SURFACE ROUGHNESS EFFECTS ON RUNOFF AND SOIL EROSION RATES UNDER SIMULATED RAINFALL

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Summary – Soil surface roughness is identified as one of the controlling factors governing runoff and soil loss. Yet, most studies pay little attention to soil surface roughness. In this study, we analyzed the influence of surface roughness on runoff and soil erosion rates. Bulk samples of a silt loam soil were collected and sieved to 4 aggregate sizes: 0.003-0.012, 0.012-0.02, 0.02-0.045, 0.045-0.1 m. The aggregates were packed in a 0.60 by 1.2 m soil tray, which was set at a slope of 5%. Rainfall simulations using an oscillating nozzle simulator were executed for 90 min at intensity of 50.2 mm.h^{-1}. The surface microtopography was digitized by an instantaneous profile laser scanner before and after the rainfall application. From the laser scanner data, a digital elevation model was produced and a roughness factor extracted. The data revealed longer times to runoff with increasing soil surface roughness as surface depressions first had to be filled before runoff could take place. Once channels were interconnected, runoff velocity and runoff amount increased as aggregates were broken down and depressions were filled. Rough surfaces were smoothed throughout the rainfall event, diminishing the effect on runoff. Final wash rates were comparable for all different applications. The simulations reveal that the significance of soil surface roughness effect is the delay in runoff for rougher surfaces rather than the decrease of soil erosion amount.

Key-words: rainfall simulations, soil roughness, surface-profile laser scanner

Introduction

Soil surface roughness is identified as one of the controlling factors governing runoff and soil loss (Eltz and Norton, 1997; Darboux et al., 2001; Jester and Klik, 2005). Many processes occurring on the soil surface are influenced by roughness, including depression storage, infiltration, runoff, flow velocity and soil loss (Darboux et al., 2001; Römkens et al., 2001). Nevertheless, most studies pay little attention to soil surface roughness. In this study, we aim to analyze the influence of random soil surface roughness on runoff and soil erosion rates.

Bulk samples were collected from the 0-0.1 m soil layer from a field in Indiana, USA. This soil is classified as a silt loam according to USDA (Soil Survey Staff, 1999). Prior to air drying, the bulk samples were sieved to 4 aggregate sizes: 0.003-0.012, 0.012-0.02, 0.02-0.045, 0.045-0.1 m. This allowed, after packing the aggregates in soil trays, four different levels of soil surface roughness, i.e., smooth, medium smooth, medium rough and a rough soil surface, in this study. The soil boxes consisted of two compartments each measuring 0.6 by 1.2 m, hence two treatments can be run simultaneously. The bottom of the soil tray was equipped with 8 interconnected tubes in order to measure percolation. The bottom was covered with a porous fabric and a 0.05 m layer of course sand, thus allowing free drainage during rainfall simulations. The sand was covered with another sheet of porous fabric, on top of which a 0.07 m thick layer of aggregates was packed. For the 2 smallest aggregate distributions, the soil pan was packed with the respective aggregates. Nevertheless, for the two larger aggregate size distributions, this would cause very large voids in between the aggregates, thus creating rapid through flow. Therefore, these soil pans were packed differently as described below. . First, a thin layer of small aggregates of 0.003 - 0.012 m were added, followed by a layer of the large aggregates. Subsequently, the large voids were filled by adding a next layer of small aggregates. As such, several layers of large aggregates with infills of small aggregates were added until the soil pan was completely filled. Finally, in order to fill the large voids which were less readily reachable, small aggregates of < 0.003 m were added and the filling of voids was facilitated by hammering on the bottom of the soil pan. The soil trays were set at a 5% slope to facilitate runoff.

Rainfall simulations were executed for 90 min at an intensity of 50.2 ± 2.1 $mm.h^{-1}$ using an oscillating nozzle simulator, consisting of two simulator troughs each equipped with two 80-100 Veejet nozzles (Spraying Systems, Wheaton, IL). The nozzles were spaced 1.07 m within the trough and the troughs are placed 1.37 m apart. A constant pressure of 42 kPa was set at the nozzles. Rainfall intensity was controlled by varying the oscillating frequency of the nozzle. Simulated rainfall was applied to ensure that a steady state runoff was attained. Runoff samples were collected at the downslope edge of the soil pan and infiltration water from the bottom of the soil pan was collected at three minute intervals. Runoff velocity was determined by recording the time for a dye to travel 1 m over the soil surface.

The surface microtopography was digitized before and after the rainfall application by an instantaneous profile laser scanner. The laser scanner consists of two diode lasers and a digital camera mounted on a single rail. The laser projects a bright line on the surface which is digitized by the camera. From the geometry of the laser-camera assembly, the line image is converted to surface heights using a triangulation algorithm (Darboux and Huang, 2003). From the laser scanner data, a digital elevation model was produced in order to extract a roughness factor. Furthermore, aggregate disintegration, sealing and micro-rilling could be followed throughout the course of the rainfall event by analyzing the the detailed topographic datasets.

Aggregate stability was determined using the three treatments of Le Bissonnais (1996). Bulk density was measured using an excavation approach in which an amount of soil is excavated and weighted and the volume is estimated by filling up the pit with a measured amount of water.

Results and discussion

Because of the specific way of packing the soil in the soil trays, differences in bulk density between the roughness classes did occur (Table 1). This can be explained by the fraction of soil under natural condition present in the soil trays: for large aggregates, a greater portion of the soil is packed in its unspoiled, natural condition. Instead, for small aggregates, a bigger portion of voids between the aggregates decreases its bulk density. As the bulk density for the higher roughness classes is higher, we would expect infiltration rate will decrease more rapidly. Nevertheless, because of the larger depression storage, this did not occur.

Table 1. Bulk density and aggregate size distribution for each roughness class.

roughness class	aggregate size distribution (m)	bulk density (Mg/m^3)
smooth	0.003 - 0.012	1.10 ± 0.05 a
medium smooth	0.012 - 0.02	1.17 ± 0.06 b
medium rough	0.02 - 0.045	1.15 ± 0.16 ab
rough	0.045 - 0.1	1.28 ± 0.04 c

Same letter indicates no significant differences (P = 0.05)

Significant differences exist between the Mean Weighted Diameters (MWD) of the different treatments of Le Bissonnais (1996), fast wetting of the aggregates yielding the lowest MWD (0.56 ± 0.19), slow wetting yielding the highest MWD (1.72 ± 0.24) and shaking after prewetting yielding intermediate MWD (1.44 ± 0.14). This is also reflected by the distribution of the aggregate size fractions shown in Fig. 1. This indicates the soil is particularly vulnerable for aggregate breakdown under dry conditions as slaking will cause aggregates to be broken down during fast wetting. Since the rainfall simulations were performed on a dry soil, this explains the intensive aggregate breakdown leading to a smoothening of the soil surface and the high soil loss observed. Prewetting the aggregates stabilizes the aggregates, resulting in a high MWD. The results also indicate that the aggregates resist mechanical disturbance relatively well.

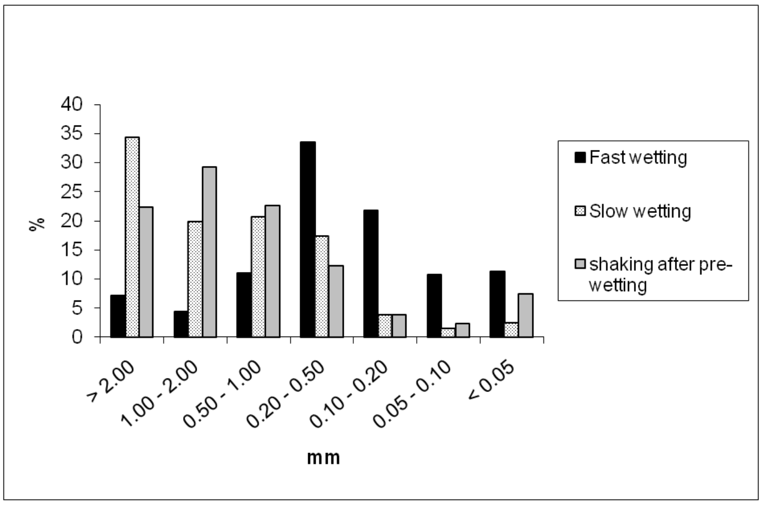

Fig. 1. Distribution of aggregate size fractions after treatments proposed by Le Bissonnais (1996).

During the first stage of the rainfall simulations, all rainfall was able to infiltrate. Due to slaking and raindrop impact, aggregates broke down and a seal was formed, causing the infiltration rate to drop. Subsequently, ponding started, hereby filling up the depressions in between the aggregates. Once channels were interconnected, runoff occurred. This process was also observed by several authors, e.g., Darboux et al. (2001) and Croft et al. (2009). Our results revealed longer times to runoff with higher initial soil surface roughness as larger surface depressions first had to be filled before runoff could take place (Fig. 2). During the rainfall event, runoff rate increased as aggregates were broken down and depressions were filled by deposition of transported sediment, hereby lowering the storage capacity of the surface. As such, rough surfaces were smoothed throughout the rainfall event, diminishing the effect on runoff. Final runoff rates were highest for the smooth soil surface and lowest for the medium rough soil surface. Indeed, final runoff rates were higher again for the rough soil surface as compared to the medium rough soil surface as water is forced by the micro-topography to flow to the depressions rather than infiltrating. Due to depositional crusts in the flow lines, water is less likely to infiltrate and will run off.

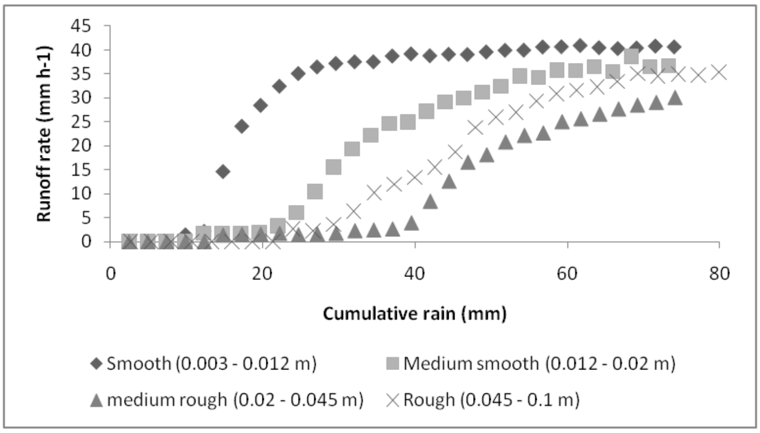

Fig.2. Runoff rate as a function of cumulative rainfall for the four roughness classes.

Our data showed lower runoff velocities with increasing soil surface roughness as water is forced to follow a more tortuous flow path (Fig. 3). Nevertheless, as rough surfaces were smoothed throughout the rainfall event, runoff velocity gradually increased.

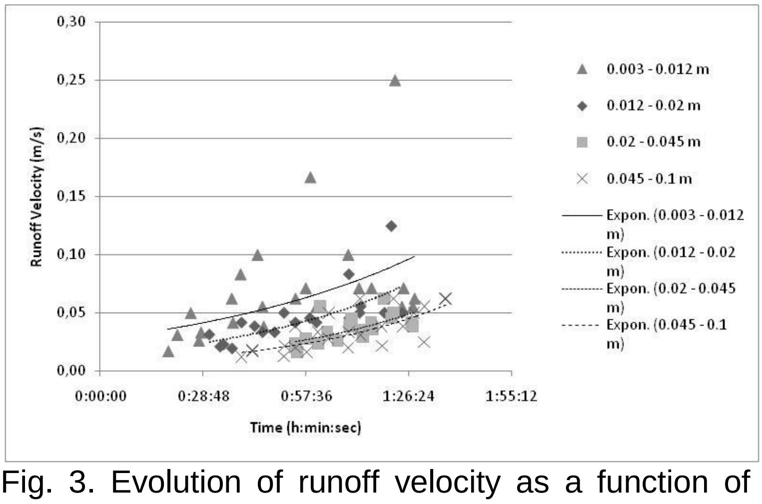

Fig. 3. Evolution of runoff velocity as a function of time for the four roughness classes

Final wash rates were comparable for all different applications (Fig. 4). Nevertheless, as final runoff rates were highest for the smooth soil surface and lowest for the medium rough soil surface, this implies sediment concentrations increased with higher soil surface roughness (data not shown). Römkens et al. (2001) stated that a higher soil surface roughness can increase soil erosion by flow concentration. Darboux and Huang (2005) also found similar final wash rates but did not found a significant difference in sediment concentrations. As time to runoff is lower for with decreasing soil surface roughness, the total soil loss was highest for the smooth soil and lowest for the medium rough and rough soil.

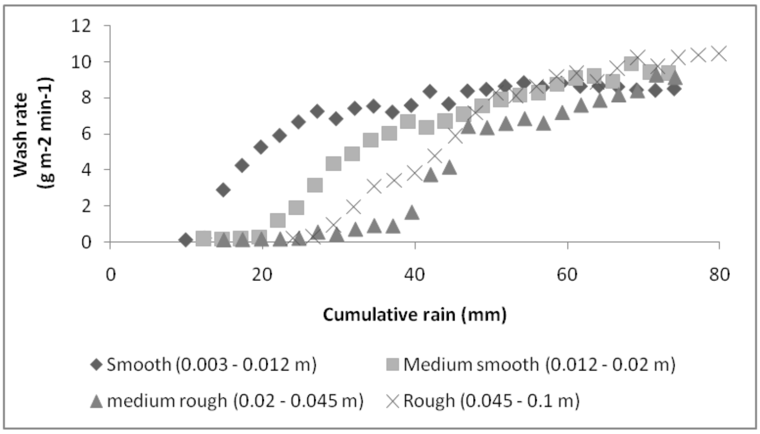

Fig. 4. Wash rate as a function of cumulative rainfall for the four roughness classes

Conclusions

The silt loam soil studied here was vulnerable to slaking which induced a strong aggregate breakdown during the rainfall simulations, resulting in a decay of the soil roughness in all treatments. The final runoff rate was highest for the smooth soil surface and lowest for the medium rough soil surface meanwhile there was no significant difference in final wash rates between the different applications. Therefore, the simulations reveal that the significance effect of soil surface roughness is the delay in runoff for rough surfaces rather than the decrease of soil erosion amount. Similar results were found by Darboux and Huang (2005) who also stressed the delay in runoff initiation as being the primary soil and water conservation benefit of soil surface roughness.

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