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Physically based modelling of soil erosion induced by rainfall in small mountain basins

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ABSTRACT

In coarse-grained, unsaturated soils, heavy rainstorms may cause either shallow landslides or superficial soil erosion. The triggering of both of these phenomena is related to infiltration, runoff and overland flow, which are key processes requiring investigation. In particular, the quantitative estimates of the sediment yield at the outlet of mountain basins requires suitable physically based modelling. In this paper, the available approaches to soil erosion analysis are first reviewed, and the capabilities and limitations of a physically based model are then evaluated through a case study of two small mountain basins. The results obtained are in good agreement with those in the literature and with specific field data from a test area. Specifically, for distinct, realistic rainfall scenarios, soil suction is found to be a key factor in the spatial–temporal evolution of infiltration and runoff inside a mountain basin, and soil suction and rainfall intensity greatly influence the total peak discharge of water and sediments. The maximum volumetric concentration of sediments transported by water to the outlet of a mountain basin is found to be primarily related to the basin's specific morphometry.

1. Introduction

Rainfall increases the pore water pressure or soil water content of unsaturated shallow soil deposits, and may induce different types of flow-like mass movements (Hutchinson, 2004), including hyperconcentrated flows (Costa, 1988; Coussot and Meunier, 1996) and first-time shallow slides that turn into debris flows, the latter defined as “a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel” (Hungr et al., 2001, 2012). Hyperconcentrated flows (Coussot and Meunier, 1996) transport a smaller amount of solids, but the volumetric concentration of sediments still exceeds 20%. The run-out distances and consequences associated with debris flows and hyperconcentrated flows differ greatly (Cascini et al., 2011a). Thus, discriminating between these distinct flow types is fundamental to an accurate assessment of source and propagation areas and to forecasting the potential damage to urban areas located near the outlet of a mountain basin. It has particular relevance for coastal mountain basins where urban settlements are often confined to alluvial fans or debris deposits.

First-time slides typically involve a soil mass that is several metres thick through distinct potential triggering mechanisms (Cascini et al., 2008), related to the specific hydraulic and static boundary conditions at the ground surface or bedrock contact area (Cascini et al., 2010, 2012). Failure can be localised or diffuse, as observed in experimental tests and reproduced in numerical models (Cascini et al., 2013). The post-failure acceleration of a mobilised mass depends on the slope geometry, stratigraphy, soil mechanical behaviour and boundary conditions (Cascini et al., 2013). A key issue in both failure and post-failure slope analysis is the accurate analysis of transient pore water pressure in saturated and unsaturated conditions. It is generally agreed in the literature that the solution of the Richards equation (Richards, 1931) is an absolute requirement for such analysis (Cascini et al., 2010, 2011b). First-time slides may or may not evolve into a debris flow, depending on the post-failure behaviour of the soil (Cascini et al., 2013, 2014).

The effects of soil erosion extend to a few centimetres below the ground surface. The mobilisation of solid particles resulting from raindrop impact, called rainsplash erosion, depends on the forces of that impact (which depend on rainfall intensity) (Mouzai and Bouhadef, 2003), soil mechanical properties, topography, vegetation and land use. Rainsplash erosion in a mountain basin is generally diffused. The mobilisation of solid particles, in contrast, is the result of overland flow (known as overland flow erosion), and is related to flow velocity and, in turn, to the tangential and uplift forces exerted on the ground surface by water and the solid particles being driven by the flow (Aksoy and Kavvas, 2005). Overland flow erosion may be diffuse (sheet erosion) or localised into rills, gullies or channels (Merritt et al., 2003). While the amount of water and sediment eroded from the ground surface conveyed to an outlet basin is generally evaluated from empirical relationships between the total peak discharge and sediment volume (Rickenmann, 1999), appropriate analysis of rainwater infiltration and runoff is a fundamental requirement for unsaturated soil slopes. Cuomo and Della Sala (2013) demonstrate that initial soil suction, i.e. the difference between the air pressure (u_a) and pore water pressure (u_w), delays the runoff time and reduces the runoff

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discharge to the extent that the topsoil does not become fully saturated. However, the runoff time may be reduced to zero in heavy rainfall independent of the initial soil suction. Heavy erosion processes lead to hyperconcentrated flows at the basin outlet.

This paper addresses the current gap in the literature between the mechanics of unsaturated soils and the analysis of erosion in small basins ($<10\ \mathrm{km}^2$) composed of unsaturated soils. A relevant case study involving hyperconcentrated flows is selected from a location in Southern Italy where unsaturated, shallow soil deposits with high soil suction are subjected to short, heavy rainfall. As the rainfall intensity is high compared with the initial soil conductivity, the pore water pressure cannot increase sufficiently to cause slope failure (Cascini et al., 2013; Cuomo and Della Sala, 2013) and any potential flow-like mass movements are exclusively related to soil erosion. The mechanics of unsaturated soil is used either to select from various distinct runoff–infiltration formulations or to evaluate the mechanical parameters of the soil. Realistic rainfall scenarios are considered and quantitative estimates are provided for either the extent of the eroded areas or the total discharge (of water and sediment) at the outlet of basins. The results obtained through numerical modelling are compared with those in the literature and with specific in situ evidence.

2. Literature review

Several quantitative models have been proposed to date for rainfall-induced soil erosion (e.g., Merritt et al., 2003; Aksoy and Kavvas, 2005; de Vente and Poesen, 2005). These models can be grouped into three main categories: empirical, conceptual and physically based models.

Empirical models are often used in the first step of analysis to identify the source areas of soil erosion, as these models require limited input data (Merritt et al., 2003). Some of these models have been established for geomorphological purposes, and others to predict or model the loss of soil, mainly for agricultural or sedimentological purposes. Such models include the well-known Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), which has been used to obtain estimates for long-term expected soil loss in Europe and Italy due to rill and interrill flow detachment erosion (van der Knijff et al., 1999, 2000) and to analyse single-storm effects over large areas (Cuomo and Della Sala, 2013). Several improvements to the original USLE model have been made in the past few decades. For instance, Ferro and Porto (2000) proposed the SEdiment Delivery Distributed (SEDD) model, through which satisfactory agreement between measured and calculated yields of sediments eroded – both for specific events and at a yearly rate – was obtained in three small experimental basins in Southern Italy. Nevertheless, none of the empirical models can account for the deposition and remobilisation of sediments.

Conceptual models involve general descriptions of catchment processes without considering the specific details of process interactions (Sorooshian, 1991). In this category, it is worth mentioning the AGriculture NonPoint Source (AGNPS) model (Young et al., 1989). In two medium-sized catchments in Central Europe (Rode and Frede, 1999) and some mixed-forest catchments of Southeastern Thailand (Najim et al., 2006), runoff volume evaluated using this model was consistent with empirical observations; mobilised sediments were, however, over-predicted. The major drawbacks of conceptual models are that calibration is site-specific and that soil mechanical properties and rainfall characteristics are only taken into account indirectly.

Physically based approaches describe the features and mutual interactions of all the main rainfall-induced processes in a catchment, such as infiltration, runoff, rainsplash erosion, flow detachment and the transportation/deposition/remobilisation of sediments. According to Merritt et al. (2003), most physically based models refer to conservation equations for the water mass, sediment yield and flow momentum of the mixture. The potential of these models is discussed in the literature. Satisfactory estimates for runoff and sediment yield were achieved by Shen et al. (2009) for a catchment in the Three Gorges Reservoir Area (China) using the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989). The model, however, under-predicted the sediment yield experimentally measured in the Apennines Mountain Range in Northern Italy (Pieri et al., 2007). Accurate predictions for yearly runoff and soil loss based on the EUROpean Soil Erosion Model (EUROSEM; Morgan et al., 1998) were reported by Veihe et al. (2001) for some catchments in Central America, but poor estimates were obtained for single-storm events.

One of the most promising of the physically based models is the LImburg Soil Erosion Model (LISEM; De Roo et al., 1994, 1996a,b; De Roo and Jetten, 1999; Jetten, 2002), which has been applied to small ($<10\ \mathrm{km}^2$; Hessel et al., 2003, 2006) and medium-sized ($>50\ \mathrm{km}^2$; Baartman et al., 2012; Rahmati et al., 2013) mountain basins. The potential of LISEM for analysing single-storm events is clearly indicated in the literature. For instance, the discharge of water and sediments and the time to peak have been accurately simulated (Hessel et al., 2006; Rahmati et al., 2013). The major drawbacks of the model are that distinct calibrations are required for small and large runoff events (Hessel et al., 2003; Baartman et al., 2012), and that soil loss may be overestimated (Hessel et al., 2006). However, the discrepancies observed between the model and empirical observations may be the result of a number of factors, for example, i) inaccurate input data; ii) uncertainty in the measured field data; iii) the complexity of rainfall events, soil types and land use; and iv) processes that are not incorporated into the model such as throughflow and baseflow.

It is evident that the analysis of single-storm events can provide detailed information about soil erosion, that is, source, transportation and deposition, when physically based models are used. Of those, LISEM currently appears to be one of the most reliable models for soil erosion analysis and is used here. However, the applicability to and performance of LISEM in real cases remains to be fully assessed; these issues are investigated in this paper with special reference to unsaturated soil conditions.

3. Case study

The case study area contains unsaturated, shallow deposits of pyroclastic (air-fall) volcanic soils (Bilotta et al., 2005; Cascini et al., 2008, 2010) derived from the explosive eruptions of Vesuvius (Southern Italy) (Cuomo et al., 2015). The eruption of 79 A.D. is famous because the Roman city of Pompeii was completely buried in ash and pumice; the last eruption of Vesuvius occurred in 1944. Pyroclastic soils mainly consist of silty sands or sandy silts (ashy soils) and coarse sands or sandy gravels (pumice soils). Details of the origin and later pedogenetic processes of pyroclastic soils are provided by Guadagno et al. (2005), and an advanced soil mechanical characterisation in saturated and unsaturated conditions is given by Bilotta et al. (2005). In brief, pyroclastic materials were ejected into the atmosphere during the volcanic eruptions, transported by the prevailing winds and deposited over a very large area (about $3000\ \mathrm{km}^2$) that includes the Amalfi Coast (Cascini et al., 2014; Cuomo et al., 2015).

The Amalfi Coast corresponds primarily to a coastal carbonate ridge (the Lattari Mountains). It is a UNESCO World Heritage site famous for its natural beauty, and is visited by thousands of tourists every year. In late summer, the Amalfi Coast is repeatedly affected by heavy rainfall able to trigger widespread soil erosion that later becomes hyperconcentrated flows (Cascini et al., 2014). Assessment of soil erosion is thus fundamental to determining the risk posed to life and property in the tourist sites located near the outlet of the mountain basins.

This paper focuses on two mountain basins, Dragone and Sambuco (Fig. 1a), located in the western part of the Lattari Mountains. The Dragone basin has an area of $9.3\ \mathrm{km}^2$ (and a perimeter of 15.7 km), with a linear main stream channel 6.5 km long. A well-developed drainage network exists on the east side of the basin, with steeper hillslopes and few drainage channels on the west side. The uppermost basin is 2 km wide with a narrow gorge 300 m wide at the outlet, where the town of Atrani is located. The Sambuco basin has an area of $5.6\ \mathrm{km}^2$ with a 12.1 km perimeter, a main stream channel 5.3 km long and