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Catena 46 (2001) 103–123

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Soil erosion under different rainfall intensities, surface roughness, and soil water regimes

M.J.M. Römkens [a,*], K. Helming [b], S.N. Prasad [c]

[a] USDA-ARS National Sedimentation Laboratory, PO Box 1157, Oxford, MS 38655, USA
[b] Department of Soil Landscape Research, ZALF, Müencheberg, Germany
[c] University of Mississippi, University, MS 38677, USA

Abstract

Soil erosion is a complex phenomenon involving the detachment and transport of soil particles, storage and runoff of rainwater, and infiltration. The relative magnitude and importance of these processes depends on a host of factors, including climate, soil, topography, cropping and land management practices, control practices, the antecedent conditions, and the size of the area under consideration. In this study, the results of a series of experiments are reported, summarizing the soil loss and runoff response from a 0.6×3.75 m area to different rainstorm regimes, slope steepnesses, subsurface soil water pressures, and surface roughnesses under controlled laboratory conditions using a flume and rainfall simulator as water applicators, and a laser microreliefmeter and tensiometric system as soil response measuring devices. The soil chosen was a highly erodible Grenada loess (fine silty, mixed, thermic, Glossic Fragiudalf). The results showed: (1) a sequence of rainstorms of decreasing intensity on an initially air-dry smooth surface caused more soil loss than a sequence of similar storms of increasing intensity; (2) the surface roughness–sediment concentration relationship was not monotonic in nature; (3) subsurface soil water pressure substantially affected sediment concentration in runoff but only marginally impacted runoff amounts; (4) initially smooth, uniform surfaces may yield less soil loss than initially rough surfaces; (5) interrill runoff occurred as spatially varying flow in which flow patterns determine the locations of rills. Published by Elsevier Science B.V.

Keywords: Erosion processes; Sediment concentration; Drainage networks; Surface microrelief; Roughness; Seepage; Soil water pressure

1. Introduction

Soil erosion is a complex and multifaceted process which involves a host of factors and conditions with combinations, variations, and interactions that substantially affect

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[*] Corresponding author. Tel.: +1-662-232-2901; fax: +1-662-232-2915.
E-mail address: romkens@sedlab.olemiss.edu (M.J.M. Römkens).

0341-8162/01/$ - see front matter. Published by Elsevier Science B.V.
PII: S0341-8162(01)00161-8

the observed soil loss. Prediction of soil erosion is largely based on models derived from measurements of soil loss from natural runoff or rainulator plots, covering a wide spectrum of soils, topographic conditions, and management practices. The best examples of such a prediction tool is the Universal Soil Loss Equation or USLE (Wischmeier and Smith, 1978), which was recently upgraded to the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), and the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995). Both models are based on a huge body of experimental and monitored data and are powerful tools for predicting soil erosion rates as a function of rainfall, topography, soil, and management factors. However, three major limitations are inherent in the development of these models for worldwide use. First, model development was based on data derived for US conditions. The application of these models and their underlying factor relationships to different climatic and management conditions of other regions in the world is not always possible or appropriate (Morgan et al., 1993). Secondly, the models describe erosion processes that are scale-dependent and were formulated predominantly for field plot scale dimensions. Since different spatio-temporal scales involve different erosion processes or similar processes of different magnitude, the models can only be applied to the specific scale they were designed for (Kirkby, 1999). Thirdly, the models describe only those aspects of the soil erosion process correctly, which are well understood. Incomplete information or knowledge of the entire set of aspects and interacting processes leads necessarily to uncertainty in prediction parameters and thus reduces the accuracy of the model predictions.

To improve the reliability, generality, and accuracy of erosion prediction and to develop a more rational-based soil erosion control technique, the development of process-based models and relationships is of paramount importance. While models are often realizations and formulations of conceptional notions of the developer(s), the complexity of real situations requires that additional and realistic experimental efforts be made that offer a better insight of the complicated and often interacting role of many of the factors involved.

Current prediction technology inadequately covers the role of surface roughness in soil erosion, the relative importance of different rainstorm intensities and intensity sequences, and the influence of subsurface soil water pressures. Of those, the role of surface roughness in soil erosion is perhaps one of the most vexing problems. The conventional wisdom has been to assume that surface roughness increases the resistance of soil to detachment by raindrop impact (Moldenhauer and Kemper, 1969; Farres, 1978; Römkens and Wang, 1987), increases the surface storage capacity of rain and reduces the flow velocity and thus erosive power of runoff (Hairsine et al., 1992; Onstad, 1984; Huang and Bradford, 1990). On the other hand, on rough surfaces, flow concentrates and the potential for scouring action, headcut development, and rilling increases (Abrahams and Parsons, 1990; Helming et al., 1998a). The relative significance of these opposing influences is further confounded by the rainfall intensity regime, surface seal development and breakdown, as well as the subsurface antecedent soil and soil water conditions. The interactions between rainfall intensity, roughness changes, and surface sealing have been studied before (Helming et al., 1993; Römkens et al., 1986), but quantitative information about the effects of those interacting processes on soil erosion and sediment yield is still limited. Antecedent subsurface water content and soil water pressure might also have opposing effects on the processes of surface sealing, runoff generation and sediment production. On one hand, a low soil water content, and thus high negative pore water pressure, increases the cohesiveness of the soil, which results in a reduced detachability by runoff shear forces and raindrop impact (Römkens et al., 1997b). On the other hand, a low water content of the soil antecedent to a rainstorm event might increase aggregate slaking and breakdown due to air escape upon rapid wetting, enhancing soil detachment by raindrop impact and the subsequent transport by overland flow (Le Bissonais et al., 1989; Auerswald, 1993; Rudolph et al., 1997). This paper summarizes and highlights recent research which examines the role of some of these factors as they affect soil erosion. The objective is to provide more insight and detail through more carefully designed and controlled experiments.

2. Materials and methods

Studies were conducted with a slope-adjustable flume equipped with a variable intensity rainfall simulator, a laser microreliefmeter, and a tensiometric system (Fig. 1). Details of the equipment, experimental set-up, soil bed preparation are briefly summarized below.

2.1. Equipment

The 3.7 × 0.61 × 0.23 m slope adjustable (0–17%) flume was provided with an inlet tank attached to the upper end of the flume that allowed for overland flow and a rainfall simulator consisting of three oscillating VeeJet type 80150 nozzles. The rainfall

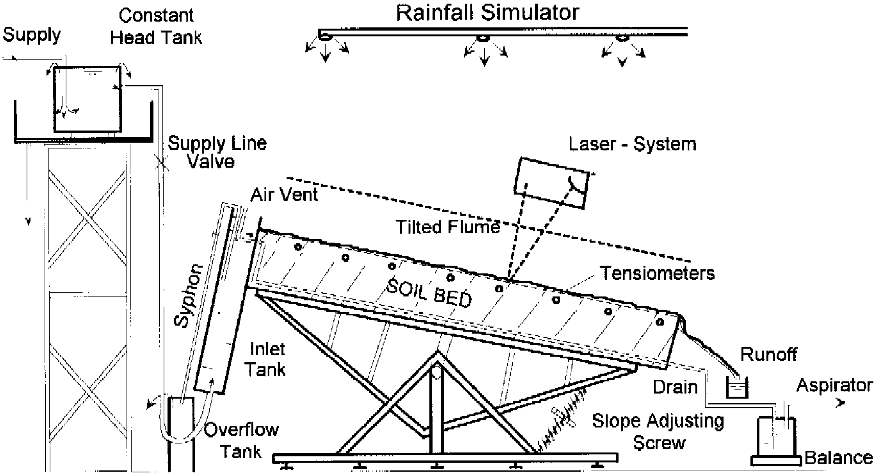

Fig. 1. A schematic representation of the experimental set-up.

simulator used was a 3-nozzle unit that in design, principle of operation, and characteristics, is similar to the multiple-intensity rainfall simulator described by Meyer and Harmon (1979). The properties of storms generated with this rainfall simulator are very similar to those of natural storms of corresponding intensity. The nozzles were spaced 1.64 m apart and capable of applying rainfall at any desired intensity and duration with an energy rate of 27 J m^{-2} per millimeter of rain. Perforated subsurface drainage pipes (OD, 12 mm), covered with polypropylene filter in the bottom of the flume allowed internal drainage and percolated water to be aspirated off and intercepted in a 20-l flask placed on a balance for continuous monitoring. This drain system also allowed the application of subatmospheric pressures to determine the effect of soil water pressure on soil detachment and runoff. A tensiometric system consisting of a series of 6 × 25 mm cylindrical, porous stainless steel cups with air entry values of about 115 cm of soil water pressure monitored the soil water pressure regime in the soil bed, while a series of TDR-probes allowed continuous monitoring of the soil water content in the soil bed. The tensiometric system was activated following the passage of the wetting front, at which point in time dummy cups, installed during the soil bed preparation, were replaced by water-filled tensiometer cups. A laser microreliefmeter was programmed to allow surface topography measurements of a 3 × 3 mm grid, surface roughness characterization, and the determination of flow paths (Helming et al., 1998a).

2.2. Soil and soil bed preparation

The soil used was the Ap material of a Grenada silt loam (18% clay, 80% silt, 2% sand) that for several years had been in corn (*Zea mays* L.). The soil was taken from a field site on the Mississippi Agricultural and Forestry Experiment Station (MAFES) at Holly Springs, MS. The soil was air-dried and crushed to pass a sieve with 4-mm openings, while the material used in the surface of the soil bed was sieved to pass either a 2-, 27- or 56-mm screen, depending on the roughness conditions that were required.

The bottom 0.02–0.03-m thick layer, the drain bed in which the perforated drains were located, consisted of very fine sand to facilitate drainage. The subsequent layer from 0.03 to 0.15 cm was packed in three to four incremental stages with soil of the 0–4-mm size fraction. Packing was conducted in a careful and systematic manner to achieve a uniform density. The soil was uniformly spread over the flume bed, followed by tamping with a wooden block and hands, then by scraping the surface to a uniform thickness. Subsequently, the soil was tamped by dropping a 15 kg aluminum block from a height of about 0.3 m, three times onto a 0.15 × 0.6 m aluminum plate placed on the surface. The next layer of about 70-mm thickness consisted of either material smaller than 2, 27 or 56 mm. This layer was packed in a similar manner. Then the surface material was carefully placed on the soil surface, thus insuring that the surface roughness was preserved. Surface roughness was thus controlled by the number and size of the largest clods.

3. Experimental studies

Several studies were conducted, each one concerned a different objective. Studies included: (1) the effect of different rainstorm intensity regimes on soil loss; (2) effect of differences in surface roughness and slope steepness on soil loss; (3) the effect of prolonged rainfall on sediment yield and the local topographic gradient field; (4) the role of subsurface soil matrix pressures on soil detachment and sediment concentration; and (5) the characterization of drainage network development in soil beds.

3.1. Rainstorm regimes

In this experiment, rain was applied in a series of four rainstorms, each having the same amount of rain but with different intensity levels. One series consisted of a sequence of decreasing storm intensities of approximately 60, 45, 30, and 15 mm h^{-1}, the other sequence consisted of a series of increasing storm intensity regimes of approximately 15, 30, 45 and 60 mm h^{-1}. The total rain applied for each storm was about 45 mm, so that adjustments in storm durations were made for storms having different intensities. The soil surface condition in this experiment was smooth, while the slope steepnesses tested were 2%, 8% and 17%.

In a different experiment, a series of rainstorms of 66 mm h^{-1} intensity and 45-min duration was applied to a soil bed of 8% slope steepness and a rough surface condition (clods < 56 mm). After each rainstorm, the surface topography was determined using the laser microreliefmeter (Römkens et al., 1988). Grid spacing was 3 mm, resulting into a digital elevation map (DEM) with 111,875 data points or grid cells per square meter. These measurements were used to further describe the surface topography in terms of the local surface topographic gradients and drainage network patterns.

3.2. Surface roughness and slope steepness effects

Three surface conditions were studied: a smooth surface with surface elevation variations of about 1 mm or less, a surface roughness obtained by placing air-dried clods and aggregated soil material sieved to pass a 27-mm screen on the surface of the soil bed, and a surface roughness condition by using air-dried material sieved to pass a 56-mm screen. Three slope steepnesses were investigated 2%, 8% and 17%. Rain was applied in a series of four 45-mm rainstorms of decreasing intensities of 60, 45, 30 and 15 mm h^{-1}, respectively.

3.3. Soil water pressure effect

For a select number of combinations of slope steepnesses and surface roughness, the soil water pressure in the soil bed was adjusted by changing the pneumatic pressure in the drain system to subatmospheric levels. Changes were introduced stepwise and usually lasted 0.5 h at each pressure level. The lowest pressure was equivalent to about 160 cm of water suction at the level of the drain system, while that at the soil surface was per definition maintained at 0 suction. The procedure was first to lower stepwise the pneumatic pressure until a minimum level was obtained after which the pneumatic pressure was increased stepwise to atmospheric levels. The tensiometer in the soil bed continually measured the soil water pressures while direct sampling of the sediment concentration and runoff indicated what the response of the soil bed was to the imposed pressure regime. The rainstorm intensity was about 60 mm h^{-1} and the soil surface was the eroded condition of the initially smooth surface which previously had been subjected to four 45-mm rainstorms of decreasing intensities.

3.4. Drainage network development

Drainage network was determined from the DEM, which were prepared after each storm. The measured elevation ranges were color-coded and flow paths became evident. The details of obtaining the drainage network have been outlined by Helming et al. (1998b). The procedure consisted of the determination of flow direction, the contributing area, and ordering of streams. From this information, different sets of parameters could be used to characterize the drainage networks, including Horton's ratios (bifurcation ratio, length ratio, drainage density), stream characteristics (gradients, sinuosity, orientation), and fractal characteristics (network similarity dimension).

4. Results

Storm sediment yield data (kg m^{-2}) for each slope steepness and surface roughness condition are listed in Table 1. For the initially smooth surface condition, the sediment yield data of both increasing and decreasing sequences of rainfall intensities are reported, while for the initially rough and medium-rough surface conditions, the data of the rainstorm sequence of decreasing rainfall intensities are given.

The following observations were made.

1. Total sediment yield increased for each intensity sequence with an increase in slope steepness.

Table 1
Sediment yield (kg m^{-2}) for a series of rainstorms on soils with different slope steepness, initial roughness, decreasing and increasing rain intensity sequences

Storm	Roughness condition								
	Smooth			Medium			Rough		
Slope	2%	8%	17%	2%	8%	17%	2%	8%	17%
Decreasing intensity sequence									
60 mm h^{-1}	0.12	0.07	0.23	0.34	0.47	1.86	0.17	0.54	1.86
45 mm h^{-1}	0.20	0.35	2.26	0.37	1.27	3.67	0.20	1.13	3.39
30 mm h^{-1}	0.14	0.63	2.87	0.20	0.85	3.09	0.13	1.11	3.28
15 mm h^{-1}	0.07	0.36	1.85	0.09	0.36	1.41	0.06	0.53	1.30
Total	0.53	1.41	7.20	1.00	2.95	10.03	0.56	3.31	9.83
Increasing intensity sequence									
15 mm h^{-1}	0.01	0.01	0.05						
30 mm h^{-1}	0.13	0.08	1.74						
45 mm h^{-1}	0.19	0.24	1.89						
60 mm h^{-1}	0.40	0.67	1.44						
Total	0.73	1.00	5.12						

2. Total sediment yield for the initially smooth surfaces was generally appreciably smaller than that for the initially medium-rough and rough surface conditions, while the sediment yield data of the latter two roughness conditions were generally very similar for corresponding slope steepnesses and rainstorm intensity regimes.

3. Total sediment yield from the initially smooth surface of the 8% and 17% slope steepness cases were larger for the decreasing rainstorm intensity sequences as compared to the increasing rainstorm intensity sequences.

4. Sediment concentration in runoff during prolonged rainfall on an initially dry soil surface first increases rapidly, then decreases gradually. This pattern reflects the dynamic nature of changes in the soil surface conditions with respect to the effect of surface sealing and rill development during rainfall.

5. Subsurface soil water pressures substantially affected the sediment concentration in runoff, but hardly affected the runoff volume.

6. Surface topography strongly affects drainage network development and runoff distribution, which in turn, are related to soil losses.

The large variations in the sediment yield data, among individual storms of 45-mm rainfall and soil beds with the same slope steepnesses, shows the large influence that rain intensity, surface roughness, and other antecedent conditions such as degree of rilling have on the measured soil loss.

5. Discussion

5.1. Effect of differences in the rainstorm intensity regime

The effect of differences in the sequence of rainstorm intensities on soil erosion is rarely considered in soil loss predictions. Table 1 shows that for the initially smooth surface, differences in total sediment yield for all 45-mm storms in a given intensity sequence vary with slope steepness. The data of Table 1 also shows: (1) A large similarity existed in the sediment yield data for the 2% slope steepness cases for storms of corresponding intensity but in different intensity sequences. Close inspection of the data of the increasing intensity sequence indicated that the sediment concentration increased gradually for the third or 45-mm h^{-1} storm, but sharply for the fourth or 60-mm h^{-1} rainstorm (Fig. 2). These increases are due to the development of rills or incisions in the soil bed following the breakdown of the surface seal (Römkens et al., 1997a,b). The sediment yield and concentration relationships for storms of decreasing intensity sequences were very uniform and did not indicate rill development (Fig. 2). (2) For the 8% and 17% slope steepness, evidence of rilling, as determined by rapid increases in the sediment concentration, was present in the second storm of both the decreasing sequence (45 mm h^{-1}), as well as the increasing rainstorm intensity sequence (30 mm h^{-1}). However, the degree of rilling was more severe in the decreasing rainstorm intensity regime as compared to the increasing intensity sequence. This finding suggests that storms with initially high intensities with the potential for development of early concentrated flow have a greater likelihood of rill development

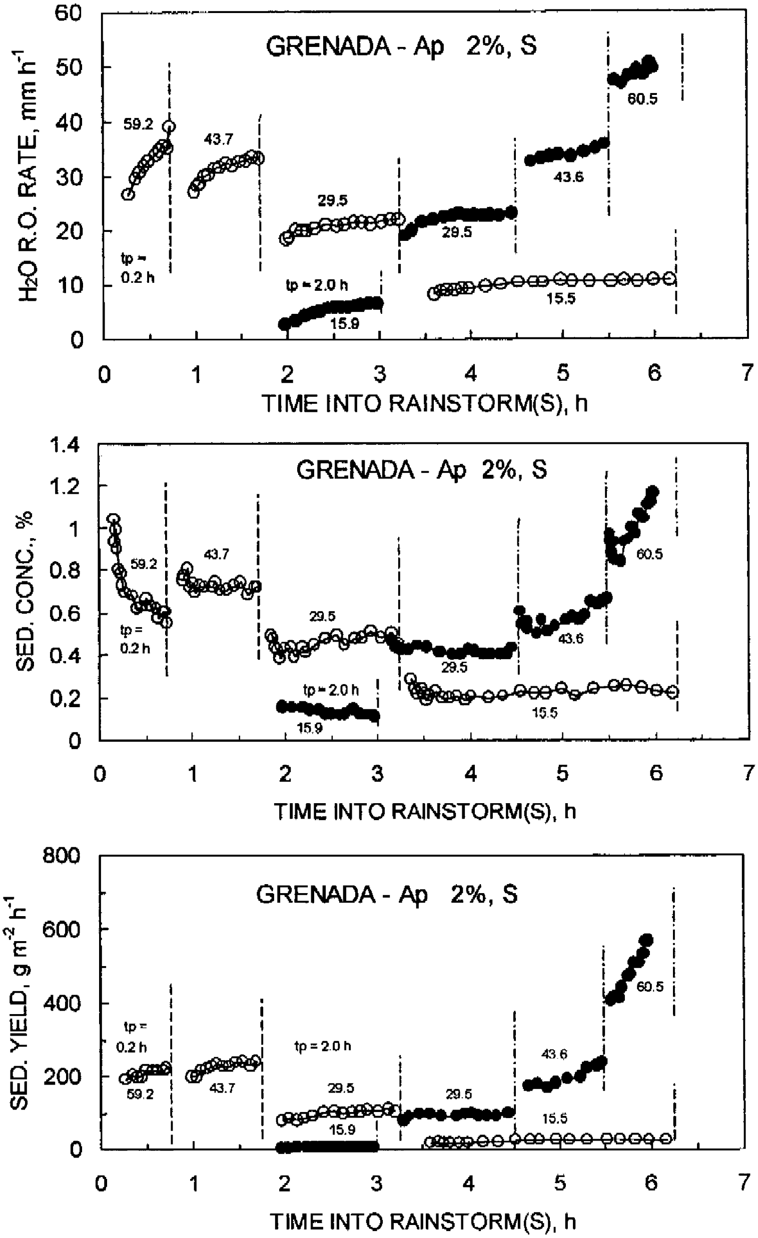

Fig. 2. Water runoff rate, sediment concentration, and sediment yield as a function of rainfall time for a series of 45-mm rainstorms of increasing and decreasing intensity. The broken vertical lines represent changes in the applied rainfall intensity. ○ denotes the data of storms with a decreasing intensity sequence and ● denotes the data of storms with an increasing rainfall intensity, ip denotes incipient ponding, S denotes initially smooth surface conditions.

than an intensity regime, where runoff becomes concentrated during the latter part of a rainstorm, at least for surfaces which are initially smooth. Also, a considerable portion of the early precipitation amount infiltrates, and thus, does not contribute to the erosive power of runoff. Finally, a storm with a lower initial rainfall intensity offers more opportunity for surface seal development, which is more resistant to erosion by surface flow. (3) Only the 60-mm h^{-1} rainstorm of the decreasing storm intensity series for both the initially rough and medium-rough soil surfaces indicated a stable or less erodible surface condition. Thus, differences in sediment yield among the 45-mm rainstorms of similar intensity can largely be attributed to differences in the soil surface dynamics during rainfall, i.e. incisions and seal development that developed during prior rainstorms.

5.2. Effect of surface roughness and slope steepness

Only experiments with a decreasing rainstorm intensity sequence were conducted for all slope steepnesses and surface roughness conditions. The total sediment yield data for the four 45-mm rainstorms showed very similar results for the initially medium-rough and rough surface conditions for corresponding slope steepnesses of 8% and 17% (Table 1). The medium-rough surface yielded a significant larger amount of total soil loss than the rough surface condition for the 2% slope steepness case. No satisfactory explanation can be given, except that on low slopes, runoff is usually more uniform and the occurrence of incisions with its rapid increase in soil loss is a more random phenomenon (Römkens et al., 1997a). The data, shown in Fig. 3, indicate: (1) higher soil losses were, as expected, consistently observed for each rainstorm intensity from large slope steepnesses, irrespective of the surface roughness condition. However, the medium-rough and rough surface condition yielded larger soil losses than the smooth surface condition due to differences in the runoff regime, i.e. uniform flow for the smooth surfaces vs. concentrated runoff for the rough and medium-rough surfaces. (2) The initial 60-mm h^{-1} rainstorm had consistently lower soil loss values than the second 45-mm h^{-1} rainstorm due to the high infiltration rate during the early stages of rainfall. Except for the smooth soil surface of the 8% and 17% slope steepness, the second 45-mm rainstorm with the 45-mm h^{-1} intensity yielded the maximum amount of soil loss for each intensity sequence, irrespective of slope steepness. This finding is attributed to the maximum amount of runoff that occurred during this storm, therefore, had more erosive power. At the same time, most of the more readily erodible soil material had not been detached at the beginning of the second rainstorm. (3) The effect of surface roughness was most significant for high intensity storms (i.e. 60 mm h^{-1}) on initially air-dry soil. In this case, storage capacity is rapidly met with excess rain accumulating in the depressions of the rough and medium-rough surfaces and the detached soil being deposited in these depressions or transported downslope. The effect was largest for the 17% slope steepness. Surface storage on the initially air-dry rough and medium-rough surfaces for all slope steepnesses is not as effective in reducing soil loss than a similar storm on an initially smooth surface. (4) Low intensity storms at the end of the decreasing storm intensity sequence, showed only marginal differences in soil loss between different roughness conditions. For those cases, there was insufficient build-up

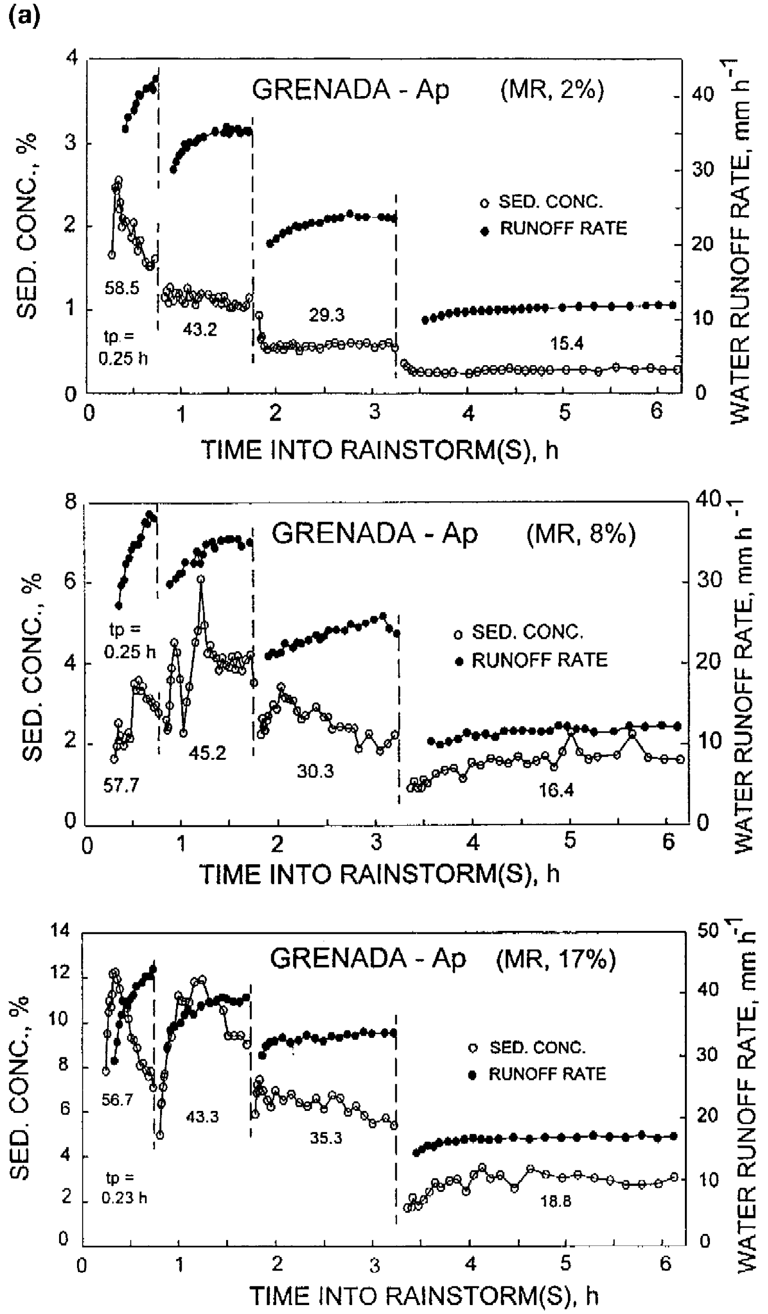

Fig. 3. The sediment concentration and water runoff rate for a series of 45-mm rainstorms of decreasing intensity, three slope steepnesses, and a rough (R) and medium-rough (MR) soil surface condition. The figures in the graph represent the actual rainfall intensities.

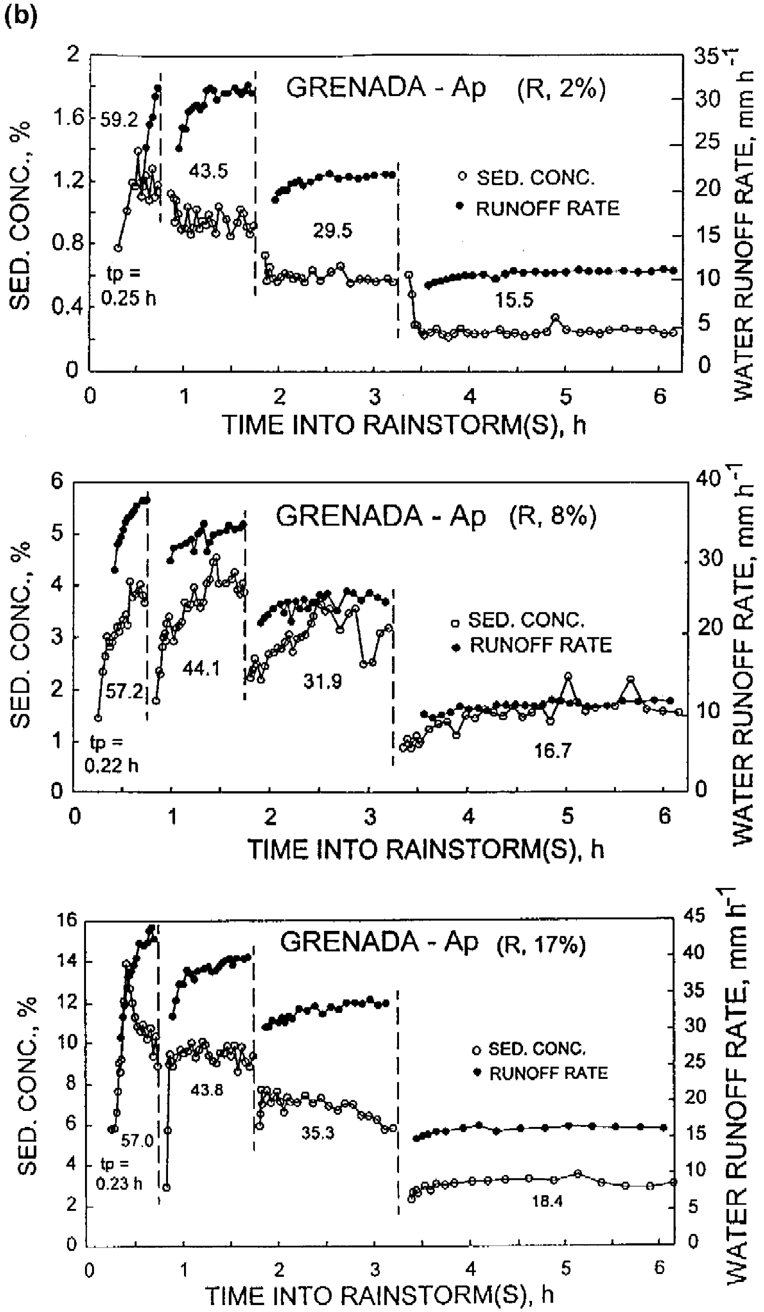

Fig. 3 (*continued*).

of runoff to show surface roughness effects. Also, at that point in the storm sequence, the initially smooth surface bed had developed a certain degree of roughness due to rill development or flow incisions, while the initially rough surfaces had smoothed, thereby reducing roughness differences antecedent to the last 45-mm rainstorm with 15 mm h^{-1} intensity. These observations show the strong interplay between changing surface conditions of roughness, surface sealing, erosive power of runoff, and antecedent soil water. Perhaps the most significant and unexpected finding is the low sediment yield from an initially air-dry, smooth surface at a high rainfall intensity. This finding reflects the diffusive nature of flow with low erosive power aided by seal development on the initially smooth surface, and the effect of flow concentration in rapidly forming rills in the depressions of the rough surfaces.

5.3. *Effect of the local topographic gradients*

In this study, the surface roughness effect was considered from the viewpoint of the local topographic gradient on soil loss. The effect of this gradient on soil detachment by rainfall and overland flow and the sediment concentration in runoff is rarely accounted for in soil erosion predictions. Fig. 4 shows the sediment concentration relationship as a function of cumulative rainfall during a series of simulated rainstorms of 66-mm h^{-1} on an initially air-dry, rough soil surface. This relationship shows the gradual decline in the sediment concentration during prolonged rainfall after an initially rapid rise during the early stages. The decrease is attributed to two simultaneously operating factors: (1) A decrease in the surface roughness or local topographic gradient and thus of reduced soil detachment by impacting raindrops, and (2) soil surface stabilization, i.e. increased resistance to erosive forces, due to compaction and sealing. Fig. 5 shows the DEMs and

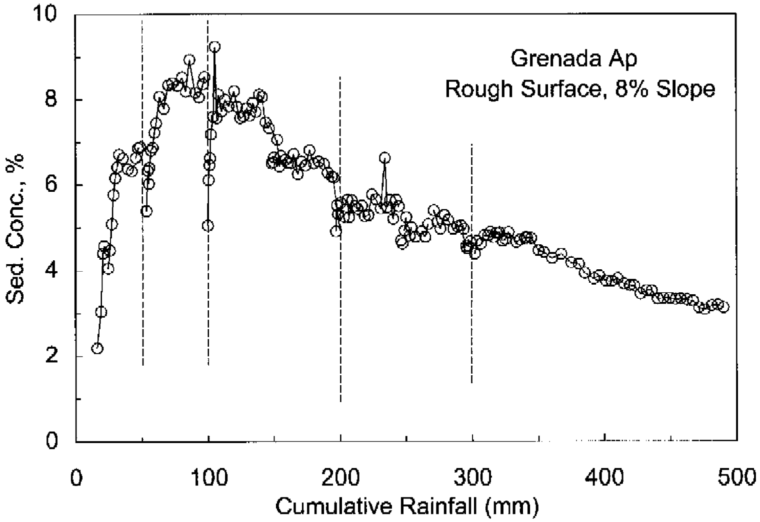

Fig. 4. Sediment concentration as a function of the accumulative rainfall during a series of 50-mm rainstorms of 66 mm h^{-1} rainstorm intensity and 8% slope steepness.

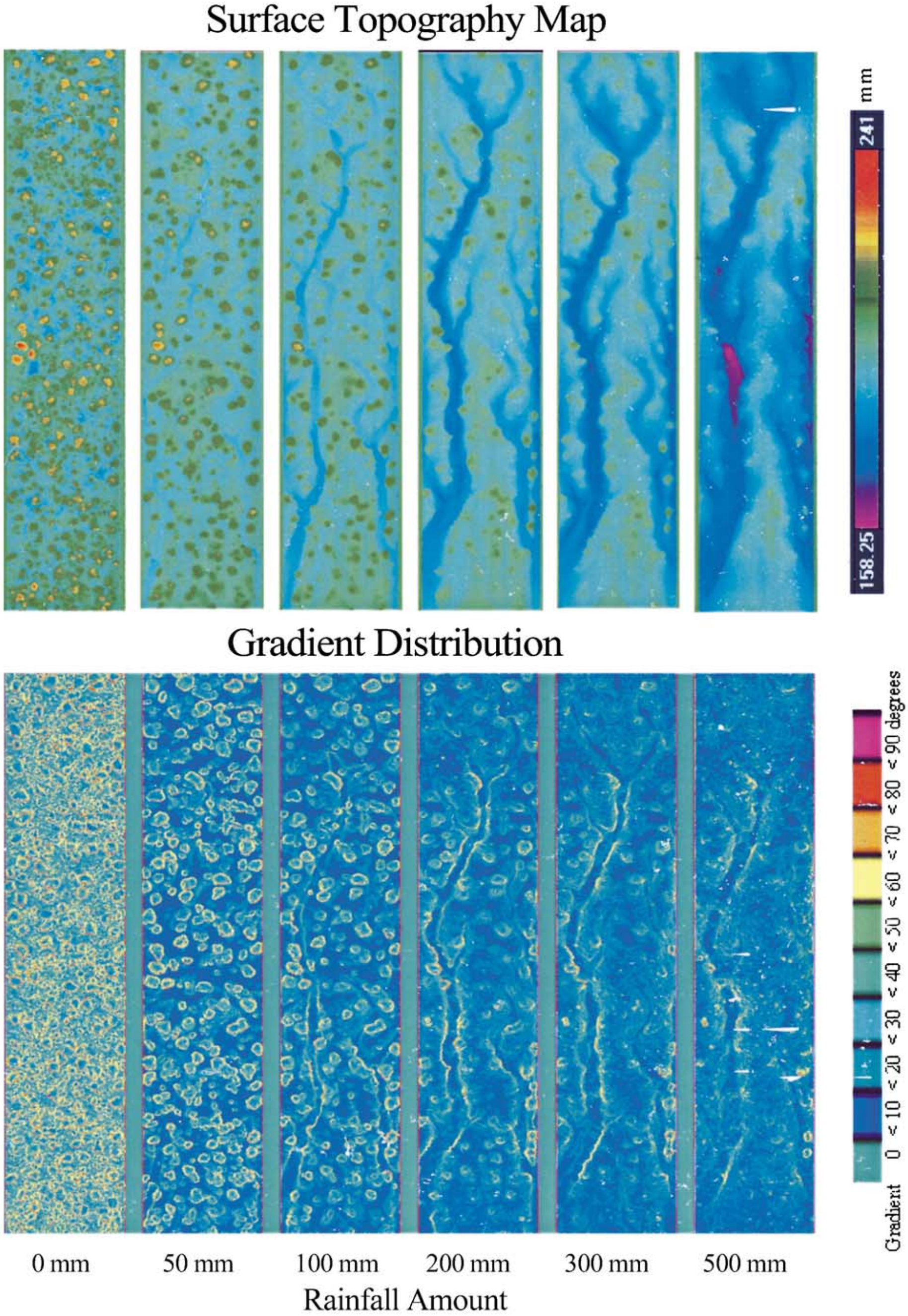

Fig. 5. The surface topography map and local topographic gradient map following each of a series of 50-mm rainstorms of 66 mm h^{-1} intensity and 8% slope steepness.

local topographic gradient maps of the soil bed at various stages during the series of simulated rainstorms. From the topographic gradient distribution of all 3 × 3 mm grid elements, the mean value of the local topographic gradient was computed and plotted against the sediment concentration at the end of each storm. This relationship, shown in Fig. 6, clearly indicates the changing sediment yield and topographic response of the soil bed during prolonged rainfall. During the early stages of rainfall, the soil erosion processes on the soil surface is dominated by soil detachment, especially that of loose soil material, due to raindrop impact and by soil translocations to local depressions (sloughing). Upon ponding, the runoff rate and also the sediment concentration rapidly increases due to rill development, while the local topographic gradient decreases. During the later stages, the soil surface has stabilized, loose soil material has been deposited and compacted, while changes in the local topographic gradients or microrelief are taking place at a much slower rate. The relationship of Fig. 6 thus reflects the dynamic response and changes in the soil surface vis-á-vis erosion processes during rainfall. A more detailed discussion and observations involving different soils have been reported by Römkens et al., in press.

5.4. Soil water pressure effect

Soil water pressure has a profound effect on the erosion rate and sediment yield. Our experiments with the prepared beds of the Grenada loess soil showed a marginal change in the runoff rate and an appreciable reduction in the sediment concentration with decreasing soil water pressures. Fig. 7 shows the relationship between the applied subatmospheric pressures in the drain system and the response in tensiometer readings at a depth of 0.08 m, as well as the measured runoff rate, and the sediment concentration

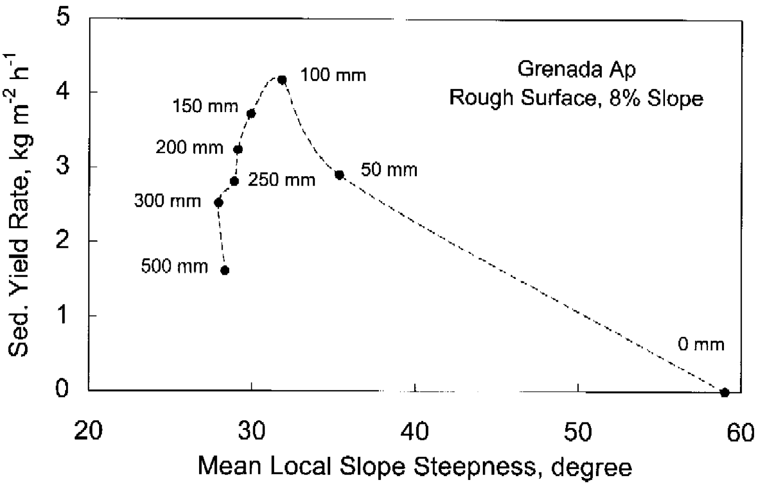

Fig. 6. The relationship between the sediment yield rate and the local topographic gradient following each of a series of 50-mm rainstorms of 66 mm h^{-1} intensity and 8% slope steepness.

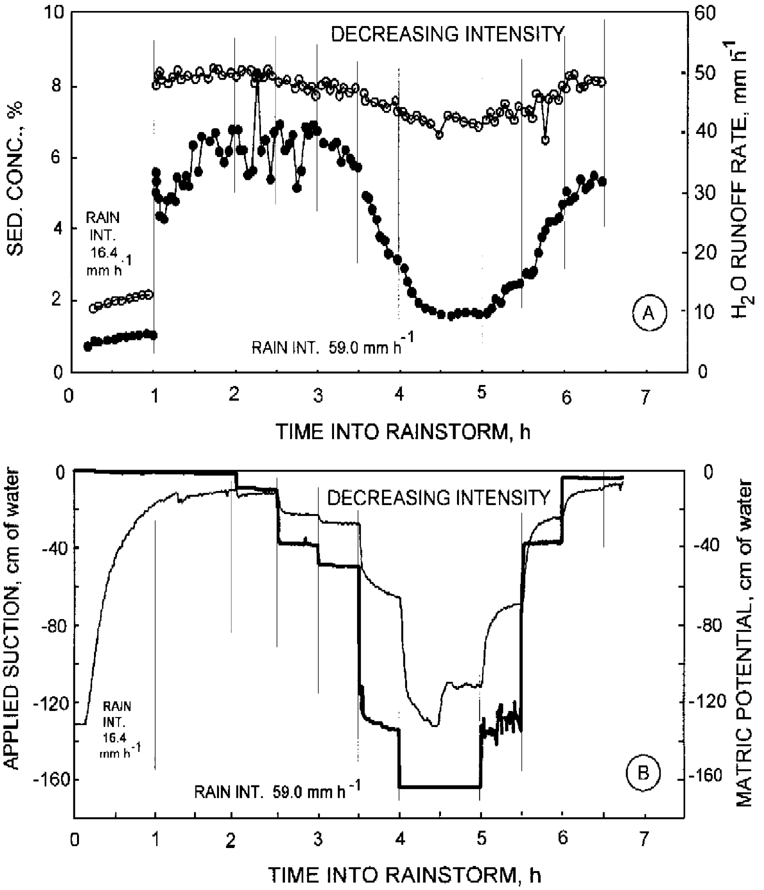

Fig. 7. The sediment concentration (A), water runoff rate (A), the applied pneumatic pressure (B), and the observed matric potential (B) as a function of time during the rainstorm. Note: (○) is the runoff rate; (●) is the sediment concentration; (heavy lines) indicate pneumatic pressure; (light line) indicate observed matric potential. The vertical lines denote moments of changes in rainfall intensity (first storm) or changes in the induced pneumatic pressures.

for a soil bed of 8% slope steepness that previously had been subjected to a sequence of four 45-mm rainstorms of decreasing storm intensities. Several observations can be made: (1) Fig. 7 shows very distinctly for some stepwise pressure changes the finite time required to reach a condition of equilibrium in the soil water regime. This adjustment time, for some incremental pressure changes on this soil, was as much as 0.5 h. No entirely satisfactory explanation can be given for the large response time. (2) A stepwise change in the pneumatic pressure in the drain system translated into a fractional change in the soil water pressure, with the smallest changes occurring near the soil surface. This is a consequence of the fact that due to continuous rainfall and runoff, the soil surface was at all times at atmospheric pressures, while the pressure in the drain lines was subatmospheric. (3) Unsteady subatmospheric pressures that were occasionally observed in the drain system during the reduction phase of the applied suction regime were attributed to the accumulation of percolated water in the drain lines, which at times, caused pressure pulsations in the suction regime. (4) The sediment concentration in runoff follows the subsurface soil water pressure regime. An increase in the soil water suction (more negative pressures) lead to a decrease in the sediment concentration. (5) The runoff rate was, at all times, appreciably less than the applied rainfall. Percolation was imperceptible, except for a small amount during the 130-cm suction interval in the relaxation phase. The difference between applied rain and runoff amount was either splash, estimated to be about 86 mm h or 15%, or storage water in the soil bed. The storage volume increased slightly during the suction regime according to TDR measurements. (6) The absence of percolation in spite of a significant suction level was attributed to a combination of factors, including the high degree of compaction, the presence of swelling clay material, and the absence of a structure with macropores, channels, or cracks that usually evolve under natural conditions. (7) A linear relationship appears to exist between the applied suction pressure and the observed sediment concentration, as measured at the end of each suction level interval (Römkens et al., 1997b). Also, the rate of change in the sediment concentration with applied suction appears to be related to the degree of rill development of the soil bed. The bed with the deepest and the largest rill density (decreasing intensity case) had the largest sensitivity to suction changes (Fig. 8). This observation is attributed to less cohesiveness of soil material in the rill system in comparison to that of the interrill areas, where raindrop impact has led to surface sealing and compaction has lead to a greater cohesion.

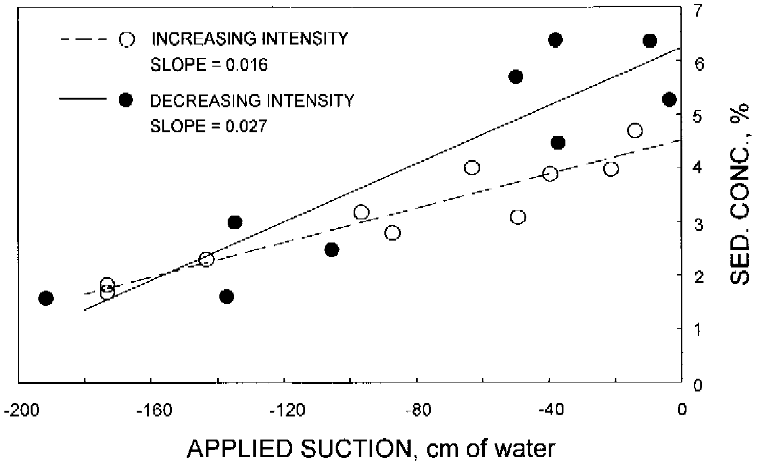

Fig. 8. Sediment concentration in runoff as a function of applied soil water suction. The ○ relationship represents the soil bed initially subjected to four 45-mm rainstorms with an increasing rainfall intensity regime, while the ● relationship represents the results of a soil bed initially subjected to four 45-mm rainstorms with a decreasing rainfall intensity regime.

5.5. Drainage network development

The observations of our studies indicate that surface topography strongly influences runoff distribution and erosion processes. Drainage networks before and after the application of 180 mm of rain on an initially dry soil bed with either a smooth and rough surface condition are shown in Fig. 9. The drainage networks of these soil beds show distinctly different initial characteristics with a highly organized or parallel pattern for the smooth surface and random directions for the rough soil bed. The application of 180 mm of rain reduced these differences and yielded a more straight, organized drainage network structure for the soil bed with the rough surface condition. On the other hand, the drainage network density of the initially smooth soil bed was reduced, but yielded deeper incisions of the remaining streams.

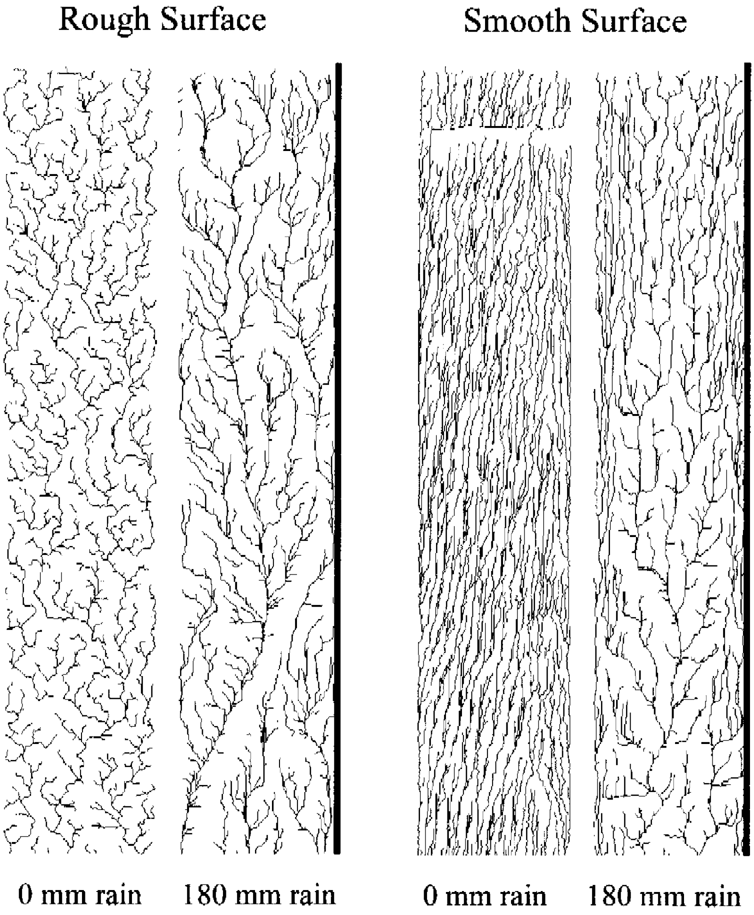

Fig. 9. Drainage networks determined from DEMs of a 0.6×2.8 m area with 3-mm grid spacings. Left: initially rough surface condition. Right: initially smooth surface condition.

An important measure of drainage network development in relation to soil erosion processes is the drainage density. It reflects the degree of flow concentration and thus the potential for scouring by surface runoff and the degree of energy absorption of impacting raindrops by surface water. The drainage densities for the initial condition and the condition after 180 mm of rain were 67.1 m m^{-2} vs. 55.9 m m^{-2} for the initially smooth surface, 34.5 m m^{-2} vs. 47.9 m m^{-2} for the medium-rough and 30.7 m m^{-2} vs. 43.3 m m^{-2} for the rough surface condition, respectively. Among the three surface conditions studied, the initially smooth surface had the highest density, reflecting diffuse surface flow with less incisions and scouring action and a greater degree of raindrop absorption by water films on the soil surface. The drainage densities for the initially rough and medium-rough surface networks were about half that of the initially smooth surface. Following rainfall, the drainage density increased on the rough surfaces but decreased on the initially smooth surface. This finding suggested that flow concentrated into fewer flow paths with deeper incision on the smooth soil bed, while the rough surface bed saw an increase in the number of flow paths. The relationship between soil loss and drainage density is of an inverse nature. The higher flow concentration in the lesser number of drainage paths led to larger soil losses due to deeper incisions. Thus, drainage network development and soil losses are related.

An example of the characteristics of a developing drainage network during a series of rainstorms is given in Fig. 10 for the soil bed of the Grenada soil Ap-material, shown in Fig. 4. The data depicts the sinuosity, gradient and orientation values of the different stream orders before rainfall, and after 100, 200, and 500 mm of rain. Several observations apply: (1) Sinuosity for the various stream orders of this initially rough soil bed was fairly constant at about 1.24, with slightly lesser values for the higher order streams following 100 mm of rain. Also, for the initially dry soil surface condition, the higher order streams had a sinuosity of about 1.35. The reduction in sinuosity, especially for the higher order streams after 100 mm of rain, is indicative of the shifting location of those streams and thus of soil detachment and removal by concentrated or rill flow. (2) The stream bed gradient decreased approximately linearly from 11% for stream order one to about 6% for stream order six. The relationship was fairly consistent, irrespective of the amount of rain that was applied. The maximum, absolute difference in the gradient for a given stream order was about 2%. Changes in the gradient affects the magnitude of the shear stress and thus of the erosive power of flow in the stream segment. In higher-order steams, the lower gradient tends to reduce the shear stress, but the larger flow rates tend to increase shear stress. (3) Stream orientation averaged initially about 40° from the downslope direction for stream orders one, two, and three. The 4th to 6th order stream orientation averaged initially between 10° and 25° from the downslope direction. The changing orientation of streams during successive rainstorms reflect the dynamic changes of the soil surface and thus of erosion and sedimentation processes. In summary, drainage network development, especially the rate of network development in relation to rainfall, reflects the dynamic response of the soil surface to erosion and sedimentation processes. Much needs to be done to ascertain and quantify the highly complex nature of this response to rainfall and surface flow. The data shows that the determination of drainage networks and drainage density might help to determine the effect of surface topography on erosion processes that are related to flow

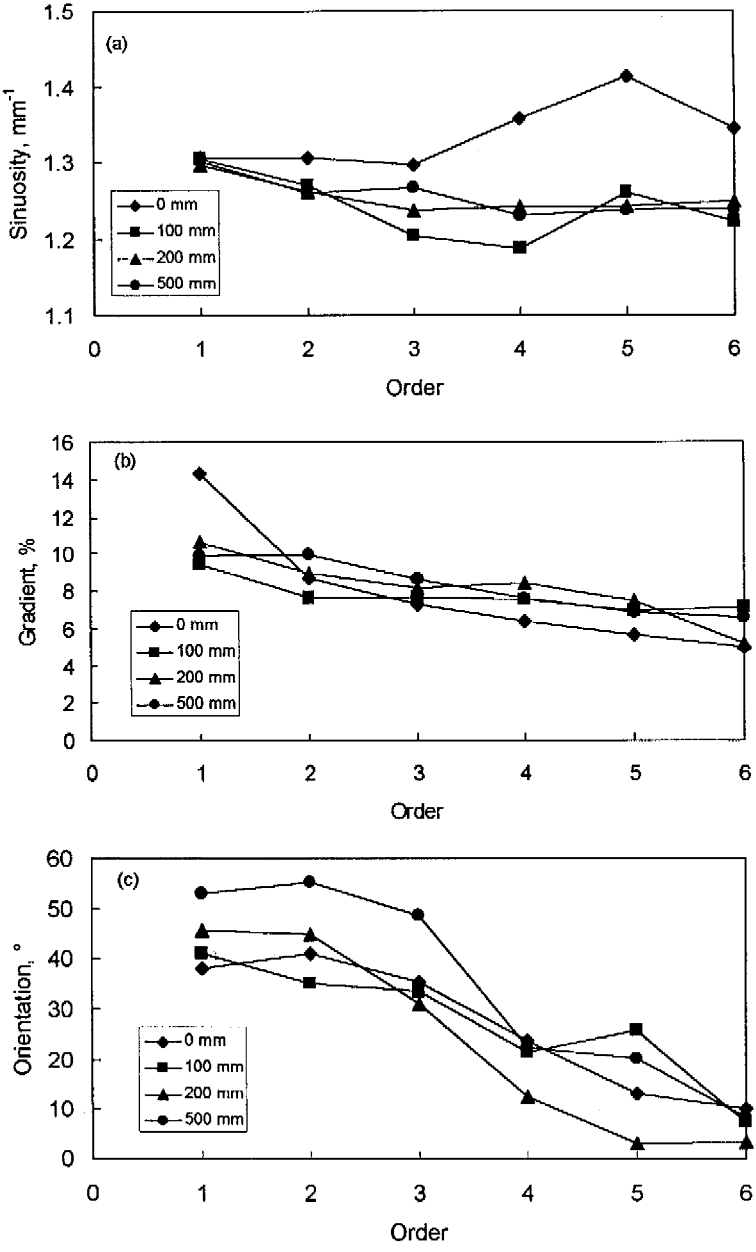

Fig. 10. Characteristics of the different stream orders of the developing drainage network after successive rainstorm events. (a) Stream sinuosity, (b) stream gradient, (c) stream orientation.

patterns. Detailed information about drainage network development, drainage network characteristics, and the effect of surface configuration on network properties and network changes are given by Helming et al. (1997, 1998b).

6. Summary

Laboratory flume experiments were conducted to better ascertain the role of surface roughness and rainstorm intensity sequences and prolonged rainfall on soil loss. The results show that smoother surfaces have less soil loss than rough surfaces. Surface roughness conditions determine drainage network development, sediment yield rates are related to the local topographic gradient distribution, and rainfall intensity sequences affect soil loss. Subsurface soil water pressure substantially affects the sediment concentration regime.

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