SOIL ROUGHNESS EFFECTS ON RUNOFF AND SEDIMENT PRODUCTION

F. Darboux[A], J.M. Reichert[B] and C. Huang[C]
[A] INRA-Science du sol, Olivet, France.
[B] Departmento de Solos, Universidade Federal de Santa Maria, Brazil.
[C] USDA-ARS National Soil Erosion Research Lab, W Lafayette, IN, USA.

Abstract

The effect of soil surface roughness on runoff and sediment production is an area not yet fully quantified. Current erosion prediction models, such as the Revised Universal Soil Loss Equation, predicts a reduced erosion from an increased soil roughness, without considering the functionality associated with different roughness forms. In this research, we used a mechanistic approach in which soil roughness is partitioned into depressions and mounds and their effects on runoff and sediment production are quantified separately. A laboratory rainfall simulation experiment was conducted using paired rough versus flat surfaces in a 5 m^2 soil box. Depressions delayed the runoff initiation by storing water into puddles and enhancing infiltration. Surface mounds did not delay runoff initiation. Once runoff reached a steady state, rough surfaces either with depressions or mounds produced mostly greater runoff with either an increased or decreased sediment flux, despite a high degree of data scatter. This effect persisted until the roughness elements disappeared, suggesting the flow concentration on rough surfaces was a likely cause. Surface roughness, subsurface condition (ie. seepage or drainage), flow erosivity and rainfall intensity and duration all affected the soil losses. Our results show no simple relationship between roughness, flow and erosion exists and the net effect on runoff and erosion depends on the dominant form and its functionality.

Additional Keywords: surface roughness, soil erosion

Introduction

Soil surface micro-topography or roughness defines the physical boundary between overland flow and soil. Due to its unique position, soil roughness potentially affects surface processes such as infiltration, flow routing, erosion and sedimentation.

Predictive models such as RUSLE (Renard *et al*., 1997) and WEEP (Flanagan and Nearing, 1995) showed a reduction in erosion from an increased soil roughness. A typical rationale for the roughness effect is from the trapping of water and sediment because rough surfaces contain many depressions and barriers. These depressions and barriers decrease the flow velocity, hence decreasing the flow detachment power and transport capacity. Furthermore surfaces with higher roughness seal less rapidly and they tend to have a higher infiltration rate than those with lower roughness (Cogo *et al*., 1984). This kind of roughness scenario has been incorporated into erosion assessment tools such as Universal Soil Loss Equation (USLE) and its revised version (Revised USLE or RUSLE) where erosion is predicted from rainfall factors (Renard *et al*., 1997). This commonly accepted roughness effect compounded the runoff effects into sediment production (ie. a reduced runoff for a reduced erosion) hence, it did not show the true roughness effects on runoff and sediment production.

In the WEPP model, an increased surface roughness causes a decrease in interrill sediment delivery and an increase in critical shear in the rills (Flanagan and Nearing, 1995). Therefore, even in a process-based model where the runoff production process supposedly has been isolated from the erosion process, soil roughness is still shown to affect erosion negatively, ie. an increased roughness will decrease sediment delivery.

Despite the hypothetical reasoning behind the roughness effects, little research results were available showing the actual roughness effects on overland flow and erosion. Most of the literature on soil surface roughness is on identifying methods to quantify soil roughness and on relating the roughness decay to rainfall amount even though geomorphic observations always associate a rough landscape to be severely eroded. Huang and Bradford (1993) demonstrated the erosion induced increase in surface roughness in a soil box.

Even most research results show an increased roughness caused a decreased runoff and total soil loss, there are evidences pointing toward the other direction. Burwell *et al.* (1968) and Burwell and Larson (1969) showed that after runoff initiation, a rougher surface might not have the distinctly higher infiltration as a smooth surface as shown before runoff. The laboratory study of Helming *et al.* (1998) where runoff and sediment delivery from different roughness surfaces were quantified in a laboratory 3.7-m wide by 0.61-m long soil box showed that while runoff was marginally affected, rough surfaces did show a greater soil loss than smooth surfaces. In this case, an increase in soil erosion has been attributed to the flow concentration on the rough surface.

We believe that the soil roughness effect in sediment production needs to be quantified under the full runoff condition. Since soil roughness can either converge or diverge flow on the surface, flow concentration may cause a localized increase in erosion, as found by Helming *et al.* (1998). On the other hand, surface depressions that trap sediment and surface mounds that increase flow meandering (or resistance) may also lead to a reduced sediment delivery. Therefore, the roughness effect on net sediment delivery depends on the counterbalance between these opposing processes and erosion can either increase or decrease as soil roughness is increased.

In this research, we carried out a laboratory experiment to assess roughness effects on runoff and soil loss. We studied two types of roughness forms: surface depressions and mounds and compared the roughness effect to a visually flat surface. The study was conducted under different near-surface hydrology (ie. drainage or seepage) and upstream inflow conditions for different erodibility and erosivity.

Materials and Methods

The experiment was carried out in the laboratory under simulated rainfall. The soil was from the surface horizon of a Cincinnati silt loam collected at Sullivan County, Indiana (USA). The experimental setup consisted of two soil boxes up and down slope to each other that could be either run independently or connected together. The upslope feeder box was used to vary the inflow to the downslope study box (Figure 1). Separate rainfall simulators were mounted above each box enabling us to rain simultaneously on both boxes with different rainfall intensities. The upslope feeder box was 1.8 m long and 1.2 m wide. The downslope study box was 5 m long and 1.2 m wide. Both boxes were 25 cm deep and filled with 5 cm of sand at the bottom and with 20 cm of soil on top of the sand layer. A landscape fabric separated the sand and soil. Both soil boxes could be adjusted in slope and a system of watering troughs controlled the hydrostatic pressure at the bottom of each box independently by adjusting the height of the water level in the troughs. The feeder and study boxes could be run separately or connected together.

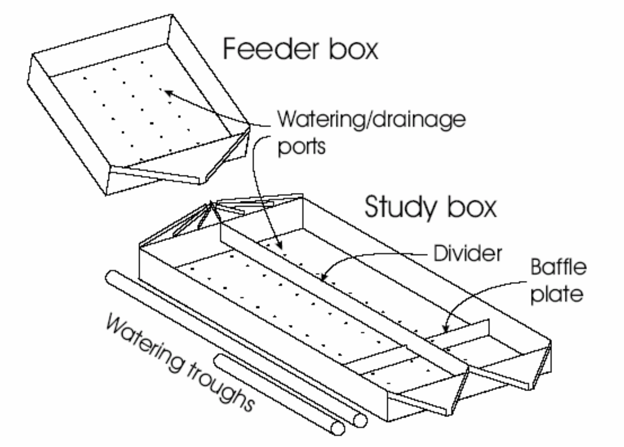


Figure 1. Experimental setup showing the soil boxes and the watering troughs.

The 5-m study box was divided in the middle to form two separate 0.6 m wide plots. This arrangement allowed us to prepare and make rainfall simulation runs on a pair of contrasting smooth and rough surfaces simultaneously. Box preparation included fan-drying of the surface soil from the previous run, loosening the surface and breaking down aggregates larger than one cm, adding new soil and smoothing to form a visually flat surface. On one side of the study box, the surface was kept smooth while hand moulded depressions or mounds were formed on the other side. The cone-shaped mounds or depressions had a base diameter of 7 to 10 cm and height (or depth) of 4 to 5 cm. The day before the experiment, the soil boxes were set to horizontal position and a gentle rain (12 mm h^{-1}) was applied for one hour. The purpose of this rain was to seal the soil surface without causing overland flow and erosion. To equalize the moisture content, both feeder and test boxes were saturated from the bottom using the watering troughs. After saturation was achieved, the watering troughs were disconnected from the feeder box and the feeder box was free drained overnight. The same operation was done on the study box if the experiment was to be conducted under the free drainage condition. For experiments under seepage condition, the watering troughs were left connected overnight. All the runs were made with the slope of the study box kept at 5% and the feeder box at 10%

Experiments were conducted under either seepage with water level at the watering trough maintained 5 cm above the soil surface or under free drainage condition. Experiments with seepage and drainage conditions were alternated to avoid changes in soil physical properties after prolonged saturation. Rough and smooth sides were also alternated to avoid a systematic bias due to potential differences in lateral conditions.

Two experiments were conducted. Experiment A was performed on surfaces with and without depressions and consisted of a sequence of three rains on each half of the study box. Rain intensities were kept constant, ie. 24 mm h^{-1} on the study box and 48 mm h^{-1} on the feeder box. To start a run, rainfall was applied to both feeder and test boxes simultaneously and runoff from the study box was sampled and weighed. After the runoff flux from the test box reached an apparent steady state, eight samples were taken simultaneously at the outlet of both boxes. Then, the outlet of the feeder box was connected to the upslope end of the study box. After the apparent steady state was reached, another eight samples were collected. Then the boxes were disconnected and after few minutes, four samples were collected again at each outlet to check the similarity of flow rates before and after the connection.

The disconnect-connect-disconnect sequence was repeated for three rain events. During the first rain event, the feeder box surface was left uncovered so that water and particles were fed to the study box. During the second rain event, the soil surface was covered with a landscape fabric and almost clear water was fed to the study box. During the third rain event, the feeder soil surface was uncovered. The rain duration depended on the time to reach the apparent steady-state and ranged from 30 to 80 minutes. The longest rain was the first event on surfaces with depressions under drainage condition and the shortest from seepage condition.

Experiment B was conducted on surfaces with either mounds or depressions paired to a flat surface on the other half of the test box. Three rainfall intensities were applied to the test surface: 24, 48 and 72 mm h^{-1}. The feeder box was not used in Experiment B.

After each rain event, the surface was visually inspected and soil micro-topography was digitized by a laser-scanner (Darboux and Huang, 2003) on the lower 3.9 m of the study box with a horizontal resolution of 1.5 mm and a vertical resolution of 0.5 mm.

Results and Discussion

Depressional storage capacity

Surface storage capacity was computed from the laser scanned DEM using the algorithm developed by Planchon and Darboux (2001). Initial storage capacities were clearly different depending on the surface condition (Figure 2). The difference in depressional storage capacity decreased with added rainwater for all the surfaces. Differences between initially-smooth surfaces and initial surfaces with depressions continued up to the second rain, at least.

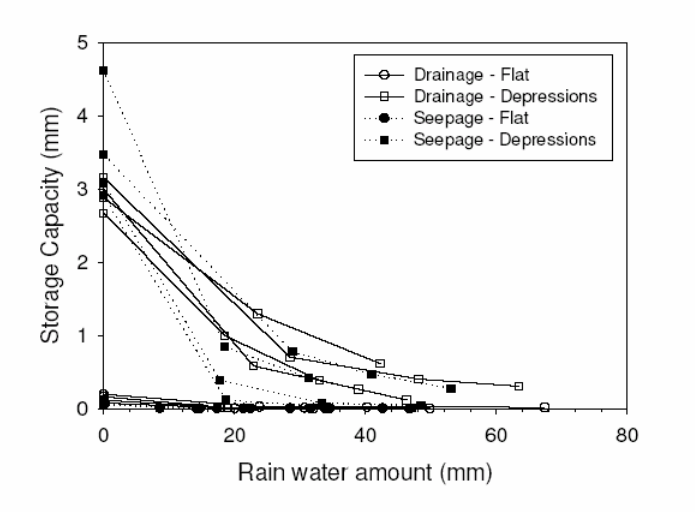


Figure 2. Evolution of calculated storage capacity from laser scanned DEMs as a function of cumulative rainfall.

The depressions appeared to be more persistent for the drainage condition than seepage condition.

Surface depressions had several different effects in delaying runoff initiation. Firstly, depressions trapped rainfall water in puddles, preventing this water to run off. Secondly, depressions kept the near-surface soil under the puddle saturated and the ponding increased the hydraulic gradient. On the other hand, we also observed a layer of fine clay and silt deposited at the bottom of the depression after the rain stopped. This could reduce the total water infiltration despite an increase in the hydraulic head from the ponded water.

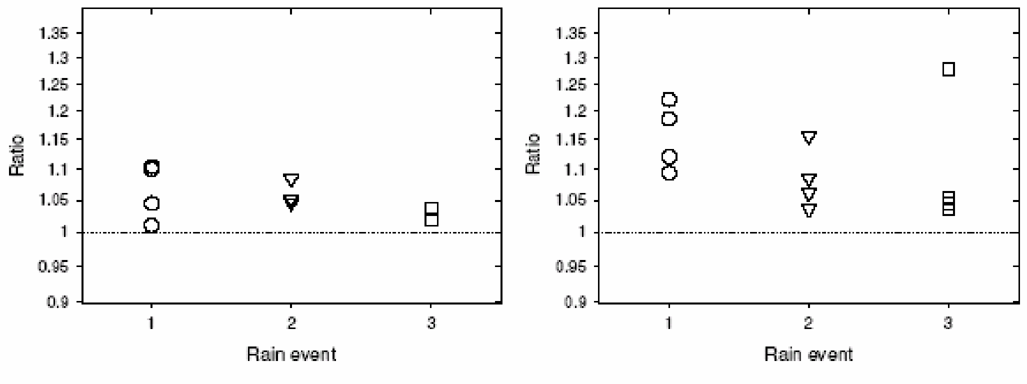
Changes in the delay of runoff initiation may be due to changes in the surface or subsurface conditions. Formation and subsequent erosion of the soil surface crust with successive rainfalls may have affected infiltration rate and contributed to the observed behavior. The changes in depression storage capacity are also a possible cause of the runoff-initiation delay. Most probably, both of those phenomena occurred simultaneously.

Runoff initiation

For each rain event, time to runoff initiation at the outlet of the study box was recorded. For surface with depressions, there was always a delay between the start of rain and runoff initiation under drainage conditions. For one specific experiment with one specific surface condition (smooth or depressions), the delay decreased with successive rain events. For the first rain event, the delay was always longer for the surface with depressions than for the initially-smooth surface. The time lag of about 10 minutes representing a rainfall amount of about 4 mm. For the second rain event, the difference in delay was much smaller, around one minute. For the third rain, no difference in the runoff delay between initially rough and smooth surfaces was found. For surfaces with mounds, there is no significant delay from the rough surfaces as compared to the flat ones.

Effect of surface depressions on runoff

To compare the roughness effects on runoff, the ratio between the runoff flux on the side with initial depressions and the runoff flux on the side without initial depressions was calculated (Figure 3). This ratio allows us an easy comparison of surface depression effects on the water flux. If the side with initial depressions produced more runoff than the initially smooth side, the ratio is higher than one. If both sides had similar runoff, the ratio is equal to one. Likewise, if the side with initial depressions gave less runoff flux than the initially-smooth side, the ratio is less than one. Figure 3 uses a logarithm scale for the runoff flux ratio to keep identical shifts along the axis for identical relative shifts in the ratios.



(a)

(b)

Figure 3. Ratios of runoff flux between surfaces with and without depressions under (a) drainage and (b) seepage conditions.

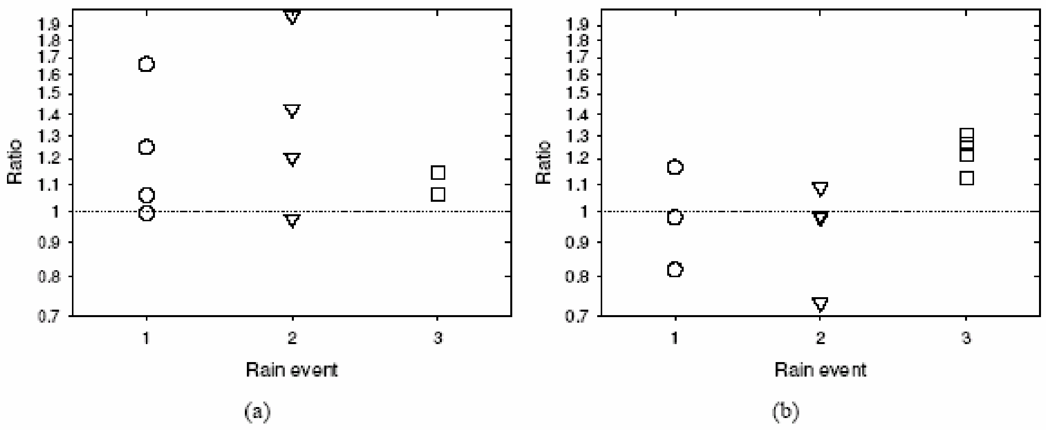
Regardless the subsurface moisture gradient (drainage or seepage), the runoff flux ratios are always larger than one. It means surfaces with initial depressions produced greater runoff when compared to initially-smooth surfaces. The effect is more pronounced for the seepage condition (up to 25% increase in flux) than for the drainage condition (up to 10% increase in flux). Under seepage, the runoff ratio showed a decreasing trend with successive rain events, possibly due to the breakdown of individual depressions in the development of a flow network.

Overall, initial depressions had a continuing effect by increasing runoff when overland flow was present. This increase in runoff from surfaces with depressions might be due to the fact that these surfaces had more water on the surface that could be released as runoff. In the meantime, the storage capacities of the surfaces with initial depressions decreased significantly with the successive rainfalls. So, the decrease in infiltration on the depression side is not associated with the depression volume but with other factors associated with the initial presence of depressions.

The depressions may have affected the drainage network geometry. Specifically, outflow from depressions tends to be localized at a lowest point along the ridges or through erosion or breaching of the ridge. After the outflow from depressions occurred, water flowed between the remaining ridges that initially delineated the depressions. Flow concentration on rough surfaces was previously noticed by Helming *et al.* (1998). This created an overland-flow pattern more localized for surfaces with initial depressions compared to initially smooth surfaces. This localized flow pattern persisted even after the initial depressions were filled with sediment deposits and no obvious depressions remained on the surface. With time, the surface geometry shifted from depression dominated to mound dominated. The flow concentration on the surface with initial depressions may have decreased the overall infiltration by limiting the water supply for infiltration on a significantly smaller part of the surface.

Effects of surface depressions on sediment discharge

A comparison of sediment flux was performed at the apparent steady-state of the rainstorm. A ratio similar to the one used for the water flux comparison was used for the sediment flux. Under drainage condition, most of the ratios were greater than one, meaning the surfaces with initial depressions produced more sediments than the initially-smooth surfaces (Figure 4). The contrast between sediment fluxes was quite variable, from almost no difference to twice more particle flux from the depression side. Under seepage condition, no significant trend was found between rough and smooth surfaces for the first two events (Figure 4b). For the third event, the side with initial depressions produced greater particle fluxes than the initially-smooth surface.



(a) (b)

Figure 4. Ratios of sediment flux between surface with and without depressions under (a) drainage and (b) seepage conditions.

The runoff-soil surface interaction of surfaces with roughness elements, through the changes in the erodibility of the soil or in the erosivity of the flow, has affected the sediment flux. Differences in surface roughness could have affected erosivity because flow patterns were different between depression and smooth sides. Soil roughness affects the surface area exposed to the rainfall and to the flow, potentially modifying the rain and flow erosivity. Because soil roughness is the interface between flow and substratum, it may affect both erosivity and erodibility, leading to ambiguous partitioning between soil and flow effects on soil loss.

Under drainage condition, surface with initial depressions increased particle runoff compared to initially-smooth surfaces for low water fluxes. The roughness can affect erosivity both positively and negatively, ie. to increase erosivity from flow concentration and to decrease erosivity from increased meandering or flow path. One possible explanation of the reversal of the roughness effects between the low and high flows is that at low flows, the roughness-induced flow concentration is sufficient to bring about an increased erosion and transport of eroded sediments.

Effects of surface mounds on runoff and sediment discharge

Comparison of runoff and sediment fluxes at steady state between surfaces with and without mounds under the free drainage condition shows that although the runoff fluxes are somewhat similar, the sediment fluxes from rough surfaces are slightly greater than those without the mounds (Table 1). The reversing trend of an increasing runoff ratio and a decreasing sediment flux ratio as the rainfall intensity is increased could be attributed to the degradation of the surface mounds as the rain intensity is increased. Additionally, under the low intensity rain, the mounds might not have been degraded and the flow concentration at low flows may have caused a significant increase in the transport capacity over a threshold, therefore causing a more pronounced increase in sediment transport. At high flow rates under high rainfall intensity, flow concentration from surface with mounds might not cause the same degree of increase in detachment and transport power as compared to low flows. The degradation of mounds may also decrease the flow convergence.

Table 1. Steady state runoff and sediment flux ratios between surfaces with and without mounds at different rain intensities under free drainage conditions.

Rain Intensity (mm h^{-1})	Runoff Ratio	Sediment Flux Ratio
24	0.99	1.64
48	1.04	1.11
72	1.16	1.09

Conclusions

A laboratory experiment was conducted to assess effects of different surface roughness forms on runoff and sediment loss. Depressions delayed the runoff initiation by storing water in puddles and enhancing infiltration. Surfaces with initial depressions increased steady state runoff as compared to initially smooth surfaces under both drainage and seepage conditions. The flow concentration on rough surfaces is a likely cause of this phenomenon.

There is no general relation for the effect of roughness on soil loss. A high roughness may increase, decrease or have no effect of soil loss depending on the subsurface conditions (drainage or seepage), flow erosivity and roughness form. Moreover, for identical conditions, the effect of roughness may shift with an increasing amount of applied rainfall. The only confirmed soil water conservation benefit from soil surface roughness is the delay in runoff initiation. When the soil is already saturated, the runoff delay from surface depressions is diminished. There is no firm data support for a decreased sediment loss from roughness surfaces once runoff is initiated as would be predicted from current process-based erosion models.

References

Burwell, R.E. and Larson, W.E. (1969). Infiltration as influenced by tillage-induced random roughness and pore space. *Soil Sci. Soc. America Proc*. 33, 449–452.

Burwell, R.E., Sloneker, L.L. and Nelson,W.W. (1968). Tillage influences water intake. *Journal Soil and Water Conservation* 23, 185–187.

Cogo, N.P., Moldenhauer, W.C., and Foster, G.R. (1984). Soil loss reductions from conservation tillage practices. *Soil Sci. Soc. America J.* 48, 368–373.

Darboux, F. and Huang, C. (2003). An instantaneous-profile laser scanner to measure soil surface micro-topography. *Soil Sci. Soc. America J.* 67(1), 92–99.

Flanagan, D.C. and Nearing, M.A. (Eds) (1995). USDA - Water Erosion Prediction Project. Hillslope profile and watershed model documentation, Nat Soil Erosion Research Lab, W Lafayette, Indiana 47907, USA. USDA-ARS. *NSERL Report* No. 10. Available at http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html (verified 1 Dec. 2003).

Helming, K., Römkens, M.J.M., and Prasad, S.N. (1998). Surface roughness related processes of runoff and soil loss: a flume study. *Soil Sci. Soc. America J.* 62, 243–250.

Huang, C. and Bradford, J.M. (1993). Application of a laser scanner to quantify properties of soil crusts. *Catena Supplement* 24, 129-139.

Planchon, O. and Darboux, F. (2001). A fast, simple and versatile algorithm to fill the depressions of digital elevation models. Catena, 146(2/3), 159–176.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (1997). Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). *Agricultural Handbook* 703, USDA-ARS.