are considerably higher for the MLEA based model, while the sliding area (i.e., the fraction of the catchment area that is predicted as unstable) is much lower compared to infinite slope analysis, thus indicating that MLEA is significantly reducing false positives.

These results were complemented by a simple sensitivity analysis that was carried out in order to investigate how a variation of the geotechnical parameters can affect model performance, and to compare these results with those of the other cases. High and low values were selected for cohesion and friction angle of the silty clay loam, which is the soil type where all the landslide occurrences are located. Upper values of 8500 Pa and 27° and lower values of 2500 Pa and 17° were selected for cohesion and friction angle respectively. The results shown in Figure 11 show that the variation of the geotechnical parameters does not significantly affect the performance of the model. The latter is definitely much more influenced by the choice of the geotechnical component and by the boundary conditions (Figure 11).

Using the ROC curve analysis, we also investigated the effect of the different hydrological components on model performance (Figure 12). For these simulations, we used the nonlinear diffusion soil depth map as boundary condition and the MLEA scheme as geotechnical component. The use of the hysteresis component offers a marginal improvement of the model performance. The inclusion of the preferential flow component, conversely, has a greater effect on model performance and plays a significant role in the distribution of pressure head along the soil profiles throughout the catchment as it can be seen in Figure 13, in which three representative pressure head profiles are shown during the 3 h event of 15–16 July 2002 with and without the preferential flow component. The inclusion of both hysteresis and preferential flow yields the best results, even if the improvement due to the inclusion of the hysteresis component is considerably less important.

6. Discussion
We believe that HYDROlisthisis provides a substantial advancement over the majority of
existing models to simulate shallow landslides. The more detailed representation of hydrological and geotechnical processes that characterize HYDROlisthesis substantially improve the performance of the model showing that a higher complexity of the hydrological and geotechnical components can indeed result in improved model predictions, at least in the presented case study. This is clearly summarized by the results of all the performed simulations illustrated in Figure 14, where the Area Under the Curve (AUC) metric shows that larger AUC—indicating better model performance—are associated with the more complex model configurations. However, the increase of the predictive ability provided by the considered components is different. Including preferential flow leads to considerably better model performance, while the role of soil hydraulic hysteresis is, at least in this case study, rather minor (Figure 12).

The considerable increase in performance when the infinite slope analysis is replaced by the MLEA is the most evident result (Figure 11). The basic assumptions behind infinite slope analysis do not hold true for catchments with complex topography and resolved at fine spatial scales (<25 m). MLEA instead takes into account the lateral soil and root cohesion forces that offer an extra stabilization effect reducing considerably the number of cells where a landslide is predicted, thus reducing false positives. We acknowledge that the MLEA as applied in this study is influenced by the adopted spatial resolution. However, alternatives solutions that account for landslide propagation are currently computationally expensive due to high number of combinations of contiguous cells that need to be explored in order to eliminate the dependence on the cell size [Dietrich et al., 2007; Bellugi...
et al., 2015]. The resolution adopted in this study (3 × 3 m) should provide, however, a good compromise with respect to the small scales at which triggering fronts of shallow landslides are observed and large scales that characterize the fully developed mass movement [Askarinejad, 2013].

Model performance is also improved when a uniform soil depth or the soil depth map obtained with an empirical exponential function are substituted with soil depth maps derived with a process-based approach (linear diffusion and nonlinear diffusion models). This finding underlines how the choice of boundary conditions, in this case the spatial organization of soil depth, plays a crucial role on model predictive ability. It reinforces recent findings [Lanni et al., 2013; Brönnimann et al., 2013] and suggests that soil depth influences both hydrological processes and lateral earth pressures (when the MLEA is used). Given the absence of distributed soil depth measurements for the considered case study, we could not verify how realistic and accurate are the maps computed with literature parameters. Nonetheless, we clearly show that the selection of an appropriate method to compute a soil depth map is an essential and delicate step for modeling shallow landslides and assessing landslide

Figure 12. ROC curves for all the simulations performed using different hydrological components.

Figure 13. Three representative pressure head profiles showing the water potential evolution during the 3 h event of 15–16 July 2002, with and without using the preferential flow component.
Related risk on a catchment basis. Its importance is comparable to the choice of the geotechnical and hydrological components and parameters. Despite the results of the application of HYDROlisthisis to the Napf catchment demonstrated an improvement in landslide prediction when compared to simpler approaches, there are a series of considerations that need to be made for future applications of HYDROlisthisis or models with a similar process-based structure. The rationale behind including many different components and additional complexity is, on the one hand, to include current knowledge in the triggering mechanisms of rainfall-induced landslides and to evaluate the importance of different physical processes. On the other hand, the continuous in space-time nature of the model is expected to allow the evaluation of long-term landslide risk, thus accounting for the effect of the hydrological history of slopes at the watershed scale. The introduction of additional processes decreases the number of simplifying assumptions but inevitably increases the number of parameters that are needed for the simulations. The process-based nature of the model implies that parameters are characterized by a rather narrow range of variability because they represent physical quantities/properties of the system. Nonetheless, the fact that many of these parameters cannot be easily and routinely measured in a distributed way and at the appropriate scales (e.g., soil depth, soil hydraulic properties) still represents a major hurdle for operational applications. In the specific case, we used all the available information to select a specific set of soil hydraulic parameters; however, we cannot dismiss the possibility that an alternative but still plausible parameter selection could have led to different results. In other words, the limited knowledge of the real boundary conditions can seriously affect practical and operational purposes. However, even in this respect, process-based models can still be very useful for performing virtual numerical experiments and quantitative analyses, for instance sensitivity analyses to poorly characterized parameters that can in turn guide targeted field studies. In this framework, HYDROlisthisis can be regarded as one of the most advanced model for the completeness of the included hydrological and geotechnical components, even though it is still based on a continuum representation of the mechanical processes and does not account for abrupt failures and fracture theory [Cohen et al., 2009; Lehmann and Or, 2012]. Furthermore, while the use of simplified or statistical models can be preferred for their small data requirements and parametrization effort, there are many cases where complexity is unavoidable. This is the case when the objective is not only to map landslide-prone areas at the regional scale, but also to elucidate the possible driving processes and mechanisms involved in landslide initiation. In addition, the investigation of the temporal dimension of the problem—made possible through continuous long-term simulations—is likely to contribute to a more realistic assessment of landslide risk for a given basin or area. Finally, process-based models additionally offer transferability across places and spatial scales, which would be impossible otherwise.

In summary, despite some recognized limitations and current uncertainties in delineating correct boundary conditions and spatial variability of parameters, this study offer support to the idea that typically neglected components such as preferential flow, soil hydraulic hysteresis, MLEA, and more realistic soil depth distribution have a paramount role on simulating shallow landslides. Further applications of the model to

Figure 14. Area under the ROC curve for all the simulation using different boundary conditions, geotechnical, and hydrological components.
catchments differing in size and climate characteristics are recommended to verify the generality of the above statements. Similarly, additional important improvements can be obtained by longer (multiyear) simulations and by approaching the problem in a stochastic framework, where uncertainty in the inputs, boundary conditions, and model parameters is fully explored.

7. Conclusions

It is widely acknowledged that hydrological conditions exert an important control on the initiation of landslides. HYDROlisthisis is a process-based distributed model built to shed light on the triggering mechanisms of rainfall-induced landslides and, thus, to overcome, at least partly, the limitations of existing techniques. Undoubtedly, a key element for the successful prediction of rainfall-induced landslides is the 3-D evolution of soil suction during the infiltration and drying processes and the resulting changes in soil shear strength. The presented model makes use of the fundamental principles of subsurface hydrology and geotechnics and includes hydrological and geotechnical components rarely considered in the existing landslide models (Milledge et al., 2014; Bellugi et al., 2015). The model succeeds in retaining an adequate level of detail without sacrificing the computational efficiency and robustness, thus being suitable for basin scale and long-term investigations. HYDROlisthisis produces a rich amount of distributed hydrological variables (soil moisture, lateral water flow, infiltration, streamflow, etc.), which are essential for a better investigation and understanding of the triggering mechanisms of landslides. Special attention was devoted to the model design and development following the concepts of object-oriented programming and taking advantage of the computational boost available through parallel computing. In this respect the use of the CUDA architecture allows to exploit the computational power of the increasingly performing graphics cards. This allowed the development and implementation in HYDROlisthisis of a new computational framework for the simulation of variably saturated flow (Anagnostopoulos and Burlando, 2012). The most notable advantage of this new framework is that the computational cost of the method is linearly connected to the number of the cells favoring the design and development of parallel code. Its robustness and accuracy were successfully verified against several case studies from the literature (Anagnostopoulos and Burlando, 2012).

A soil hydraulic hysteresis module was implemented in the hydrological component of HYDROlisthisis in order to simulate more efficiently the temporal evolution of water pressure heads and the corresponding soil shear strength fluctuations during the wetting and drying periods. The role of soil hydraulic hysteresis in the triggering of rainfall-induced landslides and generally in distributed hydrological modeling is a topic that did not receive enough attention, although it can improve the characterization of initial conditions, particularly in long-term simulations.

Preferential flow modeling was another element included in the hydrological component of HYDROlisthisis in order to take into account preferential paths in natural soils, which is an important aspect of soil hydrology especially in the upper layers of the soil profile. Although there is strong experimental evidence that preferential flow paths can contribute to the creation of high risk landslide zones (Uchida et al., 2001; Uchida, 2004; Hencher, 2010), the role of preferential flow in the initiation of landslide events was only rarely investigated in previous modeling applications (Krzeminska et al., 2013).

A new geotechnical component, which is based on a three-dimensional plastic limit equilibrium analysis, was also derived and implemented in HYDROlisthisis. To this purpose, we used the effective stress concept (Lu et al., 2010). This method makes possible the relaxation of many of the restrictions of infinite slope analysis, which is the method adopted by almost all of the previous modeling applications. Using this new geotechnical component a more realistic landslide risk assessment is achieved, especially in areas of divergent or convergent topology, where the neglect of the cell lateral boundary effects is an unrealistic assumption.

The HYDROlisthisis model was applied to a catchment in Switzerland, which is historically prone to rainfall-induced landslides. We performed several model simulations, to assess differences in the performance when new components are introduced. We also used to this purpose different boundary conditions corresponding to various soil depth maps. We analyzed in detail the effect of preferential flow, soil hydraulic hysteresis, and multidimensional limit equilibrium analysis, which are the key novel characteristics of HYDROlisthisis. Several conclusions were drawn on the importance of the different model components. The principal findings of this analysis are summarized as follows.
The distribution of soil depth within a catchment plays a very important role on model performance. The results show that soil depth maps derived from process-based models describe better the boundary conditions than maps derived from an exponential or constant depth empirical model, and substantially improve the overall HYDROlisthisis performance. The sensitivity analysis reveals that the choice of the soil depth map affects model performance much more than imprecise knowledge of geotechnical parameters.

Multidimensional limit equilibrium analysis offers a great improvement over the widely used infinite slope analysis, the assumptions of which fail for simulations at high-spatial resolution in catchments with complex topography. The consideration of lateral soil elements and root cohesion offers extra stabilization forces to the cells, which result in a considerable reduction of the destabilized area of the catchment (3 times less).

Preferential flow and soil hydraulic hysteresis components also offer enhancements of HYDROlisthisis predictive ability. Results from the application to the selected event indicate that preferential flow has a greater influence on model performance than soil hydraulic hysteresis and affects considerably the pressure head distribution along the soil profiles throughout the catchment. In the Nafp catchment, HYDROlisthisis yields the best results when both soil hydraulic hysterisis and preferential flow are explicitly accounted for in combination with multidimensional limit equilibrium analysis. This demonstrates that considering typically neglected processes and a careful implementation of the boundary conditions can lead to improve landslide predictions.

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References


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NVIDIA (2012), CUDA C Programming Guide. [Available at http://docs.nvidia.com/]


Richards, L. (1931), Capillary conduction of liquids through porous mediums, Physics, 1, 318–333.


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