Catena 152 (2017) 285–291

Contents lists available at ScienceDirect

Catena

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

Linear scaling of precipitation-driven soil erosion in laboratory flumes

S. Jomaa[a,*], D.A. Barry[b], M. Rode[a], G.C. Sander[c], J.-Y. Parlange[d]

[a] Department of Aquatic Ecosystem Analysis and Management, Helmholtz Centre for Environmental Research – UFZ, Brueckstrasse 3a, 39114 Magdeburg, Germany
[b] Laboratoire de technologie écologique (ECOL), Institut d'ingénierie de l'environnement (IIE), Faculté de l'environnement naturel, architectural et construit (ENAC), Station 2, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
[c] Department of Civil and Building Engineering, Loughborough University, Loughborough LE11 3TU, United Kingdom
[d] Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853-5701, USA

ARTICLE INFO

Article history:
Received 26 May 2016
Received in revised form 13 January 2017
Accepted 18 January 2017
Available online 26 January 2017

ABSTRACT

The proportionality between raindrop-driven soil erosion delivery and area of soil exposed to raindrops under a uniform precipitation rate was investigated in terms of individual size classes using laboratory flume experiments. In particular, we examined the dependence of soil erosion on the area exposed to raindrop detachment. Twelve experiments were performed on the same laboratory flume, filled with the same soil. The experiments entailed different (constant) precipitation rates (28 and 74 mm h^{-1}, 2–5 h duration) and various fractions of exposed surface (20, 30, and 40%, created using rock fragment cover). In addition, different initial soil conditions (dry hand-cultivated, wet sealed-compacted and dry compacted) were considered. The discharge rates and the sediment concentrations of seven individual size classes (<2, 2–20, 20–50, 50–100, 100–315, 315–1000 and >1000 μm) were measured at the flume exit. Results showed that the proportionality of soil erosion to the area exposed appears to always hold at steady state independently of the initial conditions and rainfall intensity. Across all experiments the data indicate that this proportionality holds approximately during entire erosive events and for all individual size classes. However, the proportionality for short times is less clear for the larger size classes as the data show that for these classes the erosion was sensitive to the soil's antecedent conditions and further influenced by additional factors such as surface cohesion, surface compaction and soil moisture content.

1. Introduction

The factors influencing raindrop-driven soil erosion can be divided into two main categories; rainfall characteristics (precipitation rate, duration, raindrop size) and soil properties (moisture content, topsoil compaction, surface roughness) (Butzen et al., 2014; Liu et al., 2014; Ries et al., 2014; Saedi et al., 2016). A good understanding of these factors and of their interactions is needed for predictions of sediment concentrations (Bryan, 2000; de Vente et al., 2013; Jomaa, 2012; Keesstra et al., 2016).

At the catchment scale, several studies focused on obtaining a unique relationship between flow characteristics and sediment concentrations (de Vente et al., 2013; Harmel et al., 2006; Nearing et al., 2007; Pierson et al., 2001). These studies consistently reported a non-unique relationship between sediment concentrations and runoff response. Generally speaking, sediment delivery is found to increase with the flow volume from a given basin area (Kim, 2013). Keesstra et al. (2016) reported that additional factors such as agricultural land management (e.g., tillage, herbicide and vegetation coverage) further affect the soil erosion delivery. For instance, it was found, experimentally, that straw mulch reduces soil erosion and runoff generation significantly (Cerdà et al., 2016; Prosdocimi et al., 2016). Kim (2013) listed and detailed the possible parameters influencing this relationship, i.e., rainfall characteristics, land use and cover, surface roughness, antecedent soil conditions, conservation management practices and the development of surface water connectivity as well as the steepness and length of slopes. Nearing et al. (2007) showed experimentally that event-based soil erosion delivery can differ considerably for the same hydrological response at the catchment outlet due to interactions amongst factors including soil degradation, loss of soil organic matter, or change in vegetation cover. Recently, de Vente et al. (2013) reviewed and evaluated 14 soil erosion models used in over 700 catchments. They found that prediction of sediment concentration strongly depends on the spatial and temporal scales considered. They concluded that, at the catchment scale, none of the models captures all soil erosion processes and fulfills all modelling objectives. For instance, in large catchments, nonlinear

---

* Corresponding author.
E-mail addresses: seifeddine.jomaa@ufz.de (S. Jomaa), andrew.barry@epfl.ch (D.A. Barry), michael.rode@ufz.de (M. Rode), g.sander@lboro.ac.uk (G.C. Sander), jp58@cornell.edu (J.-Y. Parlange).

http://dx.doi.org/10.1016/j.catena.2017.01.025
0341-8162/

regression models were found to represent more accurately the sediment concentrations. Factorial scoring models with identification of dominant soil erosion processes were more reliable for medium-sized catchments (de Vente et al., 2005; Haregeweyn et al., 2005). Process-based models, however, were found to better represent soil erosion delivery only when the modelled processes are dominant in the investigated study area (de Vente et al., 2013; Haregeweyn and Yohannes, 2003; Jetten et al., 1999). Thus, de Vente et al. (2013) concluded that further integration of observations and different model concepts is needed to obtain better soil erosion predictions. This work is a step in that direction. We consider the transferability of measured soil erosion data under laboratory-controlled conditions, i.e., if, at a given site, erosion measurements are available under a given set of conditions, can those results be scaled when the conditions (e.g., precipitation rate or area exposed) change?

At the field scale, the factors that influence soil erosion cannot be imposed. However, this is not the case for laboratory flume experiments. Therefore, numerous studies have highlighted the importance of the use of simulated rainfall experiments to better understand soil erosion processes and to predict sediment delivery (e.g., Cheraghi et al., 2016; Iserloh et al., 2013; Lassu et al., 2015; Martínez-Murillo et al., 2013). Jomaa et al. (2012a) investigated the relationship between the temporal evolution of total eroded mass from a laboratory flume and the area exposed to raindrop detachment. In that study, the temporal soil erosion delivery from a rock fragment-protected flume (flume 2) was estimated by multiplying the time-varying eroded mass from the bare soil flume (flume 1) by the fraction of exposed soil to raindrops in flume 2. The proportionality between soil erosion and the area exposed to raindrops worked surprisingly well for the duration of the experiment, and was able to estimate reliably the temporal behaviour in the total sediment concentration leaving flume 2. The most accurate estimates of the measured flume 2 concentrations were obtained when conditions settled down to steady state.

In this study, we consider the applicability of these findings in terms of the behaviour of the individual size classes. As with the total eroded mass discussed above, the measured sediment concentrations of the individual size classes from flume 2 were also estimated from flume 1 data based on the exposed area of soil in flume 2. Specifically, we (i) investigate the proportionality between surface area exposed and the eroded sediment concentration for individual size classes through time, and (ii) assess how much these relationships are controlled by the antecedent soil conditions.

2. Material and methods

2.1. Experiments

Previously published data from the EPFL erosion flume and an additional experiment were utilized, all of which were for the same loamy agricultural soil. To compare the effect of different exposed surface areas, the 6-m × 2-m EPFL flume was separated into two identical 6-m × 1-m flumes, identified as flume 1 and 2. Experiments for flume 1 always started with a bare soil surface, while flume 2 experiments considered different levels of surface rock fragment coverage (Fig. 1); otherwise the experimental conditions (surface roughness, soil cohesion and soil initial moisture) for each flume were identical. For all experiments, the rock fragments were placed on the top surface (not embedded in the soil). The design of experiments, the rainfall simulator characteristics and the soil property as well as its preparation procedure were described previously (Jomaa et al., 2010; Jomaa et al., 2012b; Tromp-van Meerveld et al., 2008), so only key features are discussed here. The flume was filled to a depth of 0.32 m with an agricultural loamy soil from Sullens, Switzerland, and underlain by 0.10 m of coarse gravel facilitating the drainage. The flume slope can be adjusted in the range 0–30% using a hydraulic piston. Water from Lake Geneva was applied to the flume by 10 Veejet 80,150 nozzles located on two parallel oscillating bars (each contains five Veejet nozzles), 3 m above the soil surface. The rainfall intensity can be adjusted by changing the oscillation frequency of the sprinklers. Over the course of each rainfall event, water and sediment samples were collected in individual bottles at the exit of each flume. Continuous sampling occurred at the beginning of the runoff generation to capture the early soil erosion peak. Afterwards, the sampling period increased due to less rapid changes in sediment concentration as the system tended toward steady-state.

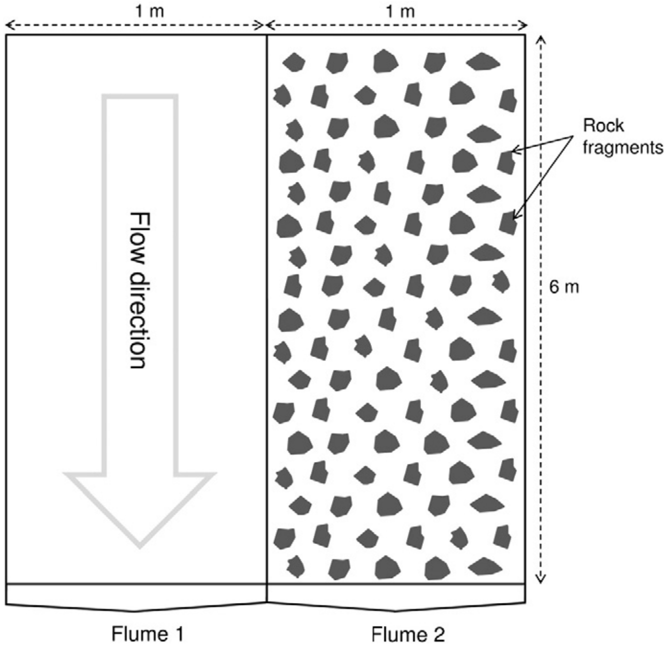

Fig. 1. Design of experiments (figure modified from Jomaa et al., 2012b). The 6-m × 2-m flume was divided into two 6-m × 1-m flumes. Note that the flumes are not drawn to scale. For experiments H6, H7- E1–E4, and H8, flume 1 was bare soil while Flume 2 was covered by surface rock fragments (Table 1).

In this study, we analyse results from 12 experiments using two rainfall intensities (28 and 74 mm h^{-1}) and three rock fragment coverages (20, 30 and 40%), as detailed in Table 1. Here, the two used rainfall intensities (i.e., 28 and 74 mm h^{-1}) are realistic rainfall rates for the city of Lausanne (Switzerland) (Baril, 1991). The lower rainfall rate was chosen as slightly exceeding 25 mm h^{-1}, the value reported as a threshold for significant erosion in central Europe (Morgan, 2005), while the higher intensity illustrates the maximum rainfall rate expected for Lausanne.

Four sequential experiments, denoted H7-E1, H7-E2, H7-E3, and H7-E4 are taken from Jomaa et al. (2013; 2012b), and experiment H6 from Jomaa et al. (2012b). Experiment H6 used two flumes, H6-F1 (bare soil) and H6-F2 (20% rock fragment coverage), each subjected to 3 h precipitation at a rate of 74 mm h^{-1}. Experiments involving multiple rainfall events (H7- E1, E2, E3 and E4) used 4 × 2-h precipitation rates (28, 74, 74 and 28 mm h^{-1}, respectively) with 22 h of natural air drying between events. These experiments permitted investigation of the effects of progressive raindrop soil compaction on the effluent sediment concentrations of the individual size classes. Again, the two flumes had the same conditions, Flume 1 was bare soil and the surface of flume 2 was covered by 40% rock fragments. In addition, a (previously unreported) 5-h duration experiment was conducted to capture long-time behaviour using a precipitation rate of 74 mm h^{-1}. This is denoted as H8 where H8-F1 used bare soil and H8-F2 had 30% rock fragment coverage. Experiment H8 was prepared similarly to the other experiments (H6 and H7), except that the topsoil surface was initially compacted dry