Environmental Modelling & Software 105 (2018) 1–16

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Integration of two-phase solid fluid equations in a catchment model for flashfloods, debris flows and shallow slope failures

B. Bout [a], [*], L. Lombardo [b], [c], [d], C.J. van Westen [a], V.G. Jetten [a]

[a] University Twente, Faculty of Geo-Information Science and Earth Observation (ITC), The Netherlands
[b] CEMSE Division, King Abdullah University of Science and Technology, Thuwal, Jeddah, Saudi Arabia
[c] PSE Division, King Abdullah University of Science and Technology, Thuwal, Jeddah, Saudi Arabia
[d] Department of Geosciences, Tübingen University, Tübingen, Germany

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form
20 March 2018
Accepted 23 March 2018

Keywords:
Spatial numerical modeling
Physically-based modeling
Flash floods
Shallow landslides
Debris flow
OpenLISEM

ABSTRACT

An integrated, modeling method for shallow landslides, debris flows and catchment hydrology is developed and presented in this paper. Existing two-phase debris flow equations and an adaptation on the infinite slope method are coupled with a full hydrological catchment model. We test the approach on the 4 km^2 Scaletta catchment, North-Eastern Sicily, where the 1-10-2009 convective storm caused debris flooding after 395 shallow landslides. Validation is done based on the landslide inventory and photographic evidence from the days after the event. Results show that the model can recreate the impact of both shallow landslides, debris flow runout, and debris floods with acceptable accuracy (91 percent inventory overlap with a 0.22 Cohens Kappa). General patterns in slope failure and runout are well-predicted, leading to a fully physically based prediction of rainfall induced debris flood behavior in the downstream areas, such as the creation of a debris fan at the coastal outlet.

1. Introduction

Shallow landslides are frequently occurring natural hazards, which may be triggered by extreme rainfall events, snow melt and earthquakes, and are characterized by a relatively small and shallow failure plane. Because the triggering of these landslides takes place predominantly during intense precipitation, the sliding soil, mixed with water, may evolve into debris flows, that have a devastating impact on villages, roads and other elements-at-risk. In order to understand and predict the behavior of debris flows, numerical models have been frequently used as both predictive and analytical tools. However, in current modeling approaches, processes that relate to debris flows, such as hydrology, shallow landslides and runout, are mostly simulated separately.

The simulation of debris flow dynamics is performed by debris flow runout models. These models use (semi-) physically-based estimations of the internal forces in debris flows to numerically calculate flow depths, velocities and routing based on topography and surface properties. A large number of runout models exist, varying both in modeling approach and used equations. Both one-dimensional channel-simulations, full depth-varied grid methods and Smooth Particle Hydrodynamics have been used to estimate debris flow behavior (Pudasaini, 2012; Huang et al., 2012). Other implementations, such as SCIDDICA S4c (D'Ambrosio et al., 2007), approximate debris flow behavior by means of cellular automata. Depth averaged equations are used in a large variety of two-dimensional models (Scheidl et al., 2013). A variety of depth averaged finite-element models, such as Ramms (Bartelt et al., 2013), Flo-2D (O'Brien, 2006) and use a fixed volume as input for the debris flow. Others, such as MassMove2D (Beguería et al., 2009), Debris Mobility Model (Kwan and Sun, 2006) and AschFlow (Luna et al., 2015), include entrainment and the addition of water flow.

The processes that cause shallow slope failures and their transition into debris flows are often also numerically simulated, although empirical methods are also often used. Hydrological models are frequently used to predict behavior of both surface and sub-surface hydrological processes. Through flow simulations, overland flow and the resulting infiltration patterns can be estimated (van Beek, 2003). Similar to debris flows, hydrology is simulated in spatially distributed numerical models such as GEOtop (Rigon et al., 2006). From the available catchment-scale

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[*] Corresponding author. University Twente, Faculty of Geo-Information Science and Earth Observation (ITC), The Netherlands.
E-mail address: bastianvandenbout@gmail.com (B. Bout).

https://doi.org/10.1016/j.envsoft.2018.03.017
1364-8152/

hydrological models, some are open-source, such as JGrass-NewAge (Formetta et al., 2014). Furthermore, hydrological models can predict soil water flow, and the resulting soil water has been used as a direct proxy for slope stability (van Asch et al., 1999). Slope stability models are used to predict both volume and timing of shallow landslides. A variety of regional slope stability models have been developed based on the limit equilibrium, which uses finite elements to estimate the forces acting on a failure plane. The infinite slope models furthermore assume that inter-cell forces can be neglected, and structural finite elements are used to calculate the local Factor of Safety (SoF). This resulting FoS, which depends on a soil description and soil water behavior, are successfully applied as a prediction for slope failure in a variety of regions around the world (Van Beek & Van Asch, 2004; Kuriakose et al., 2009a,b; Mergili et al., 2014a). Recent approaches, such as the method by Mergili et al. (2014b), are focused on providing estimation of failure probability by using more accurate estimates of stability based on three dimensional rotational slip surface analysis following Xie et al. (2004). A similar approach, but instead using Bishops Simplified method, is used in Scoops3D to find approximate failure volumes for rotational slides (Reid et al., 2015). Specialized models are thus frequently used to investigate shallow landslides and debris flows.

Despite all the currently available models, combined approaches to debris flow initiation and runout are scarce. Empirical initiation and runout models, such as Flow-R combine landslide failure criteria and possible flow patterns to create susceptibility maps (Horton et al., 2013). However, their method is semi-physical in nature and doesn't include failure volumes, rheology nor entrainment. Fan et al. (2017) introduced an innovative way to approach catchment-scale landslide modeling. For their approach, the failure plane is static, and defined as the lithic contact. Furthermore, hydrological processes are still generally neglected, and the stability and runout models are coupled through a one-way link. Finally, Mergili et al. (2011), provided a more in-depth analysis of the what sort of approaches to integrated simulation of debris flows could be taken. Their analysis covered wetting front based slope stability and failure in a small catchment, and simulation of erosion by runoff, both leading to debris flow runout. The authors solved runout by using a two-parameter semi-deterministic frictional model routed over the terrain. While the currently available models provide useful investigative and predictive tools, integrated simulations using fully physically based descriptions of all related processes could still increase understanding and usability of numerical simulations.

Most existing hydrological, slope stability and debris flow runout models focus on specific processes without the possibility of interactions or feedbacks between the processes. However, in practice processes such as slope failure, flow directions, infiltration and flow properties such as viscosity all influence each other. Flooding and debris flows in particular have frequent interactions due to their common metrological trigger. In many cases, interactions between debris flows and flooding substantially influence the behavior of both processes. When these phenomena are neglected, the predictive power of models is substantially limited. A major example of these interactions are blocked rivers or drainage channels by debris flows, resulted in alternating waves of debris flows and flooding (Tang et al., 2012; Adegbe et al., 2013; Luna et al., 2014). Debris flows can also interact with overland flow causing decreased viscosity. Nguyen et al. (2013) found that dilution of a debris flow by directed overland flow caused runout over a larger area, including the streets of a nearby village. In order to increase the understanding of hydrology, shallow landslides and the debris flows that are caused by these, a holistic and integrated approach should be considered.

A common obstacle in the modeling and prediction of shallow landslides and debris flows is the accuracy of input data and parameters (van Westen et al., 2006; 2008; Mergili et al., 2011; Nikolopoulos et al., 2015). Physically-based models are often limited in accuracy by the spatial resolution of elevation and soil data. Slope instability caused by structural weakness provides a particularly large challenge for current modeling methods since the sub-surface structure is generally unknown over larger areas (van Westen et al., 2006). The availability of accurate soil data, both in terms of their spatial variation in type and thickness, and associated geotechnical and hydrological properties can be a major limiting factor. An integrated approach to model slope failure, debris flows and hydrology could only be used when sufficient input data is available. In the past decade however, the data problem has become less severe due to increasing availability of detailed data. High-resolution elevation products such as Lidar DEMs have become widely available (Tarolli, 2014). Major improvements have been made in estimating soil data from various sources such as national soil maps and satellite data (Hengl et al., 2017). Furthermore, soil depth estimations based on statistical correlation of topographical parameters have shown increasing accuracy. Lastly, when slope failure is not estimated an initial volume is often used for runout calculation. In this case, the influence of hydrology and other processes on debris flow runout is still neglected. Thus, an integrated model can provide further improvements compared to traditional methods even when insufficient data is available for prediction of slope failure.

The objective of this paper is to develop and test an integrated model to analyze the influence of rainfall-triggered shallow landslides and debris flows in a hydrological catchment model. Slope failures are estimated by using an adaptation on the classic infinite slope stability method. To simulate debris flows, the two-phase generalized debris flow equations by Pudasaini (2012) are implemented. These methods are included in the OpenLISEM model (Bout and Jetten, 2018). In order to test the performance of the aforementioned model, we attempt to model the impact of a convective storm that hit the south-eastern coast of Sicily in 2009 (Lombardo et al., 2015, 2018a). Finally, several alternatives of the developed modeling method are tested and a sensitivity analysis is performed.

2. Materials and methods

2.1. Schematic model description

Combining the discussed methods, we created a modeling method that incorporates both hydrological processes such as rainfall, interception, infiltration, flow, and morphological processes such as shallow landslides, slope failure, and landslide runout. A simplified flow chart for the final model is shown in Fig. 1. When sediment components are absent, the model reduces to a fully functioning hydrological catchment model.

2.2. Model basis

In order to integrate the occurrence of shallow landslides, debris flows and flash flooding within a single model, we used the Open Source Limburg Soil Erosion Model (OpenLISEM) as a basis. OpenLISEM is a physically-based numerical model with the purpose of event-based runoff, flooding and erosion modeling on a catchment scale. LISEM is fully spatially distributed and uses a topography-following grid to solve both cell specific processes, and the differential equations governing flow.

The OpenLISEM model implements multiple types of infiltration models such as Smith and Parlange (1978) and the SWATRE full vertical soil water balance model (Bastiaanssen et al., 1996). The