SEDIMENTS, SEC3 • HILLSLOPE AND RIVER BASIN SEDIMENT DYNAMICS • RESEARCH ARTICLE

Sediment concentration and hydraulic characteristics of rain-induced overland flows in arid land soils

Sara Arjmand Sajjadi · Majid Mahmoodabadi

Abstract

Purpose Rain-induced overland flow involves the detachment of soil particles by raindrop impact and the transportation by the resultant overland flow. The purpose of this study was to investigate the relationship between sediment concentration and different hydraulic parameters including flow depth, flow velocity, shear stress, stream power, and unit stream power. The effects of soil particle size distribution, rain intensity, and slope steepness on measured sediment concentration in rain-induced sheet flow were also examined.

Materials and methods Two arid land soils with different particles size distributions (D_{2mm} and $D_{4.75mm}$) were subjected to simulated rains using a detachment tray under infiltration conditions. Two rain intensities of 57 and 80 mm h^{-1} were simulated on slope gradients ranging from 0.5 to 20 %, resulting in rain-induced overland flows. After pre-wetting each soil, the sediment-laden overland flow was sampled at several time intervals (2, 5, 15, 20, 30, and 40 min) and the sediment concentration was determined. Different hydraulic parameters including flow depth, flow velocity, shear stress, stream power, and unit stream power were measured. The hydraulic parameters were used to model the sediment concentration, and the model performance was evaluated.

Results and discussion The result showed that the measured sediment concentration was greater in the higher rainfall intensity and at steeper slopes. With increasing slope steepness, sediment concentration increased from 4.3 to 15.5 kg m^{-3} and from 3.8 to 12.5 kg m^{-3} for soils D_{2mm} and $D_{4.75mm}$, respectively. There was a direct relationship between sediment concentration and the rain-induced flow velocity, shear stress, stream power, and unit stream power. Nevertheless, the values of sediment concentration increased as flow depth decreased on steeper slopes. Also, sediment concentration was lower in the soil containing larger aggregates than in the finer soil. The hydraulic parameters tended to overestimate low amounts of sediment concentration and underestimate high values.

Conclusions In general, the accuracy of the hydraulic parameters in predicting sediment concentration was: flow velocity > stream power > shear stress > unit stream power > flow depth. Flow velocity was the best predictor of sediment concentration with a linear relationship, whereas the other parameters showed nonlinear relationships. This study revealed that rain-induced sediment concentration at small scales can be modeled precisely on the basis of the flow velocity parameter.

1 Introduction

Soil erosion is one of the major environmental problems in the arid and semiarid regions (Martinez-Mena et al. 2002; Leh et al. 2013; Mandal and Sharda 2013; Wang and Shao 2013; Zhao et al. 2013), which lead to soil productivity reduction, pollution in water bodies, and an increase in sediment transport in rivers (Deng et al. 2008; García-Orenes et al. 2009; Cerdà et al. 2010; Kuhn et al. 2012; Ligonja and Shrestha 2013). Rainfall and the resultant overland flow are two important erosive agents in water erosion having the ability to detach and/or transport soil particles from the surface (Zhang et al. 2007). As a concept, pre-detached soil particles can be transported by overland flow and, in the case that the energy of flow is not sufficient to transport soil particles, deposition

S. Arjmand Sajjadi · M. Mahmoodabadi (✉)
Department of Soil Sciences, Agriculture Faculty, Shahid Bahonar University of Kerman, Kerman, Iran
e-mail: mahmoodabadi@uk.ac.ir

occurs (Shih and Yang 2009). In this context, the modeling of soil erosion can be used for the prediction of soil loss and sediment deposition for different conditions (Yu 2003).

Rain-induced erosion is recognized as the first step in which soil particles are detached by raindrop impact and transported by shallow surface flow (Wuddivira et al. 2009). Sheet and interrill erosion are two forms of erosion where detachment and transport processes are dependent on the raindrop impact (Kinnell 2009). Raindrop-induced overland flow occurs when the overland flow does not have sufficient energy to detach soil particles unless raindrops impacting the flow disturb the bed underlying the flow (Kinnell 2005). According to Kinnell (2010), in rain-impacted flows, detachment and transport processes are highly dependent on the dissipation of raindrop kinetic energy. Thus, it is essential to have information about the drop characteristics (Cerdà 1997) and the soil erodibility (Cerdà and Doerr 2007).

Sediment concentration depends on the reaction of the soil surface to the erosive stress produced by either raindrop impact or overland flow or both (Kinnell 2000). Different factors such as rainfall intensity, slope steepness, and soil properties are assumed to be the important parameters to determine sediment concentration (Defersha and Melesse 2012). Also, several hydraulic parameters (e.g., flow depth, flow velocity, shear stress, stream power, and unit stream power) are used to characterize the erosive power of the overland flow for determining sediment concentration (Trout and Neibling 1993; Shih and Yang 2009). In situations of higher erosive powers, due to greater flow rates, sediment concentration increases (Sirjani and Mahmoodabadi 2012a). In addition, slope steepness has an important role in controlling stream power. In fact, stream power is obtained by multiplying hydraulic shear stress and flow velocity; both depend on slope steepness. Furthermore, aggregate breakdown under rainfall, which depends on soil strength, is a key parameter controlling sediment concentration (Le Bissonnais 1995; Cerdà 1996; Bryan 2000). In general, aggregate breakdown occurs when its strength is reduced by wetting to a level where the stress imposed by raindrops is sufficient to disrupt the aggregate (Assouline 2004).

Many studies have investigated sediment concentration at large scales (Gabet and Dunne 2003; Yuill and Gasparini 2011; Shi et al. 2012a, b). Nevertheless, few, if any, studies have assessed sediment concentration at small scales (Defersha and Melesse 2012; Sirjani and Mahmoodabadi 2012a). Also, soil erosion modeling contributes to the understanding of the erosion processes (Mahmoodabadi and Cerda 2013; Mahmoodabadi et al. 2014a). Only a few studies have investigated rain-induced erosion processes and the controlling erosive agents in arid and semiarid regions. Therefore, in this study, a simulated rainfall was applied at a small scale (i.e., detachment tray) to assess sediment concentration in relation to hydraulic parameters of arid region soils. The main objectives of this study were the following: (1) to characterize the influence of rain intensity, slope steepness, and particle size distribution on the hydraulic characteristics of rain-induced overland flow, as well as sediment concentration and (2) to investigate the relationship between sediment concentration and hydraulic parameters in arid land soils.

2 Materials and methods

2.1 Soil samples

The soil used for the experiments was taken from an agriculture field in an arid region. At the time of soil sampling, the field was under fallow for 2 years. The soil is classified as Haplocalcids. A long-term mean precipitation of the area is 140 mm year^{-1}, which mainly occurs in winter. During the recent 25 years, the maximum and minimum amounts of rainfall were recorded in 1992 (307.2 mm year^{-1}) and 1998 (56.3 mm year^{-1}), respectively. The average annual temperature for this region is 16.5 °C and varies from 1.9 to 28.9 °C.

The soil sample was air dried and then passed through 2 and 4.75 mm sieves separately. By this way, two soil subsamples with different particle size compositions were prepared, which were named D_{2mm} and $D_{4.75mm}$, respectively. Soil texture analysis was done using the hydrometer method, and aggregate size distribution was determined using a sieve shaker facility in cases of dry and wet (Kemper and Rosenau 1986). In addition, pH and EC were measured in 1:5 (soil/water) suspension (Page et al. 1992). The organic matter content was determined using the Walkley and Black (1934) procedure. The CaCO$_3$ equivalent was measured using the titration method (Page et al. 1992). The measured properties of the soils are presented in Table 1. The texture of both soils is classified as sandy loam, while the percentages of sand, silt, and clay were different in the soils. The soil containing larger aggregates ($D_{4.75mm}$) had greater content of silt and lower amounts of clay and sand. The distribution of primary particles in different aggregate size classes is not necessarily the same (Mahmoodabadi and Ahmadbeygi 2011, 2013). The values of dry and wet mean weight diameters (MWD) for soil $D_{4.75mm}$ were 0.78 and 0.3 mm, respectively while, in soil D_{2mm}, these were 0.46 and 0.26 mm, respectively. Both soils showed a very low organic carbon content (<1 %) as is usual in semiarid and arid soils, whereas the content of CaCO$_3$ equivalent was considerable (>10 %).

2.2 Experimental framework

In this study, three factors including particle size distribution at two levels, slope steepness at five levels, and rain intensity at two levels were examined. The experiment was designed as factorial in a completely randomized design with three replications; thus, a total of 60 runs were performed. In general,

Table 1 Some physical and chemical properties of the two study soils

Soil	Sand (%)	Silt (%)	Clay (%)	Dry MWD (mm)	Wet MWD (mm)	OC (%)	pH	EC (dS m^{-1})	CaCO$_3$ (%)
Soil D$_{2mm}$	58.8	23.4	17.8	0.46	0.26	0.9	7.13	3.11	17.4
Soil D$_{4.75mm}$	56.6	31.3	12.1	0.78	0.3	0.75	7.47	3.31	21

MWD mean weight diameter, *EC* electrical conductivity, *OC* organic carbon

two different soil samples (D$_{2mm}$ and D$_{4.75mm}$) were placed at 0.5, 2.5 5, 10, and 20 % slope gradients under two rain intensities of 57 and 80 mm h^{-1}.

2.3 Rainfall simulator

To study rain-induced erosion, a rainfall simulator equipped with a single pressurized nozzle was used. The nozzle can produce raindrops from a height of 1.5 m with a constant intensity. The raindrops diameter was measured experimentally using the stain method described by Hall (1970). The obtained median raindrop size was 2.2 mm (standard deviation ±0.08 mm) and 2.5 mm (standard deviation ±0.09 mm) for rain intensities of 57 and 80 mm h^{-1}, respectively. The uniformity coefficient for the simulated rains was calculated using the Christiansen coefficient uniformity (Mahmoodabadi et al. 2007), which, for the rain intensities of 57 and 80 mm h^{-1}, was 86 and 80 %, respectively.

2.4 Detachment tray

The experiments were conducted using a drainable detachment tray (Fig. 1), 35-cm long, 30-cm wide, and 10-cm deep. The tray consisted of two splash buffers placed on two sides of the detachment tray and a test area with 15-cm wide and 30-cm long in which the studied soils could be examined by
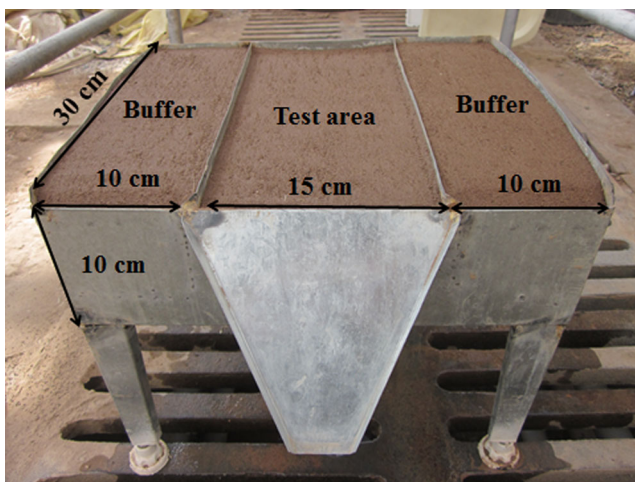

Fig. 1 The detachment tray used in the rainfall simulation experiments

collecting overland flow and transported sediment. At the base of the tray, a percolation outlet was used for collecting infiltrated water.

2.5 Determination of hydraulic parameters

In all experiments, each soil sample was put in the detachment tray, then was saturated from the bottom for 24 h. Afterwards, the drainage water was removed out of the tray, and the experiment lasted for 40 min. For each rainfall event, the sediment-laden overland flow was sampled at selected time intervals (2, 5, 15, 20, 30, and 40 min) and volumetrically measured. The sediment in the collected samples was allowed to settle, separated from the water, and dried in an oven at 105 °C for 24 h. The sediment concentration was determined as the ratio of dry sediment mass to sampled runoff volume for each time interval.

Mean flow velocity was measured using the dye method (Sirjani and Mahmoodabadi 2012b). Afterwards, for each experiment, the average depth of flow was calculated as:

$$D = \frac{q}{V} \tag{1}$$

where D is the average flow depth (m), q is the average unit flow discharge per unit width (m^2 s^{-1}), and V is the measured flow velocity (m s^{-1}). Since the tray length was short (30 cm) and the rain was introduced on the whole surface of the soils, the changes of q over the tray length were assumed to be negligible.

The shear stress was determined as (Nearing et al. 1997):

$$\tau = \rho g D S \tag{2}$$

where τ is shear stress (Pa), ρ is flowing water density (kg m^{-3}), and g is the gravitational acceleration (m s^{-2}).

The stream power (Ω; W m^{-2}) was calculated as (Mahmoodabadi et al. 2014b):

$$\Omega = \tau V \tag{3}$$

Unit stream power (U; m s^{-1}) was determined as (Sirjani and Mahmoodabadi 2012b):

$$U = VS \tag{4}$$

Accordingly, for each rainfall event, the average of sediment concentration and corresponding hydraulic parameters were calculated (40 min). Finally, to analyze the effects of rain intensity, slope gradient as well as soil type on sediment concentration and hydraulic parameters, statistical analysis was done in the SAS framework. For obtaining the main differences between the obtained values, the Duncan's (α=0.05) test was applied.

3 Results and discussion

3.1 Hydraulic parameters

Table 2 shows the minimum, maximum, and average values of different hydraulic parameters. In general, greater values of the parameters were obtained for soil D_{2mm} compared to soil $D_{4.75mm}$, indicating higher erosivity of overland flow generated on the soil containing finer particles. Figure 2 shows the results of hydraulic parameters for soil D_{2mm} at various slope gradients and rain intensities. The mean flow velocity varied from 0.013 to 0.039 m s^{-1} and 0.013 to 0.041 m s^{-1} as slope steepness increased from 0.5 to 20 % for rain intensities of 57 and 80 mm h^{-1}, respectively (Fig. 2a). Also, the effects of slope steepness and rain intensity on flow velocity intensified as slope gradient became steeper. It is obvious that at steeper slopes, the flow velocity and the resultant stream power and transport capacity of runoff increase so that more pre-detached materials can be transported by the raindrop-driven overland flow (Grismer 2012). In other words, due to higher flow velocities generated on steeper slopes, soil particles can be transported easier (Fu et al. 2011).

According to Fig. 2b, the obtained flow depth ranged from 7.19×10^{-5} to 2.18×10^{-4} m for a rain intensity of 57 mm h^{-1} and from 7.95×10^{-5} to 2.13×10^{-4} m for a rain intensity of 80 mm h^{-1}. The depth of flow decreased with increasing slope steepness for both rainfall intensities. In fact, due to higher flow velocities at steeper slopes, shallower flow depths were achieved. Moreover, shear stress changed for 57 and 80 mm h^{-1} rain intensities from 0.011 to 0.141 Pa and 0.010 to 0.156 Pa, respectively, as slope gradient increased from 0.5

to 20 %, respectively (Fig. 2c). Also, the overland stream power ranged from 1.4×10^{-4} to 5.5×10^{-3} W m^{-2} and 1.3×10^{-4} to 6.4×10^{-3} W m^{-2} on 0.5 to 20 % slopes under rain intensities of 57 and 80 mm h^{-1}, respectively (Fig. 2d). The values of unit stream power varied from 6.4×10^{-5} to 7.7×10^{-3} m s^{-1} for rain intensity of 57 mm h^{-1} as slope gradient increased from 0.5 to 20 %. In contrast, this parameter changed from 6.3×10^{-5} m s^{-1} at 0.5 % slope to 8.2×10^{-3} m s^{-1} at 20 % slope (Fig. 2e).

With increasing slope steepness and rain intensity, all the hydraulic parameters, except flow depth, increased (Fig. 2). Consequently, the maximum values were observed at the steepest slope (20 %) under higher rain intensity (80 mm h^{-1}). Also, the results indicated that the hydraulic parameters had greater values at a rain intensity of 80 than at 57 mm h^{-1}. This finding implied that the higher rain intensity led to stronger stream powers of overland flow.

The hydraulic parameters for different slope gradients and rain intensities for soil $D_{4.75mm}$ are reported in Fig. 3. The results showed that the measured flow velocity for a rain intensity of 57 mm h^{-1} increased from 0.0099 to 0.0313 m s^{-1} as slope gradient increased from 0.5 to 20 %, respectively. For a rain intensity of 80 mm h^{-1}, flow velocity increased from 0.0113 to 0.0378 m s^{-1} with increasing slope steepness from 0.5 to 20 % (Fig. 3a). For a rain intensity of 57 mm h^{-1}, the depth of flow decreased from 1.49×10^{-4} to 5.24×10^{-5} m as slope steepness increased from 0.5 to 20 %. In addition, for a rain intensity of 80 mm h^{-1}, there was a reduction in the obtained values of flow depth from 1.80×10^{-4} m at 0.5 % slope to 6.97×10^{-5} m at 20 % slope (Fig. 3b). For both rain intensities, the overland shear stress was found to increase with increasing slope steepness. As a result, for rain intensities of 57 and 80 mm h^{-1}, shear stress increased from 0.0073 to 0.1028 Pa and from 0.0088 to 0.01366 Pa as slope gradient increased from 0.5 to 20 %, respectively (Fig. 3c). The overland stream power varied from 7.3×10^{-5} to 3.2×10^{-3} W m^{-2} and from 1.0×10^{-3} to 5.2×10^{-3} W m^{-2} as slope gradient increased from 0.5 to 20 % for rain intensity of 57 and 80 mm h^{-1}, respectively (Fig. 3d). Furthermore, after increasing slope gradient from 0.5 to 20 %, the measured unit stream power for a rain intensity of 57 increased from 4.96×10^{-5} to

Table 2 Minimum, maximum, and average values of the hydraulic parameters for the two study soils

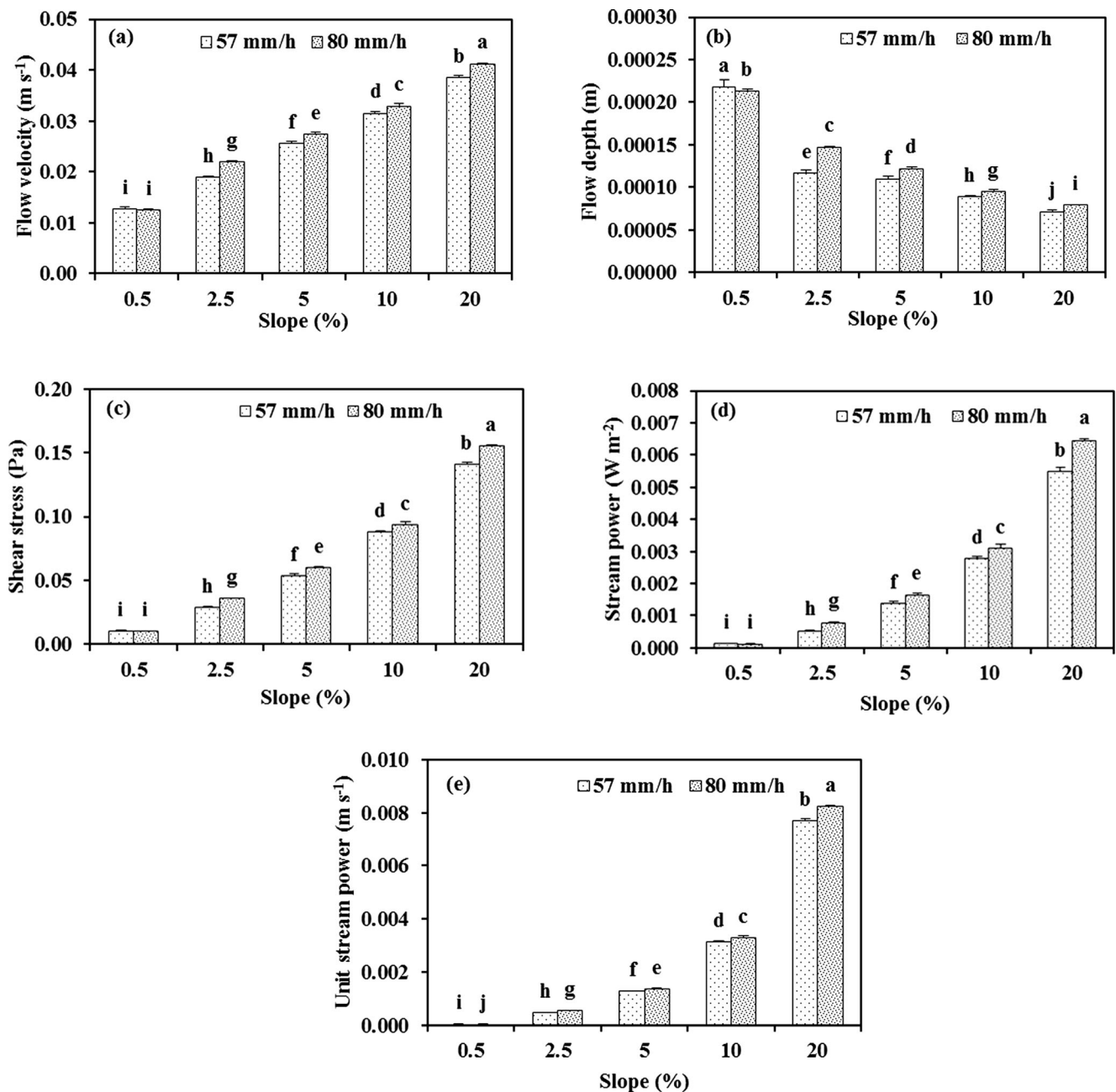| Parameter	Soil D_{2mm}			Soil $D_{4.75mm}$		
	Max	Min	Average	Max	Min	Average
Flow velocity (m s^{-1})	0.04144	0.01216	0.02641	0.03837	0.00985	0.02257
Flow depth (m)	0.00022	0.00007	0.00013	0.00019	0.00005	0.00009
Shear stress (Pa)	0.15652	0.00989	0.06781	0.13945	0.00722	0.05423
Stream power (W m^{-2})	0.00651	0.00012	0.00225	0.00537	0.00007	0.00158
Unit stream power (m s^{-1})	0.00829	0.00006	0.00263	0.00767	0.00004	0.00227

Fig. 2 Measured hydraulic parameters including **a** flow velocity, **b** flow depth, **c** shear stress, **d** stream power, and **e** unit stream power at different slope gradients and rain intensities for soil D_{2mm}. Mean comparison using Duncan's test (α=0.05) and *error bars* represent standard errors of the means

6.26×10^{-3} m s^{-1} while for a rain intensity of 80 mm h^{-1}, the values changed from 5.63×10^{-5} to 7.57×10^{-3} m s^{-1} (Fig. 3e).

For the higher rain intensity of 80 mm h^{-1}, the measured hydraulic parameters (flow depth, flow velocity, shear stress, stream power, and unit stream power) were greater than for the rain intensity of 57 mm h^{-1}. The comparison of hydraulic parameters in both soils (Figs. 2 and 3) showed that the measured parameters in soil $D_{4.75mm}$ were lower than in soil D_{2mm}. This means that the generated overland flow is not only affected by slope steepness and rainfall intensity, but it is also

influenced by the aggregate size distribution of the soils. Bryan (2000) reported that the percentage of larger aggregates at the surface of soil can control flow velocity and flow stream power. The plausible reason for lower hydraulic parameters in soil $D_{4.75mm}$ may be attributed to the existence of larger aggregates and the subsequent larger pores in this soil, which enable water to pass easily through the soil and generate less overland flow. The result showed that the maximum infiltration rates for soils D_{2mm} and $D_{4.75mm}$ were 24.7 and 39.1 mm h^{-1} for the rain intensity of 57, and 30.6, and 45.1 mm h^{-1} for the rain intensity of 80 mm h^{-1}.
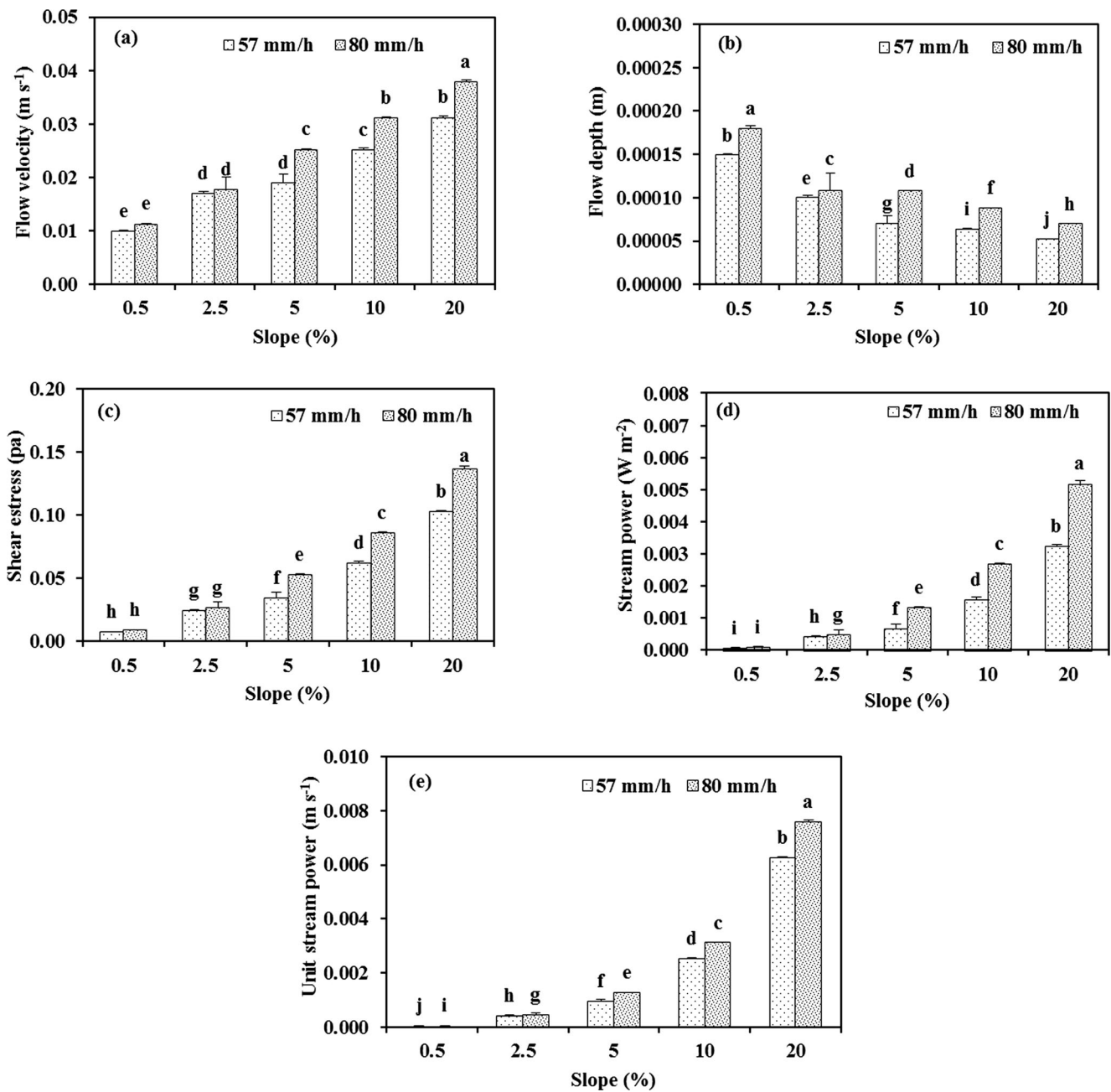
Fig. 3 Measured hydraulic parameters including **a** flow velocity, **b** flow depth, **c** shear stress, **d** stream power, and **e** unit stream power at different slope gradients and rain intensities for soil $D_{4.75mm}$. Mean comparison using Duncan's test ($\alpha=0.05$) and *error bars* represent standard errors of the means

3.2 Sediment concentration

The comparison of sediment concentration between the soils due to different rain intensities and slope gradients is shown in Fig. 4. It was found that sediment concentration was greater in the higher rainfall intensity and at steeper slopes. For soil D_{2mm}, as slope steepness increased from 0.5 to 20 %, the measured sediment concentration increased from 4.3 to 14.6 kg m^{-3} and from 7.7 to 15.5 kg m^{-3} in rain intensities of 57 and 80 mm h^{-1}, respectively (Fig. 4a). The obtained

values of sediment concentration for soil $D_{4.75mm}$ under a rain intensity of 57 mm h^{-1} increased from 3.8 to 11.2 kg m^{-3} when slope steepness increased from 0.5 to 20 % and correspondingly increased from 4.1 to 12.5 kg m^{-3} under a rain intensity of 80 mm h^{-1} (Fig. 4b). Defersha and Melesse (2012) found that rain intensity and slope gradient had significant influences on sediment concentration. Slope gradient is important as more soil particles are splashed down-slope than up-slope (Dunne et al. 2010; Grismer 2012). In fact, slope gradient has a significant influence on the down-slope splash
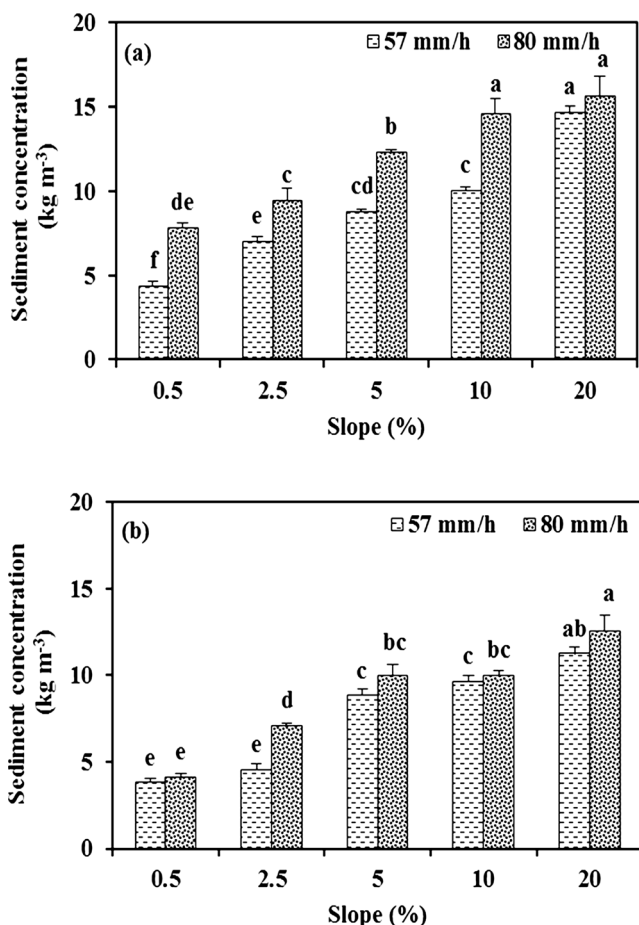
Fig. 4 The changes of sediment concentration at different slope gradients and rain intensities for **a** soil D_{2mm} and **b** soil $D_{4.75mm}$. Mean comparison using Duncan's test ($\alpha=0.05$) and *error bars* represent standard errors of the means

loss (Fu et al. 2011) as well as total splash rate (Van Dijk et al. 2003).

Comparison of sediment concentration between the studied soils showed that soil D_{2mm} exhibited higher values of sediment concentration than soil $D_{4.75mm}$ (Fig. 4a, b). However, flow hydraulic conditions determine the erosive forces acting on the eroding surface, although soil properties can also control these conditions, most notably through the aggregate stability influencing on surface roughness (Parsons et al. 1994; Bryan 2000). In fact, soil properties affect rain-induced overland flow through soil detachability by distributing erosive forces and water infiltration into the soil (Dlamini et al. 2011).

3.3 Relationship between sediment concentration and the hydraulic parameters

Figures 5 and 6 show the relationship between the measured sediment concentration and hydraulic parameters for soil D_{2mm} and for soil $D_{4.75mm}$, respectively. As is shown, the sediment concentration had positive relationships with flow velocity, shear stress, stream power, and unit stream power

and a negative relationship with flow depth. Also, the result indicated that the sediment concentration had greater values at higher rain intensity (80 mm h^{-1}) as hydraulic parameters (except flow depth) increased with increasing rain intensity. Ziadat and Taimeh (2013) investigate the effect of rainfall intensity, slope, land use, and antecedent soil moisture on soil erosion and runoff. They found that rainfall intensity was the most important factor affecting soil erosion. Kinnell (2010) found that the presence of water layer on the soil surface can cause the dissipation of raindrop kinetic energy. In fact, an increase in flow depth decreases the rate at which sediment was transported by flow, consequently leading to a decline in sediment concentration. It was also found that all the studied hydraulic parameters had a significant relationship with the measured sediment concentration. Shih and Yang (2009) concluded that gravity is the significant driving force for overland flow and the unit stream power dominates sediment concentration among all hydraulic parameters. Proffitt et al. (1993) concluded that for stream powers <0.01 W m^{-2}, the most contribution to sediment concentration was related to soil detachment by raindrop impact, while overland flow entrainment was the dominant contributor at higher stream powers. Due to the small scale of the detachment tray and low erosivity of the flows, the overland stream power seems to be insufficient to entrain soil materials from the surface, but was sufficient to transport the materials pre-detached by raindrop impact.

Among the different hydraulic parameters, just flow velocity exhibited a linear relationship with sediment concentration, whereas the other parameters showed nonlinear (power) relationships. Cao et al. (2013) found a linear relationship between the soil loss on loess road surface and stream power. Sirjani and Mahmoodabadi (2012b) reported that the nonlinear relationships make the determination of erodibility and critical values disputable, while in a linear trend, these two process-based parameters can be determined more easily and accurately.

In this study, the hydraulic parameters were used to model sediment concentration. The best fitted equations obtained were:

$$c = 0.016\, D^{-0.68} \quad \left(R^2 = 0.396\right) \tag{5}$$

$$c = 280.2\, V^{0.919} \quad \left(R^2 = 0.841\right) \tag{6}$$

$$c = 30.89\, \tau^{0.405} \quad \left(R^2 = 0.819\right) \tag{7}$$

$$c = 60.97\Omega^{0.282} \quad \left(R^2 = 0.828\right) \tag{8}$$

$$c = 39.88\, U^{0.22} \quad \left(R^2 = 0.774\right) \tag{9}$$

where c is the predicted sediment concentration (kg m^{-3}) using the hydraulic parameters. Figure 7 shows plots
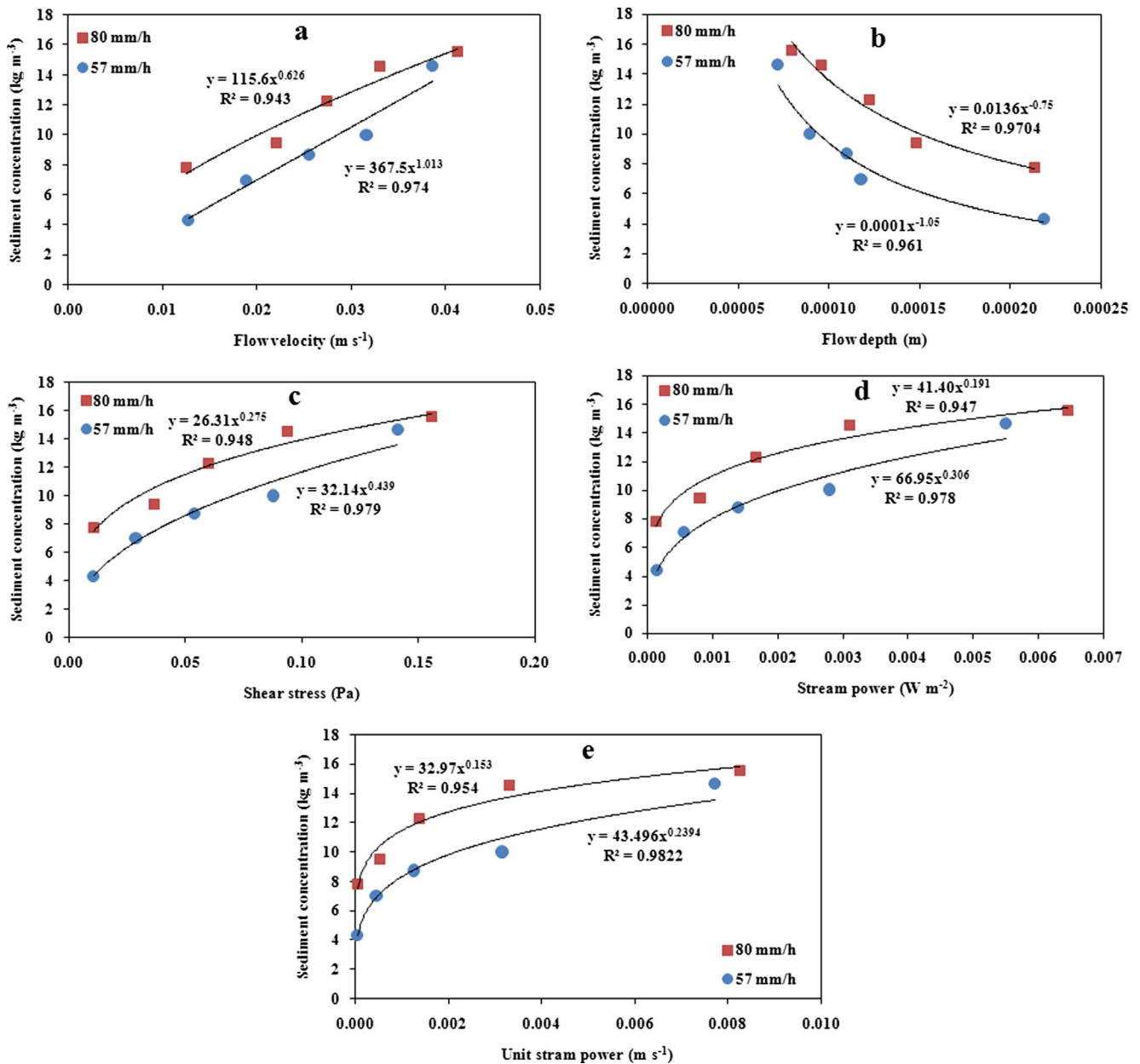
Fig. 5 The relationship between sediment concentration and measured hydraulic parameters including **a** flow velocity, **b** flow depth, **c** shear stress, **d** stream power, and **e** unit stream power for soil D_{2mm}

measured against predicted values of sediment concentration estimated by the above equations and shows that almost all the hydraulic parameters tended to overestimate low amounts of sediment concentration and underestimate high values. There is usually a tendency for erosion models to over-predict small erosion values and under-predict large ones (Tiwari et al. 2000; Kinnell 2003; Mahmoodabadi and Cerda 2013). Nearing (1998) explained part of the reason for this trend in terms of the natural variability of the measured within-treatment variability. However, Tiwari et al. (2000) stated that this is common in most erosion models.

Among the studied hydraulic parameters, flow velocity showed the best performance in predicting sediment concentration ($R^2 = 0.841$), followed by stream power ($R^2 = 0.828$) and shear stress ($R^2 = 0.819$) of the rain-induced overland flow. In contrast, flow depth had no acceptable performance in estimating sediment concentration due to lower coefficient of determination ($R^2 = 0.396$) and higher deviation from the 1:1 line. This finding reveals that for rain-induced overland flow at the small scale of the detachment tray, flow velocity can be used for modeling of sediment concentration. Similarly, Fox and Bryan (1999) tested the relationship of soil loss by interrill
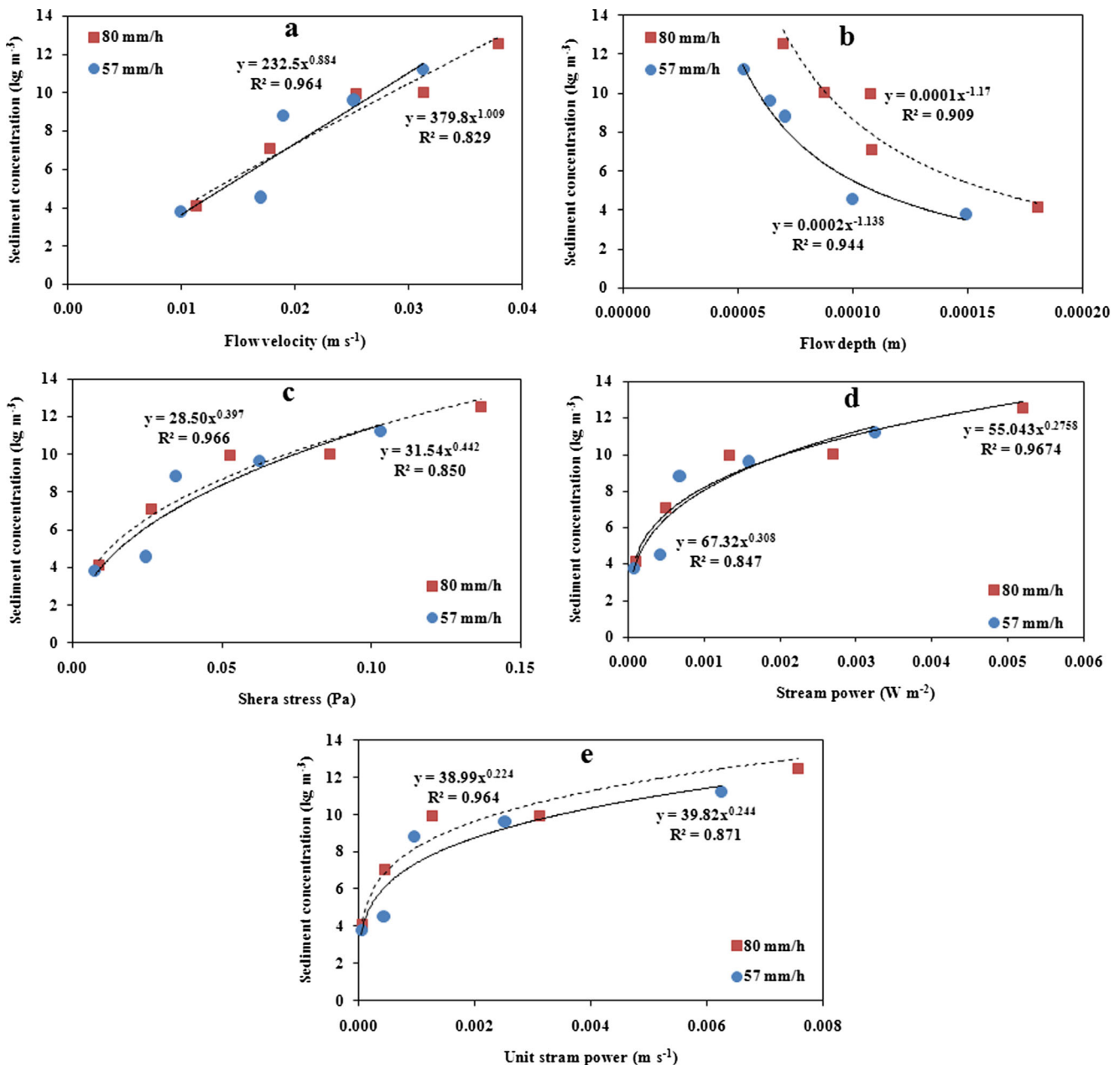
Fig. 6 The relationship between sediment concentration and measured hydraulic parameters including **a** flow velocity, **b** flow depth, **c** shear stress, **d** stream power, and **e** unit stream power for soil $D_{4.75mm}$

erosion to different hydraulic parameters including mean runoff velocity, shear stress, shear velocity, and unit stream power. They found that among the hydraulic parameters, soil loss was best correlated with flow velocity.

On the other hand, due to the relatively low accuracy of flow depth applied in the formulas of the other hydraulic parameters, some reductions in their performance occurred. Another plausible reason for this finding is that sediment concentration depends on both raindrop impact and the resultant overland flow. In rain-impacted flows, the dissipation of raindrop kinetic energy plays an important role in the detachment

and transportation of soil particles (Kinnell 2010; Mahmoodabadi and Rouhipour 2011). Consequently, at deeper flow depths, the measured values of sediment concentration were reduced. Bryan (1979) examined the influence of slope angle on soil entrainment by sheetwash and rainsplash and observed very considerable variability in the result. The high variability of results was attributed to microscale variations in surface soil characteristics, in surface water depth, and in raindrop size and point of impact. In addition, there may be an interaction between rain-induced sediment concentration and seal formation, but this could not be proven in this
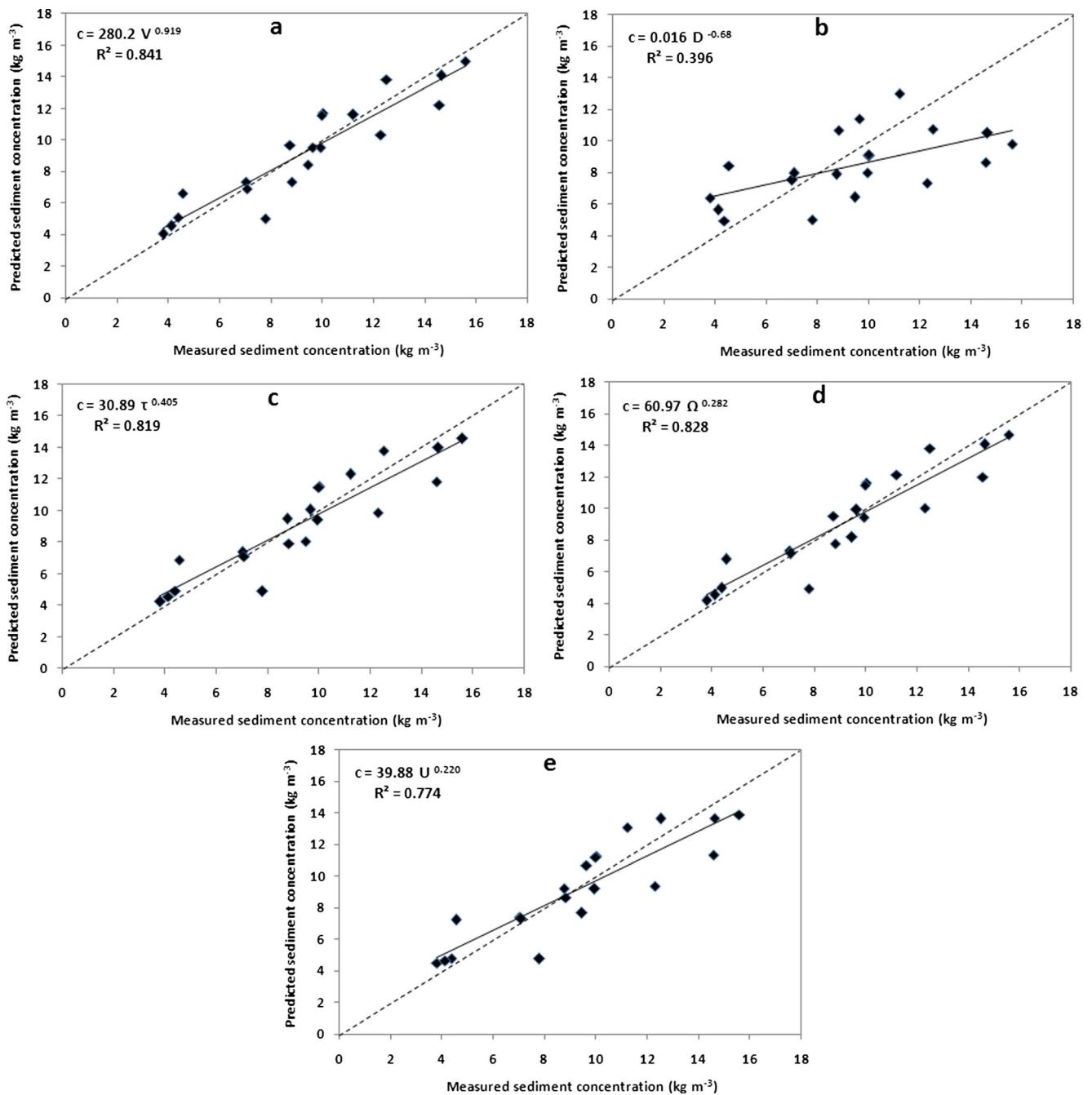
Fig. 7 Measured vs. predicted values of sediment concentration using different hydraulic parameters including **a** flow velocity, **b** flow depth, **c** shear stress, **d** stream power, and **e** unit stream power

experiment. Rainfall, runoff, and erosion all change soil surface roughness, cohesion (crusting), as well as infiltration (sealing) and, therefore, affect the hydraulic properties of the soil surface (Kuhn et al. 2012). It seems that due to the small scale of the detachment tray, the overland flow can only transport those materials pre-detached by raindrop impact. Alternatively, at steeper slopes, shallower flow depths were observed. This means that in spite of lower flow depths at steeper slopes, higher flow velocities were generated, which can result in higher sediment concentrations.

The results of the experiment have implications for rain-induced erosion studies. Flow velocity was found to be the most important hydraulic parameter affecting sediment concentration. On the other hand, on longer slopes, the overland flow has greater runoff velocity, thereby increasing erosion rates (Fox and Bryan 1999). In fact, this study was performed at the small scale of a detachment tray, which may be different from continuous field conditions, as soil erosion measurements are scale dependent (Bryan 1979; Iserloh et al. 2012; Palacio et al. 2014). Also, flow velocity increases the transport

capacity of overland flow in rain-induced erosion conditions (Fox and Bryan 1999). The results indicate that flow velocity must be measured routinely in rain-induced erosion experiments.

4 Conclusions

This study focused on the interaction between sediment concentration and some hydraulic parameters in a rain-induced erosion experiment. The results showed that there was a direct relationship between sediment concentration and flow velocity, shear stress, stream power, and unit stream power. Also, with increasing slope steepness and rain intensity, the measured sediment concentration increased. Nevertheless, the values of sediment concentration increased as flow depth decreased at steeper slopes. The results imply that sediment concentration was lower in the soil containing larger aggregates than in the other, finer soil. Flow velocity was the only parameter that exhibited a linear relationship with sediment concentration, whereas the other parameters showed nonlinear (power) relationships. Also, flow velocity was found to be the best predictor of sediment concentration among the studied hydraulic parameters. In general, the priority in the applied hydraulic parameters was: flow velocity > stream power > shear stress > unit stream power > flow depth. Overall, all of the hydraulic parameters tended to overestimate low amounts of sediment concentration and underestimate high values. Due to the small scale of the detachment tray and the low erosivity of the flows, the overland flow stream powers were insufficient to entrain soil particles from the surface, but were sufficient to transport those materials pre-detached by raindrop impact. The findings of this study revealed that sediment concentration at small scales can be modeled precisely based on the velocity of the rain-induced overland flow. It was concluded that flow velocity must be measured routinely in rain-induced erosion experiments.

References

Assouline S (2004) Rainfall-induced soil surface sealing: a critical review of observations, conceptual models, and solutions. Vadose Zone J 3: 570–591

Bryan RB (1979) The influence of slope angle on soil entrainment by sheetwash and rainsplash. Earth Surf Process 4:43–58

Bryan RB (2000) Soil erodibility and processes of water erosion on hillslope. Geomorphology 32:385–415

Cao L, Zhang K, Dai H, Liang Y (2013) Modeling interrill erosion on unpaved roads in the loess plateau of China. Land Degrad Dev. doi: 10.1002/ldr.2253

Cerdà A (1996) Soil aggregate stability in three Mediterranean environments. Soil Technol 9:133–141

Cerdà A (1997) Rainfall drop size distribution in Western Mediterranean Basin, València, Spain. Catena 30:169–182

Cerdà A, Doerr SH (2007) Soil wettability, runoff and erodibility of major dry-Mediterranean land use types on calcareous soils. Hydrol Process 21:2325–2336

Cerdà A, Hooke J, Romero-Diaz A, Montanarella L, Lavee H (2010) Soil erosion on Mediterranean type-ecosystems. Land Degrad Dev 21: 71–74

Defersha MB, Melesse AM (2012) Effect of rainfall intensity, slope and antecedent moisture content on sediment concentration and sediment enrichment ratio. Catena 90:47–52

Deng ZQ, Lima JLD, Jung HS (2008) Sediment transport rate-based model for rainfall-induced soil erosion. Catena 76:54–62

Dlamini P, Orchard C, Jewitt G, Lorentz S, Titshall L, Chaplot V (2011) Controlling factors of sheet erosion under degraded grassland in the sloping land of KwaZulu-Natal, South Africa. Agric Water Manag 98:1711–1718

Dunne T, Malmon DV, Mudd SM (2010) A rain splash transport equation assimilating field and laboratory measurements. J Geophys Res Earth Surf 115, F01001. doi:10.1029/2009JF001302

Fox DM, Bryan RB (1999) The relationship of soil loss by interrill erosion to slope gradient. Catena 38:211–222

Fu S, Liu B, Liu H, Xu L (2011) The effect of slope on interrill erosion at short slopes. Catena 84:29–34

Gabet EJ, Dunne T (2003) Sediment detachment by rain power. Water Resour Res 39:1–12

García-Orenes F, Cerdà A, Mataix-Solera J, Guerrero C, Bodí MB, Arcenegui V, Zornoza R, Sempere JG (2009) Effects of agricultural management on surface soil properties and soil-water losses in eastern Spain. Soil Tillage Res 106:117–123

Grismer M (2012) Standards vary in studies using rainfall simulators to evaluate erosion. Calif Agric 66:102–107

Hall MJ (1970) Use of the stain method in determining the drop-size distributions of coarse liquid sprays. Trans ASAE 41:33–37

Iserloh T, Ries JB, Cerdà A, Echeverría MT, Fister W, Geißler C, Kukn NJ, Leon FJ, Peters P, Schindewolf M, Schmidt J, Scholten T, Seeger M (2012) Comparative measurements with seven rainfall simulators on uniform bare fallow land. Z Geomorphol 57:11–26

Kemper WD, Rosenau RC (1986) Aggregate stability and size distribution. In: Klute A (ed) Methods of soil analysis. ASA and SSSA, Madison, pp 425–442

Kinnell PIA (2000) The effect of slope length on sediment concentration associated with side-slope erosion. Soil Sci Soc Am J 64:1004–1008

Kinnell PIA (2003) Event erosivity factor and errors in erosion predictions by some empirical models. Aust J Soil Res 41:991–1003

Kinnell PIA (2005) Raindrop impact induced erosion processes and prediction: a review. Hydrol Process 19:2815–2844

Kinnell PIA (2009) The impact of slope length on the discharge of sediment by rain impact induced saltation and suspension. Earth Surf Process Landf 34:1393–1407

Kinnell PIA (2010) Comment on a new splash and sheet erosion equation for range lands. Soil Sci Soc Am J 74:340–341

Kuhn NJ, Armstrong EK, Ling AC, Connolly KL, Heckrath G (2012) Interrill erosion of carbon and phosphorus from conventionally and organically farmed Devon silt soils. Catena 91:94–103

Le Bissonnais Y (1995) Soil characteristics and aggregate stability. In: Agassi M (ed) Soil erosion, conservation and rehabilitation. CRC Press, pp 41–60

Leh M, Bajwa S, Chaubey I (2013) Impact of land use change on erosion risk: an integrated remote sensing geographic information system and modeling methodology. Land Degrad Dev 24:409–421

Ligonja PJ, Shrestha RP (2013) Soil erosion assessment in Kondoa eroded area in Tanzania using universal soil loss equation, geographic information system and socioeconomic approach. Land Degrad Dev. doi:10.1002/ldr.2215

Mahmoodabadi M, Ahmadbeygi B (2011) Effect of some physical and chemical properties of soil on aggregate stability in some cultivation systems. J Soil Manag Sustain Prod 1:61–79

Mahmoodabadi M, Ahmadbeygi B (2013) Effect of primary particle size distribution on aggregate stability at different size classes. Water Soil Sci 23:207–219

Mahmoodabadi M, Cerda A (2013) WEPP calibration for improved predictions of interrill erosion in semi-arid to arid environments. Geoderma 204–205:75–83

Mahmoodabadi M, Rouhipour H (2011) Study on process changes in some indices of soil erodibility and deposibility using rainfall simulator. J Water Soil Conserv 18:145–166

Mahmoodabadi M, Rouhipour H, Arabkhedri M, Rafahi HG (2007) Intensity calibration of SCWMRI rainfall and erosion simulator. J Watershed Manag Sci Eng 1:39–50

Mahmoodabadi M, Ghadiri H, Bofu Y, Rose C (2014a) Morpho-dynamic quantification of flow-driven rill erosion parameters based on physical principles. J Hydrol 514:328–336

Mahmoodabadi M, Ghadiri H, Rose C, Bofu Y, Rafahi H, Rouhipour H (2014b) Evaluation of GUEST and WEPP with a new approach for the determination of sediment transport capacity. J Hydrol 513:413–421

Mandal D, Sharda VN (2013) Appraisal of soil erosion risk in the Eastern Himalayan region of India for soil conservation planning. Land Degrad Dev 24:430–437

Martinez-Mena M, Castillo V, Albaladejo J (2002) Relations between interrill erosion processes and sediment particle size distribution in a semiarid Mediterranean area of SE of Spain. Geomorphology 45:261–275

Nearing MA (1998) Why soil erosion models over-predict small soil losses and underpredict large soil losses. Catena 32:15–22

Nearing MA, Norton LD, Bulgakov DA, Larionov GA (1997) Hydraulics and erosion in eroding rills. Water Resour Res 33:865–876

Page AL, Miller RH, Jeeney DR (1992) Methods of soil analysis, Part 2, Chemical and mineralogical properties. SSSA. Pub., Madison, p 1159

Palacio RG, Bisigato AJ, Bouza PJ (2014) Soil erosion in three grazed plant communities in northeastern Pataginia. Land Degrad Dev 25:594–603

Parsons AJ, Abrahams AD, Wainwright J (1994) On determining resistance to interrill overland flow. Water Resour Res 30:3515–3521

Proffitt APB, Hairsine PB, Rose CW (1993) Modeling soil erosion by overland flow: application over a range of hydraulic conditions. Trans ASAE 36:1743–1753

Shi ZH, Fang NF, Wu FZ, Wang L, Yue BJ, Wu GL (2012a) Soil erosion processes and sediment sorting associated with transport mechanisms on steep slopes. J Hydrol 454–455:123–130

Shi ZH, Yue BJ, Wang L, Fang NF, Wang D, Wu FZ (2012b) Effects of mulch cover rate on interrill erosion processes and the size selectivity of eroded sediment on steep slopes. Soil Sci Soc Am J 77:257–267

Shih HM, Yang CT (2009) Estimating overland flow erosion capacity using unit stream power. Int J Sediment Res 24:46–62

Sirjani E, Mahmoodabadi M (2012a) Effects of sheet flow rate and slope gradient on sediment load. Arab J Geosci 7:203–210

Sirjani E, Mahmoodabadi M (2012b) Study on flow erosivity indicators for predicting soil detachment rate at low slopes. Int J Agric Sci Res Technol 2:55–61

Tiwari AK, Risse LM, Nearing MA (2000) Evaluation of WEPP and its comparison with USLE and RUSLE. Trans ASAE 43:1129–1135

Trout TJ, Neibling WH (1993) Erosion and sedimentation processes on irrigated fields. J Irrig Drain Eng 119:947–963

Van Dijk AIJM, Bruijnzeel M, Eisma EH (2003) A methodology to study rain splash and wash processes under natural rainfall. Hydrol Process 17:153–167

Walkley A, Black IA (1934) An examination of the degtjareff method for determining soil organic matter, and proposed modification of the chromic acid titration method. Soil Sci 37:29–38

Wang YQ, Shao MA (2013) Spatial variability of soil physical properties in a region of the loess plateau of PR China subject to wind and water erosion. Land Degrad Dev 24:296–304

Wuddivira MN, Stone RJ, Ekwue EI (2009) Clay, organic matter and wetting effects on splash detachment and aggregate breakdown under intense rainfall. Soil Sci Soc Am J 73:226–232

Yu B (2003) A unified framework for water erosion and deposition equations. Soil Sci Soc Am J 67:251–257

Yuill BT, Gasparini NM (2011) Hydrologic controls on wash load sediment concentrations within a low-ordered, ephemeral watershed. J Hydrol 410:73–83

Zhang GS, Chan KY, Oates A, Heenan DP, Huang GB (2007) Relationship between soil structure and runoff/soil loss after 24 years of conservation tillage. Soil Tillage Res 92:122–128

Zhao G, Mu X, Wen Z, Wang F, Gao P (2013) Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. Land Degrad Dev 24:499–510

Ziadat FM, Taimeh AY (2013) Effect of rainfall intensity, slope and land use and antecedent soil moisture on soil erosion in an arid environment. Land Degrad Dev 24:582–590