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# Effect of antecedent conditions and fixed rock fragment coverage on soil erosion dynamics through multiple rainfall events

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## SUMMARY

The effect of antecedent conditions and specific rock fragment coverage on precipitation-driven soil erosion dynamics through multiple rainfall events was investigated using a pair of 6-m × 1-m flumes with 2.2% slope. Four sequential experiments – denoted E1, E2, E3 and E4, involved 2-h precipitation (rates of 28, 74, 74 and 28 mm $h^{-1}$, respectively) and 22 h without rainfall – were conducted. In each experiment, one flume was bare while the other had 40% rock fragment coverage. The soil was hand-cultivated and smoothed before the first event (E1) only, and left untouched subsequently. Sediment yields at the flume exit reached steady-state conditions over time scales that increased with sediment size. Experiments were designed such that both steady and non-steady effluent sediment yields were reached at the conclusion of E1. Results from subsequent experiments showed that short-time soil erosion was dependent on whether steady-state erosion was achieved during the preceding event, although consistent steady-state effluent sediment yields were reached for each sediment size class. Steady-state erosion rates were, however, dependent on the rainfall intensity and its duration. If steady-state sediment yields were reached for a particular size class, that class's effluent sediment yield peaked rapidly in the next rainfall event. The early peak was followed by a gradual decline to the steady-state condition. On the other hand, for size classes in which steady state was not reached at the end of the rainfall event (i.e., E1), in the following event (E2), the sediment yields for those classes increased gradually to steady state, i.e., the sharp peak was not observed. The effect of rock fragment cover (40%) on the soil surface was also found to be significant in terms of the time to reach steady state, i.e., their presence reduced the time for steady conditions to be attained. Effluent sediment yields for the bare and rock fragment-covered flumes (E1) showed steady conditions were reached for the latter, in contrast to the former. We used the Hairsine-Rose (H–R) model to simulate the experimental data as it explicitly models soil particle size classes. Experiments E1 and E2 involved soil compaction by raindrops, and in this case the model predictions were found to be unsatisfactory. However, compaction was effectively completed by the end of experiment E2, and the model provided reasonable predictions for experiments E3 and E4.

## 1. Introduction

Soil erosion is influenced by several interacting factors, including rainfall intensity, soil properties, topography, land cover, spatial scale, and initial and antecedent soil conditions (Hancock et al., 2008; Neave and Rayburg, 2007; Rudolph et al., 1997). Surface sealing and crusting also play an important role. These are differentiated by their moisture content; seals are wet while crusts are dry (Singer and Shainberg, 2004). Their effect is decrease the infiltration rate, thereby increasing runoff and potential for soil loss (e.g., Le Bissonnais et al., 1998; Neave and Rayburg, 2007).

When aggregates are broken down by raindrop impact and/or slaking processes, the disaggregated particles are deposited within soil pore spaces forming a thin, low permeability surface layer

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(Assouline, 2004). Furthermore, when soil with low moisture content experiences a rain event, there is enhanced aggregate slaking and breakdown due to air escape upon rapid wetting. This enhances soil detachment by raindrop impact and subsequent transport by overland flow (Le Bissonnais et al., 1989; Römkens et al., 2002; Rudolph et al., 1997).

While initial moisture content during individual storms affects soil erosion delivery, the soil water regime over longer periods includes repeated wetting–drying cycles that also influence erodibility producing considerable uncertainty in event-based erosion predictions (Bryan, 2000; Fohrer et al., 1999; Le Bissonnais and Singer, 1992). Luk et al. (1993) showed that soil loss reduced over successive storms due to the formation of a cohesive crust during the drying cycles. Furthermore, Mamedov et al. (2006) highlighted that antecedent moisture content and soil surface aging (i.e., wetting and keeping the soil at given moisture content) affect the seal formation and erosion rate. Consequently, the antecedent soil conditions affect the surface soil structure differently, which in turn affects soil erosion. Although the interactions between rainfall intensity, antecedent soil conditions and the surface sealing have been investigated previously, quantitative information about the effects of those interacting processes on soil erosion and sediment yield is limited (Kuhn et al., 2010; Römkens et al., 2002).

Rock fragment cover affects both the hydrological response and soil erosion (Jomaa et al., 2012b,c; Poesen et al., 1990, 1994; Rieke-Zapp et al., 2007). Surface rock fragments delay the time-to-runoff and prevent surface sealing, resulting in decreased runoff generation and an increased infiltration rate into the soil, which in consequence reduces the erosion delivery. Jomaa et al. (2012b) showed, using different rock fragment coverages (fragments were arranged regularly on top of the soil) in controlled laboratory flume experiments, that raindrop detachment is proportional to the effective rainfall and the area of exposed soil, other factors being equal (antecedent moisture content, bulk density and surface roughness). They found that, to a lesser extent, this relationship is also controlled by the initial moisture content and bulk density of soil. Nevertheless, other studies reported that rock fragments can lead to different soil erosion outcomes depending on their characteristics (cover, size and emplacement) (Jomaa et al., 2012c; Loosvelt, 2007). Jomaa et al. (2012c) showed that rock fragments affect the soil particle size classes differently, depending on the time scale of the erosion event.

The experiments reported herein focus on the temporal response of the soil's individual sediment size classes under a sequence of rain events. A formulation that accounts explicitly for the transport of different size classes is the Hairsine and Rose (H–R) soil erosion model (Hairsine and Rose, 1991). The H–R model incorporates a mechanistic description of the shielding effect of eroded soil that forms the deposited layer on top of the parent soil, which built on the earlier work of Rose et al. (1983a,b). The H–R model predictions were compared favourably with experimental data for single rainfall events (Heng et al., 2011; Jomaa et al., 2010; Proffitt et al., 1991; Rose et al., 2007; Sander et al., 1996, 2007; Tromp-van Meerveld et al., 2008). Here, we test the ability of H–R model to predict the details of sediment yields of different size classes through multiple rainfall events and in the presence of a rock fragment cover. The experiments involve soils that initially undergo rapid sealing/compaction, followed by a relatively stable condition, giving the opportunity to check the model's performance during this transition.

Specifically, the aims of this study were to investigate, in a laboratory flume and at the level of individual sediment size classes, (i) the effect of antecedent conditions and (ii) specific rock fragment coverage on soil erosion yields under multiple erosion events. In addition, the data set provides (iii) an opportunity to assess the ability of the H–R model to predict soil erosion dynamics under multiple rainfall events for a soil undergoing compaction.

## 2. Methods

### 2.1. Experimental setup

Four simulated rainfall events were conducted on successive days using the EPFL erosion flume (Baril, 1991; Viani, 1986). Descriptions of the indoor flume (6-m × 2-m, 2.2% slope) and rainfall simulator are given elsewhere (Jomaa et al., 2010; Tromp-van Meerveld et al., 2008). A summary of the experimental conditions and characteristics of each individual event is reported in Table 1. A low precipitation-rate rainfall event (28 mm $h^{-1}$) was followed by two events with the same high precipitation rate (74 mm $h^{-1}$), and again by one with the same low precipitation rate as the first event.

The duration of each rainfall event was 2 h and was followed by 22 h of natural air-drying without altering the soil surface. The flume was divided into two identical 1-m wide flumes by installation of a thin, vertical barrier. Flume 1 was kept with bare soil. The same soil was used in flume 2 except that 40% of its surface was covered by rock fragments. Before the first precipitation event (E1), the soil was hand-cultivated to a depth of 20 cm and then mechanically smoothed. Flume 2 was covered by a uniform, triangular pattern of rock fragments placed on the surface (not embedded in the soil matrix). Before the commencement of precipitation, both flumes were gently pre-wetted using a sprinkler (Table 1 reports the volumetric initial moisture content). More experimental details can be found in Jomaa (2012a). Note that identification of the erosion events was slightly changed compared with our previous work (Jomaa et al., 2012b). The label "H7" was removed resulting in four sequential rainfall events denoted E1, E2, E3 and E4 rather than H7-E1, H7-E2, H7-E3 and H7-E4, respectively. An agricultural loamy soil from Sullens, Switzerland, was used. Its particle size distribution is reported in Table 2, with a detailed description of its properties given by Baril (1991). For all experiments, visual inspection showed there was no rill formation, so raindrop detachment was the dominant erosion process. The absence of rills is consistent with stream power calculations (Jomaa et al., 2010). Experiment E3 had the higher runoff rate (Table 1) and in consequence the highest stream power estimate (0.02 W $m^{-2}$), which is much lower than the critical stream power (0.15 W $m^{-2}$) value required for rill erosion of loamy soils (Beuselinck et al., 2002).

Effluent discharge samples were used to determine discharge rates and sediment yield rates. Samples were analysed to quantify the total sediment yield and the sediment yields of seven size classes (< 2, 2–20, 20–50, 50–100, 100–315, 315–1000 and > 1000 μm). Larger size classes (larger than 100 μm) were sieved, while for the finer particles (2–100 μm) the laser diffraction technique was employed (Jomaa et al., 2010).

### 2.2. Modelling

Measured sediment yields were analysed using the H–R erosion theory. Model assumptions and governing equations have been described and analysed previously (e.g., Barry et al., 2010; Hairsine and Rose, 1991; Heng et al., 2009; Hogarth et al., 2004; Lisle et al., 1998; Parlange et al., 1999; Rose et al., 1983a,b; Sander et al., 2007). Jomaa et al. (2012c) accounted for the effect of rock fragment coverage using an additional parameter, $\eta$, which is the fraction of soil surface exposed (i.e., not covered by rock fragments). Sander et al. (1996) presented an analytical solution to the H–R model that agreed well with data obtained using different