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Experimental evidences and numerical modelling of runoff and soil erosion in flume tests

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ABSTRACT

Rainfall causes runoff and soil erosion in artificial and natural slopes and important insight may derive from quantitative physically-based models or laboratory tests. Measurements of runoff and sediment discharges in small-scale experimental flume tests have become popular in recent years and a wide range of slope angles, soil grain-size-distributions and rainfall characteristics has been tested so far. In the literature, there are numerous studies dealing with a comparison between experimental data and model predictions using appropriate assumptions. However, there are still scientific gaps under complex experimental circumstances. The main goal is to discuss the performance of a physically-based numerical model in simulating well-documented runoff–erosion laboratory flume tests, also highlighting the uncertainties one may expect for real cases when applying numerical modelling of runoff and soil erosion to a real catchment.

The paper deals with the numerical analysis of four experimental flume tests available in the literature, which investigate the erosion of bare gentle slopes due to constant-intensity rainfall; the behaviour of a steeper slope, bare or vegetated, under constant rainfall larger than in the previous experiments; the role of a sequence of different rainfall intensities (with the same cumulated rainfall), and different surface roughness in gentle slopes. Those experimental tests were simulated through LISEM, and the numerical results reproduce satisfactorily the global behaviour of the experimental plots eroded by artificial rainfall in all the four flume tests. As far as the ratio of the observed to the predicted peaks of water discharge and sediment concentration, the simulated peaks are very close to those observed in the laboratory experiments, except for low slope angle conditions where water discharge peak is overestimated and for one flume where sediment concentration peak is underestimated in two out of three cases. This analysis highlights that LISEM allows reasonably estimating the peak values of water and sediment discharge, which are generally used as design parameters of erosion control works. With reference to peak times of water discharge and sediment concentration, this paper highlights that LISEM has limitations in properly assessing the peak times of water discharge and sediment concentration; better results are, instead, expected when LISEM is used to simulate erosion and runoff on vegetated slopes. Globally, the results allow the assessment of the overall performance of the selected erosion model to correctly interpret the experimental evidences. As well, the discrepancies among the laboratory evidences and numerical results are discussed in relation to slope geometry and soil properties.

1. Introduction

The superficial topsoil can be eroded by rainfall along natural or artificial slopes, and the erosion process is particularly complex in mountain catchments made of steep slopes and cohesionless unsaturated soils (Della Sala, 2014; Cuomo et al., 2015; Cuomo and Della Sala, 2016). The effects of soil erosion extend to a few centimetres below the ground surface. The mobilisation of solid particles resulting from raindrop impact, known as rainsplash erosion (Kinnell, 2005, 2006), depends on the impact forces of raindrops, rainfall intensity, soil mechanical properties, topography, vegetation type and land use. Rainsplash erosion in a mountain basin is generally diffused. In addition, the mobilisation of solid particles is caused by overland flow. This mechanism is known as overland flow erosion. It is related to flow velocity and, in turn, to the tangential and uplift forces exerted on the ground surface by water, thus the solid particles are driven by flow. Overland flow erosion may be diffuse (sheet erosion) or localized into rills, gullies or channels. 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

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between the air pressure (u_a) and pore water pressure (u_w), delays the runoff time and reduces the runoff discharge to the extent that the topsoil does not become fully saturated. However, the runoff time may be decreased to zero in case of heavy rainfall, independent of initial soil suction. One important concern is that heavy erosion processes may lead to hyperconcentrated flows at the outlet of a catchment (Cuomo et al., 2015). Adequate estimates of the water and solid discharges are important to safely design the erosion control works, reducing the maintenance costs of the man-made slopes, such as embankments or excavations for highways and railways. However, the spatial variability of both initial soil water content and saturated hydraulic conductivity is a relevant issue in real catchments (Hu et al., 2015; Cuomo et al., 2015), and uncertainties may be related to either complex field conditions or limited data-sets.

Several quantitative models exist to analyze the overall process of rainfall-induced soil erosion and specific details are widely discussed in the literature (e.g. Merritt et al., 2003; Aksoy and Kavvas, 2005; Hessel et al., 2006). Among these approaches, the so-called physically-based models allow quantitative simulations of water infiltration, runoff and sediment mobilisation. The latter is due to either rainsplash erosion or overland flow erosion of topsoil particles. Physically-based models are based on the conservation equations for water mass, sediment yield and flow momentum of mixture (Merritt et al., 2003). Models can be lumped if they use single values of input parameters in the whole computational domain or spatially-distributed approaches can be used. A complete review is proposed by Aksoy and Kavvas (2005) and Merritt et al. (2003). It is also worth mentioning the Harsine and Rose model (Hairsine and Rose, 1991; Jomaa et al., 2012, 2013), which simulates size class-dependent erosion and deposition processes, and predicts the development of a shield layer composed of (re-)deposited sediment, which acts to protect the original soil. Some of the physically-based models can be applied to simulate the sediment mobilisation produced by consecutive rainfall–runoff events occurring during a season or a longer time period at hillslope scale, such as the WEPP model (Nearing et al., 1989) or to simulate the sediments produced by one single rainfall–runoff event at catchment scale, such as EUROSEM (Morgan et al., 1998), KINEROS (Smith, 1981; Woolhiser et al., 1990) and LISEM (De Roo et al., 1994, 1996a,b; De Roo and Jetten, 1999; Jetten, 2002). To this aim, accurate knowledge of slope geometry (e.g. slope angle), soil properties (e.g. soil suction, water content, and hydraulic conductivity), surface features (e.g. roughness and vegetation) and rainfall pattern is required. In most of the real cases, very limited information is available, such as peak discharge of water and sediments measured at the outlet of the catchment, and in a few cases estimates of sediment volumes, erosion areas, eroded thickness and the grain-size of the eroded material are also on hand. Thus, the calibration of any erosion model is quite difficult and uncertain (Aksoy and Kavvas, 2005). This paper will use the LISEM (LImburg Soil Erosion Model), which is a spatially-distributed and physically-based model, implemented in a GIS platform. The model was selected here as it is well-known, validated, and applied so far in different catchments in Europe, such as the Netherlands (De Roo and Jetten, 1999), France (Rahimy, 2012), Spain (Baartman et al., 2012, 2013), Belgium (Jetten et al., 2003; Takken et al., 2005), and Norway (Kværnø and Stolte, 2012) and in other countries such as China (Hessel et al., 2003), Africa (De Roo and Jetten, 1999), and the Philippines (Clutario and David, 2014). Thus, the paper aims to evaluate this kind of modelling approach in well documented cases – like laboratory plots – where geometry, soil mechanical properties and boundary conditions are well known. Thus, the discrepancy of the model into simulating the experimental evidence will be simply related to the soundness of the theoretical background.

One possibility explored in the last decades relates to small-scale erosion tests, performed in well equipped testing devices. Measurements of runoff and sediment yield rate have been extensively performed through laboratory flume tests, which allowed investigating the single effect of specific factors such as slope geometry, vegetation cover, soil type, surface roughness and rainfall characteristics. The great potential of flume tests is the accurate control of geometry, stratigraphy, soil properties and initial conditions; thus, the spatial variability of initial soil water content and saturated hydraulic conductivity is much reduced. In addition, accurate measurements can be collected for the water flow discharge, weight of water-driven sediments, and changes of topography in time. Conversely, the main limitation is that only the very initial stage of the erosion process can be consistently observed. This is due to the employment of a single fixed slope angle in most of the small-scale flumes. The use of in-series slopes (differently steep) may help in measuring solid particle deposition and remobilization; however, the results would be dependent on the length of each piece of the slope. In a real catchment, the global time sequence of sediment transportation, deposition and re-mobilisation highly affects the response to heavy rainfall. Nevertheless, reduced-scale laboratory tests allow observing the fundamental features of the erosion process (e.g. localized or diffuse) and the principal mechanisms (e.g. runoff generation, time sequence of erosion and deposition, and so on). It's worth mentioning, among others, the experimental works of Bryan and Rockwell (1998), Jayawardena and Bhuiyan (1999), Abrahams et al. (2000, 2001), Römkens et al. (2002), Pan and Shangguan (2006), Acharya et al. (2011), Ran et al. (2012) and Aksoy et al. (2013). These experiments highlight the dependence of soil erosion on different factors: i) slope geometry (steepness and slope length), ii) vegetation cover, iii) rainfall intensity and duration, iv) surface conditions, among others.

The availability of good-quality experimental results provides a good chance to investigate the performance of physically-based numerical models towards accurate estimates of peak discharges (of water and sediments), sediment concentration, time to peaks, etc. In the literature, there are numerous studies dealing with a comparison between experimental data and model predictions using appropriate assumptions, particularly in terms of total eroded mass. However, there are still scientific gaps in terms of individual size classes under complex experimental circumstances (different initial and antecedent soil conditions, soil cover, multiple rainfall intensity etc). The scientific gaps are more pronounced in situations where the soil and experimental conditions become complex (soil conditions, varying precipitation rate, heterogeneous roughness etc) and when more details are required (such as the behaviour of individual size classes).

In this paper, four well-documented flume tests were selected, which investigate: i) the erosion of bare gentle slopes due to constant-intensity rainfall (Bryan and Rockwell, 1998); ii) the behaviour of a steeper slope, bare or vegetated, under constant rainfall larger than in the previous experiments (Pan and Shangguan, 2006); iii) the role of a sequence of different rainfall intensities (with the same cumulated rainfall), and different surface roughness in gentle slopes (Römkens et al., 2002). Those experimental tests were simulated through LISEM (Jetten, 2002, 2014), a widely validated tool, which can take accurately into account the slope geometry, rainfall characteristics, surface features and vegetation cover.

The main goal of the paper is to discuss the performance of a physically-based numerical model in simulating well-documented runoff–erosion laboratory flume tests, also highlighting the uncertainties one may expect for real cases when applying numerical modelling of runoff and soil erosion to a real catchment. The paper is structured as follows: the experimental evidence of the selected literature tests is presented first, the main characteristics of the numerical model are summarized, and the numerical analyses are presented; then, experimental and numerical results are compared and discussed; finally, some conclusions are drawn and future developments are illustrated.

2. Experimental tests

This paper aims to combine the experimental evidence of runoff–erosion flume tests available in the literature to novel numerical