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Effects of rain intensity, slope gradient and particle size distribution on the relative contributions of splash and wash loads to rain-induced erosion

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ABSTRACT

Soil erosion during rainfall is a complex phenomenon resulting from detachment by raindrop impact and overland flow. The objective of this study is to investigate the transportation rate of splash load (*SL*) and that of wash load (*WL*) and their relative contributions to the rain-induced erosion rate affected by rain intensity, slope gradient and particle size distribution. A total of 60 simulation runs were carried out using a detachment tray under simulated rainfall with no inflow. The experiments were done on two soil samples (aggregate sizes finer than 2 and 4.75 mm) from an agricultural land use at different rain intensities (57 and 80 mm h^{-1}) and varying slope gradients (0.5%, 2.5%, 5%, 10%, and 20%). Under unsteady state conditions, *WL* showed relatively high dependency on slope gradient, whereas approaching steady state conditions, nearly similar values of *WL* occurred at different slopes. *SL* and *WL* increased with increasing rain intensity and slope gradient, implying the importance of rain-induced erosion on bare agriculture lands especially at steeper slopes. The ratio of *WL*/*SL* decreased when slope gradient increased; however, *WL* increased more significantly than *SL* as soil aggregates became finer. The result indicates that at all the slope gradients, *WL* was much larger than *SL*, indicating that wash load significantly contributes to the rain-induced erosion in the agricultural soil. Furthermore, with increasing slope gradient, the contribution of wash load to rain-induced erosion decreased, while it was greater in the soil containing finer aggregates. Also, with increasing rain intensity at lower slope gradients (<10%), further increase in splashed materials than that in washed materials occurred, whereas the reverse order was found at steeper slopes (>10%). The finding of this study revealed that the rain-induced erosion was transport-limited at the gentler slopes, whereas at the steeper slopes, it shifted to detachment-limited conditions.

1. Introduction

Soil erosion is a worldwide problem that threatens local natural resources (Cerdà et al., 2009; Zhao et al., 2013). Detachment, transport, and deposition are three basic processes of soil erosion, which occur simultaneously during an erosion event (Hairsine and Rose, 1992; Kinnell, 2005; Mahmoodabadi et al., 2014a,b). Rain-induced erosion includes the detachment and transport of particles respectively by erosive agents of raindrops and runoff (Zhang et al., 2007; Kinnell, 2009; Wakiyama et al., 2010). Soil aggregates are detached by raindrops impact (i.e. splash loss) and transported by shallow overland flow (i.e. wash loss) (Wuddivira et al., 2009; Bhattacharyyaa et al., 2010). In this context, it is important to know the characteristics of raindrops (Cerdà, 1997).

The rain-induced erosion occurs due to erosive agent of rain (Chaplot and Le Bissonnais, 2000; Mouzai and Bouhadef, 2003), and depends on raindrops characteristics, soil properties and local flow patterns (Planchon et al., 2000; Angulo-Martinez et al., 2012). Mermut et al. (1997) found that the amount of splash load under a rainfall intensity of 100 mm h^{-1} was 2.5 to 4 times higher than that under a lower rainfall intensity (40 mm h^{-1}). Therefore, a positive relationship has been reported between rainfall intensity and splash erosion rate (Quansah, 1981; Iserloh et al., 2012). In other words, rain intensity and duration are important factors in controlling soil erosion rate (González-Hidalgo et al., 2010, 2012; Serrano-Muela et al., 2015). In an arid environment, Ziadat and Taimeh (2013) found that rainfall intensity significantly influenced the amount of soil erosion.

Slope gradient also affects splash erosion, because as steepness increases, more soil particles are splashed downslope than upslope (Grismer, 2012). Indeed, slope gradient significantly influences downslope splash loss (Fu et al., 2011) as well as total splash rate (Van Dijk et al., 2003). Furthermore, the influence of slope steepness on soil erosion and runoff rates depends on cultivation systems and land use. Ziadat and Taimeh (2013) found that the rate of soil erosion in cultivated land was primarily affected by moisture content, while in uncultivated land, it was mostly influenced by slope steepness.

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Detached materials by splash are partly or totally available for transportation as wash load (Defersha et al., 2010). In some studies performed on gentler slopes, significant relationships were found between wash load and slope steepness (e.g., Liu et al., 1994; Sirjani and Mahmoodabadi, 2012), while in some others, no significant relationship was reported (e.g., Chaplot and Le Bissonnais, 2003). Fu et al. (2011) found that the amount of wash load increased with increasing slope gradient if the gradient is less than 58%; whereas, the opposite relationship was observed at steeper slopes. Liu et al. (1994) reported that the amount of wash load linearly increased with increasing slope gradient. In contrast, Chaplot and Le bissonnais (2003) applied low rainfall intensities between 1.5 to 30 mm h^{-1} to slopes with gradients from 4% to 8% and found that the measured wash load was not correlated with slope gradient..

Previous experimental studies (e.g. Van Dijk et al., 2003; Fu et al., 2011) reported contradictory results about the contribution of wash load and splash load to erosion rates. Bryan and Luk (1981) found that downslope splashed material was less abundant than wash load. In contrast, Van Dijk et al. (2003) found that on several slopes ranging from 0 to 40° under natural rainfall, both downslope and total splash load were more abundant than wash load. Also, Mermut et al. (1997) found that total splash load was much higher than wash load in loess soils. Van Dijk (2005) reported that the relative importance of splash load and wash load varied with test area, soil properties and rainfall characteristics.

Soil erosion models need accurate determination of parameters under different environmental conditions (Mahmoodabadi and Cerdà, 2013; Haregeweyn et al., 2013). The relative contributions of splash load and wash load due to rain-induced erosion in arid and semiarid environments has been rarely taken into account. The ability to quantify the relative contributions will enhance our understanding of sediment generation and redistribution processes. The first hypothesis of this study is that under higher rain intensities and at steeper slope gradients, splash and wash loads increase. The second hypothesis is that agricultural soils containing smaller aggregates have higher rain-induced erosion rates than soils with larger aggregates. Therefore, the objectives of this study are to 1) measure the amounts of wash load and splash load separately under different simulated rain intensities and slope gradients for agricultural soils with different aggregate size distributions; and 2) investigate temporal changes of wash load at different rain intensities and slope gradients under unsteady and steady state conditions..

2. Materials and methods

2.1. Soil sampling and properties

The soil used in the experiments is sandy loam, which was collected from a 0–20 cm upper depth of an agriculture field located in the Kerman province, central Iran (30° 14′ N and 57° 06′ E). The experimental field has been under agricultural cropping for more than 10 years, with a conventional management (moldboard plowing, two or three crops a year, without amendment incorporation and fertilization with urea). Irrigation has been performed with water having an electrical conductivity 0.86 dS m^{-1} and sodium adsorption ratio 1.21. At the moment of soil sampling, the field was under fallow for 2 years and was not fertilized. The soil is classified as Haplocalcids. The study area is known as semi-arid region, and the amount of monthly rainfall fluctuates sharply, and some erosive floods occur each year. A long-term mean annual precipitation of the area is 140 mm, and rainfall mainly occurs in winter. During the last 25 years, the maximum and minimum amounts of rainfall were recorded for years 1992 (307.2 mm) and 1998 (56.3 mm), respectively. The average annual temperature for this region is 16.5 °C and varies from 1.9 °C to 28.9 °C (Mahmoodabadi and Heydarpour, 2014).

The soil sample was air dried and crushed to pass separately through 2 and 4.75 mm sieves to prepare soil sub-samples $D_{2\ mm}$ and $D_{4.75\ mm}$ (Zamani and Mahmoodabadi, 2013). Soil texture was determined using the hydrometer method (Gee and Or, 2002). Aggregate size distribution was determined by sieving under both dry and wet conditions (Kemper and Rosenau, 1986). $CaCO_3$ equivalent was measured using the titration method (Page et al., 1992). Organic carbon content was determined by the modified Walkley and Black's (1934) method. Organic matter from the soil (1 g) was oxidized with $K_2Cr_2O_7$ 1 N (10 ml) in concentrated sulphuric acid for 30 min, followed by titration of the excess of $K_2Cr_2O_7$ with ferrous-ammonium sulfate 0.5 N and N-phenyl anthranilic acid to indicate the end point. Soil pH and electrical conductivity (*EC*) were measured in 1:5 (soil:water) extract (Pansu and Gautheyrou, 2006).

Table 1 shows the physical and chemical properties of the soil sub-samples $D_{2\ mm}$ and $D_{4.75\ mm}$ used in the experiment. $D_{4.75\ mm}$ had a greater content of silt and a lower amount of clay. The mean weight diameter (MWD) values for the dry and wet $D_{4.75\ mm}$ sub-samples were 0.78 and 0.3 mm, respectively, while those for $D_{2\ mm}$ were 0.46 and 0.26 mm. The content of organic carbon in both sub-samples was less than 1%; however, $D_{2\ mm}$ had more organic carbon than $D_{4.75\ mm}$. This may be because the decomposition rate of organic carbon can vary in different sizes of aggregate (Mangalassery et al., 2013). Strong et al. (2004) reported faster decomposition rates of organic carbon in soils with relatively larger aggregate and macro pore sizes. In general, macro pores contributes to ease the aeration of soil and consequently affects on soil microbial respiration as well as carbon mineralization. Also, the content of $CaCO_3$ equivalent was higher than 10%, which is dominant in arid and semiarid regions (Mahmoodabadi et al., 2013). The aggregate size distribution of the soil sub-samples is presented in Fig. 1. For both sub-samples, the percentage of the fraction of larger aggregate sizes was nearly the same, while in finer sizes it was higher for $D_{2\ mm}$ than $D_{4.75\ mm}$..

2.2. Experimental setup

Different rain intensities and slope gradients were used to simulate rain-induced erosion on each soil sub-sample. For this purpose, 60 experiments were carried out on two soil sub-samples with different particle size distributions. The soils were subjected to rain intensities of 57 and 80 mm h^{-1} and varying slope gradients of 0.5%, 2.5%, 5%, 10%, and 20%. These two simulated rain intensities were selected from typical thunderstorms occur once every 5 and 20 years in the study region. Each experiment was repeated three times and average values were used to evaluate the results of experiments. The experiments were carried out using a rainfall simulator and detachment tray facility (Fig. 2) as described by Arjmand Sajjadi and Mahmoodabadi (2015a,b). The rainfall events were simulated using a pressured nozzle placed 1.5 m above the soil surface. Measurement of drop sizes was taken using the stain method (Hall, 1970) and to assess the uniformity of rainfall, the Christiansen coefficient uniformity was used (Mahmoodabadi et al., 2007). The average drop size (± standard deviation) was 2.2 ± 0.08 mm and 2.5 ± 0.09 mm for rain intensities of 57 and 80 mm h^{-1}, respectively. For these intensities the coefficient of uniformity was 86% and 80%, respectively.

Table 1
Some physical and chemical properties of the soils used in the experiment.

Soil property	Soil sub-sample $D_{2\ mm}$	Soil sub-sample $D_{4.75\ mm}$
Sand (%)	58.8	56.6
Silt (%)	23.4	31.3
Clay (%)	17.8	12.1
Dry *MWD* (mm)	0.46	0.78
Wet *MWD* (mm)	0.26	0.3
Organic carbon (%)	0.9	0.75
pH	7.13	7.47
EC (dS m^{-1})	3.11	3.31
$CaCO_3$ eq. (%)	17.4	21

MWD: mean weight diameter, *EC*: electrical conductivity.