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The effect of slope steepness and antecedent moisture content on interrill erosion, runoff and sediment size distribution in the highlands of Ethiopia

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Abstract. Soil erosion is a two-phase process consisting of the detachment of individual particles and their transport by the flowing water. This study discusses the results of laboratory experiments in which for three soils, the runoff depth, sediment yield, splash erosion and sediment size were measured. Rainfall intensity, slope and antecedent moisture contents were varied in the experiment. The soil types ranged from clay to sandy clay loam (Alemaya Black soil, Regosols and Cambisols). Rainfall was applied for six sequential 15-min periods with rainfall intensities varying between 55 and 120 mm h^{-1}. The three slopes tested were 9, 25, and 45 %. Results show that as slope increased from 9 to 25 %, splash erosion and sediment yield increased. An increase in slope from 25 to 45 % generally decreases in splash erosion. Sediment yield for one soil increased and one soil decreased with slope and for the third soil the trend was different between the two initial moisture contents. Sediment yield was correlated ($r = 0.66$) with runoff amounts but not with splash erosion. Interrill erosion models that were based on the flowing water and rainfall intensity fitted the data better than when based on rainfall intensity solely. Models that assume a positive linear relationship between erosion and slope may overestimate sediment yield.

1 Introduction

Most of sub-Saharan Africa suffers from environmental degradation that is negatively affecting agricultural production (Fekadu, 2000). In east Africa, soil degradation is most severe in Ethiopia (Hurni, 1985). Soil erosion continues to be a major agricultural problem in the Ethiopians highlands (Constable, 1985). Little research has been done on the mechanisms of soil erosion and information is limited for sound soil conservation measures.

Detachment, transport, and deposition are basic processes of soil erosion. In this paper, we are interested in understanding the loss of soil from interrill areas. For interrill erosion, detachment is caused by raindrop impact. Transport of detached particles is by overland flow (Bradford and Huang, 1996). Rainfall intensity, topography, and soil properties are the main factors that determine interrill erosion. Several models have been proposed to explain the process of erosion.

Currently available interrill erosion models vary from a simple rainfall intensity-erosion relationship (Meyer, 1981) to more complex models which include one or more of the following parameters: soil properties, intensity, runoff, and slope steepness such as by Foster (1982), Liebenow et al. (1990), Watson and Laflen (1986), Neal (1938) and Kinnell (1993) (Table 1).

Models III, IV and V (Table 1) assume that there is positive correlation of erosion rate with slope. Although this correlation has been observed for selected soils (Bradford and Foster, 1996), it is not true in every case (Lillard et al., 1941; Neal, 1938). While, generally, erosion becomes greater with increasing slopes from 0 to 10 %, in many cases erosion rate decreases when the slope is greater than 10 %.

With such contradictory research results, applying models without further experimentation may lead to erroneous interrill erosion estimates. Specifically, the assumption that erosion increases with slope may grossly overestimate soil loss in countries like Ethiopia, where cultivated lands as steep as 60 % slope are common. Interrill equations that were developed on agricultural lands in which slopes are less than 30 % are not applicable under high slope conditions. Given the lack of experimental soil erosion research in Ethiopia, the specific objectives of our research are to (1) determine the

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Table 1. Available interrill erosion models and slope steepness factor.

Models	Equation	Parameters
Model I	$E = aI^b$ Meyer (1981) and Foster (1982)	a and b are fitting constants, I rainfall intensity, q is runoff rate, K_i is interrill erodibility coefficient, S is slope gradient, S_f slope steepness factor, and θ is angle in degree
Model II	$E = K_i I^2$ Meyer (1981)	
Model III	$E = K_i I^2 S_f$ Liebenow et al. (1990)	
Model IV	$E = K_i I q S$ Neal (1938)	
Model V	$E = K_i I q S_f$ Kinnel (1994) $S_f = 1.05–0.85\,\mathrm{e}^{-4\sin\theta}$ Liebenow et al. (1990)	

effect of slope steepness and antecedent soil moisture content on splash erosion, infiltration, runoff and soil loss, (2) estimate the interrelation between various soil erosion and runoff parameters and evaluate the validity of different rainfall intensity and rainfall intensity-runoff based soil erosion models, and (3) test the hypothesis that the slope steepness term as expressed in several interrill erosion models varies with soil conditions. The research is carried out for three major soils of the Alemaya watershed and that at the same time are representative for other soils in Ethiopia.

2 Methodology

2.1 Description of the study area

This study consists of a laboratory based soil erosion experiment on soils found in the Alemaya watershed, eastern Ethiopia. The Alemaya watershed (area between 1850 and 2200 meters above mean sea level elevation) is classified as "Woina Dega" agro-ecological zone with an average annual rainfall of 870 mm (560–1260 mm range). There are six months (March to September) with more than average monthly rainfall. The area receives rainfall amounts more than 160 mm per month in April, May, August and September.

2.2 Experimental design and treatments

2.2.1 Experimental design

These experiments were conducted in the laboratory using an FEL 3-A, rotating disc nozzle type, rainfall simulator and laboratory erosion pans. The research was proposed to be done at predetermined intensities and, as a result, calibration of the simulator was found essential to determine the various combinations of pressure, disc speed and aperture size that provide different intensities. Accordingly, calibration of the simulator was made prior to the commencement of the study following the procedures given by the manufacturer of the simulator and the spatial uniformity of simulated rainfall was also determined.

The FEL 3-A (rotating disc type) rainfall simulator used consists essentially of two units: the rainfall simulator and its service module which stands alongside. The service module comprises a glass fiber tank which is connected to the main water supply via a ball-lock to maintain the level. Water is pumped from the tank to the rainfall simulator by a centrifugal pump through the flexible PVC tube.

In this study, an erosion pan similar in design to Bradford and Foster (1996) with slight modification in size was used. The test area of this pan was 320 mm wide by 450 mm long and 150 mm deep. An additional component, a 200 mm wide soil buffer surrounding the central test area, was also provided. Two 30 mm wide by 450 mm long troughs located along both sides of the test area were used to collect splash. A slot along the lower end of the test area collected runoff and wash. Drainage outlets at the bottom of each compartment were provided for percolation of water. The advantage of this type of erosion pan is the ability to measure splash and sediment yield separately and the buffer areas reduce the edge effect.

2.2.2 Selection of treatments

Four treatments (soil type at three levels, slope steepness at three levels, antecedent moisture content at two levels, and three rainfall intensities in two sequences) were selected. The experiment was a four factor factorial experiment ($3 \times 3 \times 2 \times 2$) in a completely randomized design at two replications which was a total of 72 simulations run.

Three soil materials from freshly plowed surface soils were selected from the available major soil series that occur in the study area. The selected soil series (Regosols, Cambisols, and Vertisols) represent about 70 percent of the

Table 2. Particle size distribution (%) of soils studied.

Soil	Major soil classifications	Coarse sand	Medium Sand	Fine sand	Silt	Clay	Organic matter
Soil A	Alemaya black soil (Vertisol)	8	9	7	41	35	6*
Soil B	Godie soil series (Cambisols)	18	23	11	16	32	14*
Soil C	Alemaya series eroded phase (Regosols)	21	17	11	32	19	4*

* Percent taken from the total soil material.

Table 3. Mean size distribution of soil aggregate (%).

	Particle size distribution (%)						
Soil type	5.60 mm	4.475 mm	2.675 mm	1.59 mm	0.89 mm	0.45 mm	0.225 mm
Soil A	33.0	15	18	11	18	3	2
Soil B	15	13	32	16	17	4	3
Soil C	4	8	9	34	29	7	9

soils occurring in Alemaya area. Prior to the collection of sample, maize was grown on Soil-A (Vertisols) and Soil-C (Cambisols). On Soil-B (Regosols), the crop grown was forage and naturally fertilized (livestock dug) for more than ten years. Each soil sample was air dried and sieved through a 10 mm sieve before being used in simulation runs.

In each simulation run, a 60 mm thick layer of soil was packed over laying 90 mm of gravel in the central area of the erosion pan. Soil particle size distribution of the three soils, which were determined by pipette methods following the procedures of the US Soil Conservation Service (1967) and sedimentation time recommended by Tanner and Jackson (1947), is described in Table 2 and the mean size distribution of soil aggregate is described in Table 3. Two levels of antecedent moisture content, i.e., air-dried and pre-wetted conditions, were selected. Pre-wetting took place by applying water through the drain for 24 h. The experiment was conducted at 9, 25, and 45 % slopes. Rainfall intensities were applied in 15 min sequences (55, 70, 120, 70, 55, 120 mm h^{-1}) for a total of 90 min.

2.3 Data collection and analysis

2.3.1 Data collection

Splash detachment, runoff and sediment yield were measured at 15 min intervals throughout the 90 min rainfall. Surface shear strength/resistance was measured using a fall cone penetrometer after each rainfall sequence application, following procedures adopted by Al-Durrah and Bradford (1981), Bradford et al. (1987a, b) and Truman and Bradford (1993). Stream power was calculated using the equation: Stream power $(\omega) = \rho g q S$, where ρ is density of water, g acceleration due to gravity, q is the volumetric flux of runoff per unit width of erosion surface ($m^3\,m^{-2}\,s^{-1}$) and S is the sine of the erosion surface slope. Flow depth was calculated using the following equation: Flow depth $(h) = (qn/s^{1/2})^{2/5}$; where q is discharge; n is Manning's hydraulic roughness and S is slope steepness.

To evaluate interrill erosion models, data collected at each 15 min interval were used. However, to evaluate the effect of slope steepness and antecedent moisture content on the erosion variables, the 15 min interval data were merged for the total 90 min rainfall. The collected samples were oven dried at 105 °C for 24 h for further analysis.

Particle sizes of the collected sediment were determined by gently sieving sand-sized particles followed by drying and weighing. Silt and clay were determined in the suspension passing the sieve by drying pipetted volumes of the suspension that were sampled at fixed depths after different settling times.

2.3.2 Data analysis

Analysis of variance was carried out according standard procedures and means were separated using a protected least significance difference method at 0.05 probability level (Fisher, 1935). The significance of factors influencing splash erosion, soil loss, runoff, and sediment size distribution were evaluated. Using the appropriate statistical tests, the correlations between erosion variables were calculated and significances

Table 4. Shear strength (Resistance), sediment yield, splash detachment and runoff rate values for each combination of soil type, slope steepness, and initial moisture contents.

Soil	Slope (%)	Initial MC	Shear strength (K Pa)	Sediment yield ($\mathrm{kg\,m^{-2}\,h^{-1}}$)	Splashed erosion ($\mathrm{kg\,m^{-2}\,h^{-1}}$)	Proportion of sediment transported by runoff	Runoff rate ($\mathrm{mm\,h^{-1}}$)	Stream power* $\times 10^{-2}$ ($\mathrm{W\,m^{-2}}$)	Mean interrill overland flow overland flow
Soil A	9	AD	6.9	1.0	2.6	0.4	62.7	1.6	1.4
		PW	7.4	0.7	2.4	0.3	37.6	0.9	1.0
	25	AD	8.3	1.4	5.2	0.3	56.1	3.9	1.0
		PW	7.6	0.8	3.2	0.3	50.6	3.5	0.9
	45	AD	9.5	1.5	4.0	0.4	49.4	6.2	0.8
		PW	16.3	0.6	2.8	0.2	31.4	3.9	0.6
Soil B	9	AD	7.7	0.8	3.5	0.2	47.3	1.2	1.2
		PW	9.9	0.5	2.6	0.2	59.9	1.5	1.4
	25	AD	6.0	0.8	4.2	0.2	43.1	3.0	0.8
		PW	8.2	0.7	2.2	0.3	49.6	3.4	0.9
	45	AD	9.1	0.1	2.9	0.1	5.8	0.7	0.2
		PW	10.0	0.4	3.1	0.1	22.6	2.8	0.5
Soil C	9	AD	14.7	0.7	3.1	0.2	62.2	1.6	1.4
		PW	14.5	0.5	2.3	0.2	39.4	1.0	1.1
	25	AD	13.0	1.3	3.7	0.4	61.2	4.3	1.0
		PW	12.7	1.2	3.1	0.4	47.3	3.3	0.9
	45	AD	16.7	1.5	2.8	0.5	46.0	5.8	0.7
		PW	17.0	1.5	2.3	0.6	68.4	8.6	0.9

* calculated values. AD = Air dried, PW = Pre-wetted.

of the correlation coefficients were tested. In this study, all relations with $p < 0.05$ were considered as significant.

2.4 Evaluation of interrill erosion models and Slope steepness factor

The 15-min soil loss and runoff data were fitted to the five models. Their performances in replicating the observed data were evaluated and their R^2 values were compared. Regression analyses were conducted to identify or estimate the fitted constants of the selected interrill erosion models.

3 Results and discussion

3.1 Runoff and infiltration rates

Soil types have a highly significant effect on runoff rate. The mean runoff rate observed on Soil C ($54\,\mathrm{mm\,h^{-1}}$) was significantly greater than the mean runoff rate value of $38\,\mathrm{mm\,h^{-1}}$ for Soil B (Tables 4 and 5). Soil B and C had approximately the same sand content (50 %, Table 2) but the organic matter was 14 % for Soil B while it was only 4 % for Soil C. Thus Soil B was better structured and therefore has a greater conductivity and more interflow than Soil C.

As indicated in Fig. 1, runoff rate generally decreases with increased slope except for Soil C wet. Greater slope increases interflow and therefore reduces runoff. In addition, Soil A and Soil C at 9 and 25 % slope have greater runoff rates for the dry soils than for wet soils. This was not expected because it is generally assumed that infiltration rates for dry soils are greater than for wet soils and suggests that these soils have some form of water repellency. Only Soil B, which has the greatest organic matter content (Table 2), has less runoff when dry than when wet.

Table 5. Effect of the different combinations of soil type and moisture content on runoff rate.

Moisture content	Runoff rate (mm h^{-1})			
	Soil A	Soil B	Soil C	Mean
Air-dry	56.1	32.1	56.4	48.2
Pre-wetted	39.9	44.0	51.7	45.2
Mean	48.0	38.0	54.0	46.7
	Soil type	Moisture content	Moisture-Soil interaction	
SEM (Standard Error of the Mean)	1.5	1.3	2.2	
LSD (Least Significant Difference)	4.4	3.6	6.2	

Table 6. Effect of the different combinations of antecedent moisture content and slope on splash detachment.

Slope (%)	Splash (kg $m^{-2}h^{-1}$)		
	AD	PW	Mean
9	3.0	2.4	2.7
25	4.4	2.8	3.6
45	3.2	2.7	3.0
Mean	3.5	2.6	
	Slope	Initial moisture content	Slope x initial moisture
SEM	0.11	0.09	0.16
LSD	0.32	0.26	0.46

3.2 Splash erosion

Although there were no any discernable differences and trends of splash erosion among the different soil types, the magnitude of the mean splash from Soil A at higher slopes (25 and 45 %) was higher than that of Soil C (Table 4). Less splash erosion took place for initially wet soils than for dry soils (Tables 4 and 6). The average splash rate for wet soil was almost the same at 2.6 kg m^{-2} h^{-1} and varied for wet soil from 3.0 (Soil A) to 4.4 kg m^2 h^{-1} (Table 6). Although the splash rate for the 25 % slope is generally greater than for the other two slopes, there is no consistent trend of splash rate with slope (Fig. 2). Similarly, there is no consistent relationship between the amount of splash and shear strength (third column, Table 4). Although other studies have reported a decrease of splash with water depth, the relationship is not valid for this set of experiments, because water depth, generally decreased with slope (last column, Table 4) while splash was the greatest at the middle slope. Our results are similar to Foster and Martin (1969), who found the maximum splash at 33 % and less for other slopes.

Table 7. Effect of the different combinations of soil type and moisture content on sediment yield.

Moisture content	Sediment yield (Kg $m^{-2}hr^{-1}$)			
	Soil A	Soil B	Soil C	Mean
AD	1.3	0.6	1.2	1.0
PW	0.7	0.6	1.0	0.8
Mean	1.0	0.6	1.1	0.9
	Soil	Moisture condition	Soil X moisture	
SEM±	0.03	0.03	0.05	
$LSD_{0.05}$	0.10	0.08	0.07	

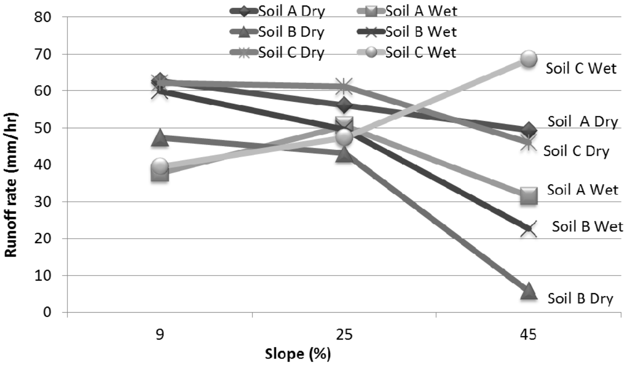

Fig. 1. Effect of the different levels of slope steepness on runoff rate for the three soils at two levels of initial moisture content.

3.3 Sediment yield

The rate of sediment yield varied significantly with moisture content (Table 7). Wetting decreased sediment yield of Soil A by almost 50 %. The sediment yield for Soil B was independent of wetness. The erodibility of wet Soil C was 20 % less than for the dry soil (Table 7). As slope increased from 9 % to 25 %, sediment yield increased for all three soils. However, as slope increased from 25 % to 45 %, sediment yield decreased for the wet Soil A and Soil B, but increased for Soil C and the dry Soil A (Fig. 3). Even though little work has been done on steeper slopes, the results of our study are in part consistent with findings of Lillard et al. (1941) and Neal (1938), who found a decrease in soil loss for steeper slopes.

Similarly to the sediment yield, the sediment splash ratio increased for both initial moisture contents of Soil C and the dry Soil A and the ratio decreased for the wet Soil A and both antecedent moisture contents of Soil B (Fig. 4). As expected from Fig. 4, correlation was poor between splash erosion and sediment yield, indicating higher splashed sediment does not necessarily mean higher sediment yield.

Table 8. Size distribution of the washed and splashed sediment for the three soils.

Soil	Slope (%)	Moisture content	Fraction by weight in size class (%)				
			Coarse sand 2.0–0.60 mm (Washed; Splashed)	Medium sand 0.6–0.21 mm (Washed; Splashed)	Fine sand 0.21–0.08 mm (Washed; Splashed)	Silt 0.08–0.002 mm (Washed; Splashed)	Clay <0.002 mm (Washed; Splashed)
Soil A	9 %	AD	(0.11; 0.13)	(0.07; 0.04)	(0.07; 0.03)	(0.48; 0.49)	(0.27; 0.31)
		PW	(0.08; 0.14)	(0.05;0.04)	(0.04; 0.04)	(0.39; 0.39)	(0.44; 0.39)
	25 %	AD	(0.10; 0.15)	(0.07;0.04)	(0.10;0.05)	(0.51;0.44)	(0.22;0.32)
		PW	(0.08;0.12)	(0.06;0.04)	(0.06;0.05)	(0.33;0.41)	(0.47;0.38)
	45 %	AD	(0.08;0.12)	(0.06;0.04)	(0.06;0.06)	(0.40;0.67)	(0.40;0.11)
		PW	(0.05;0.11)	(0.04;0.04)	(0.04;0.05)	(0.29;0.47)	(0.58;0.33)
Soil B	9 %	AD	(0.11;0.16)	(0.10;0.10)	(0.11;0.07)	(0.36;0.35)	(0.32;0.32)
		PW	(0.10;0.19)	(0.07;0.04)	(0.09;0.03)	(0.44;0.27)	(0.30;0.47)
	25 %	AD	(0.14;0.14)	(0.13;0.10	(0.13;;0.09)	(0.30;0.35)	(0.30;0.32)
		PW	(0.23;0.25)	(0.05;0.05)	(0.09;0.05)	(0.42;0.43)	(0.21;0.22)
	45 %	AD	(0.19;0.23)	(0.03;0.05)	(0.02;0.12)	(0.38;0.45)	(0.38;0.15)
		PW	(0.09;0.13)	(0.04;0.06)	(0.04;0.03)	(0.12;0.68)	(0.71;0.10)
Soil C	9 %	AD	(0.09;0.12)	(0.02;0.06)	(0.15;0.16)	(0.31;0.36)	(0.43;0.30)
		PW	(0.12;0.32)	(0.03;0.10)	(0.13;0.14)	(0.28;0.10)	(0.44;0.34)
	25 %	AD	(0.13;0.44)	(0.10;0.12)	(0.07;0.02)	(0.32;0.21)	(0.38;0.21)
		PW	(0.33;0.37)	(0.11;0.10)	(0.05;0.03)	(0.22;0.25)	(0.29;0.25)
	45 %	AD	(0.23;0.40)	(0.11;0.11)	(0.10;0.06)	(0.32;0.32)	(0.24;0.11)
		PW	(0.18;0.36)	(0.15;0.11)	(0.10;0.09)	(0.21;0.22)	(0.36;0.22)

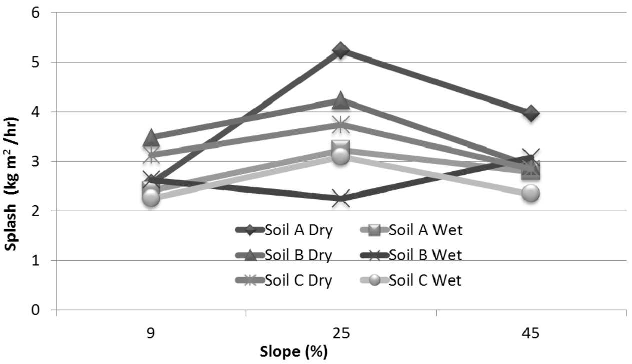

Fig. 2. Effect of the different levels of slope steepness on splash for the three soils at two levels of initial moisture content.

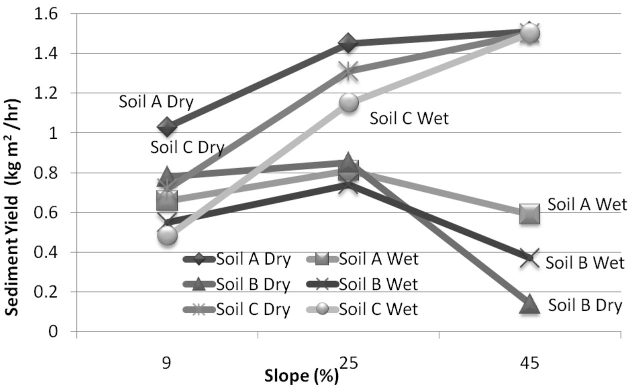

Fig. 3. Effect of the different levels of slope steepness on sediment yield for the three soils at two levels of initial moisture content.

Table 9. Exponents, coefficients, and R^2 values for equations describing interrill soil loss.

Soil	Slope (%)	Moisture content	Model I		Model II		Model III		Model IV		Model V	
			b	R^2	$K_i \times 10^6$	R^2	$K_i \times 10^6$	R^2	$K_i \times 10^6$	R^2	$K_i \times 10^6$	R^2
Soil A	9	AD	0.46	0.65	0.10	0.34	0.21	0.61	1.73	0.66	0.34	0.73
		PW	0.57	0.99	0.86	0.94	0.19	0.98	2.05	0.99	0.41	0.99
	25	AD	0.72	0.81	0.22	0.64	0.30	0.81	1.43	0.80	0.49	0.83
		PW	1.16	0.88	0.20	0.81	0.28	0.91	1.29	0.95	0.44	0.95
	45	AD	1.14	0.99	0.41	0.98	0.47	0.99	1.56	1.00	0.79	1.00
		PW	0.79	0.99	0.11	0.99	0.12	0.99	0.57	0.99	0.29	0.99
Soil B	9	AD	1.24	0.85	0.25	0.88	0.54	0.94	5.53	0.91	1.09	0.91
		PW	1.58	0.99	0.21	0.99	0.45	0.84	3.03	0.99	0.60	0.99
	25	AD	1.30	0.95	0.09	0.94	0.35	0.97	1.54	0.95	0.53	0.95
		PW	0.98	0.99	0.06	0.98	0.24	0.99	1.04	0.98	0.36	0.99
	45	AD	1.48	0.91	0.13	0.92	0.14	0.96	1.37	0.98	0.70	0.99
		PW	1.75	0.87	0.18	0.92	0.24	1.00	0.34	0.94	0.43	1.00
Soil C	9	AD	0.71	0.96	0.12	0.92	0.26	0.96	2.00	0.99	0.39	0.99
		PW	1.72	0.64	0.13	0.52	0.17	0.98	1.09	0.98	0.22	0.98
	25	AD	0.93	0.98	0.30	0.98	0.41	0.99	1.85	0.99	0.64	0.99
		PW	1.03	0.99	0.29	0.98	0.40	0.99	1.89	0.99	0.65	0.99
	45	AD	0.82	0.99	0.30	0.98	0.34	0.99	1.28	0.99	0.65	0.99
		PW	1.47	0.60	0.34	0.41	0.23	0.91	0.67	0.96	0.33	0.96

Increase in runoff rate was reasonably well correlated with increase in sediment yield ($r = 0.83$ with 0.001 significant level). When the correlations between these variables were analyzed for each soil, the best correlation coefficient was obtained for Soil B.

3.4 Sediment size distribution

Independent of the original soil composition, the splashed sediment had a large fraction of silt and clay particles than the original soil (compare Tables 2 and 8). Both Soil B and Soil C had over 50 % sand in the original soil, while in all cases the sand and silt fraction in the splashed sediment was over 50 %. Thus the sand fraction is increasing at the surface of the soil and forms a shield (Gao et al., 2003; Rose et al., 1994). In addition, since Soil A had the smallest sand fraction in both the original soil and the splashed sediment, a dependence of sediment size distribution existed with the original soil. Finally, in almost for all soils, Table 8 shows the clay fraction in the splashed sediment was greater for the initially wet soil than for the dry soil. In few of the cases, there was an opposite trend, where the silt content increased more than the clay content decreased.

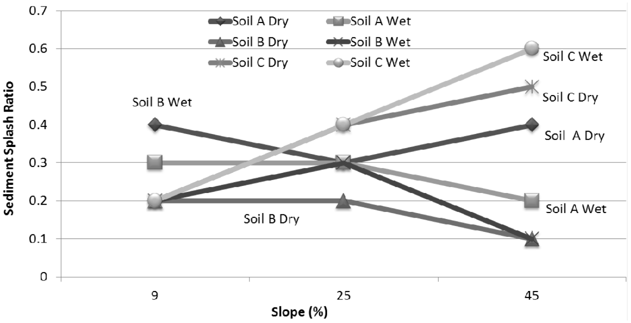

Fig. 4. Sediment splash ratios by soil type and moisture content under different slope steepness.

3.5 Evaluation of interrill erosion models

To test the validity of the assumption that $b = 2$, in Model I ($E = aI^b$), values for each treatment combination were determined by linear regression of the log transformed data (Table 9). Values of b ranged from, 0.46 for Soil A-dry at 9 % slope, to 1.75 for Soil B-wet at 45 % slope. In general, the b values were smaller for the fine structured Soil A than for the sandier Soils B and C. Other than that, we could not discover a consistent trend for b with either slope or initial moisture content. Our results are consistent with the findings of Meyer (1981) who found similarly that clay soils had lower b values than for sandier soils.

For Model II ($E = K_i I^2$), the effect of initial moisture content on the erodibility coefficients (K_i) were determined for each soil at three levels of slope. For Soil A, at 9 % and 25 % slope, pre-wetting had little effect. However, there was a highly significant difference between the erodibility values of air-dry and pre-wetted treatments at 45 % slope. For Soil B, the effect of pre-wetting on K$_i$ was little. Pre-wetting decreased the erodibility coefficient at 9 % and 25 % slope and increased the coefficient at 45 % slope by 38.5 %. For Soil C, the effect was little and its decrease or increase depended on slope steepness (Table 9).

Erodibility coefficient values were also determined for Model III, including the slope factor ($E = K_i\ I^2 S_f$). There were differences between calculated values of the erodibility coefficients at the three levels of slope. An appropriate slope steepness factor should result in equal K_i values for a range of slope steepness (Truman and Bradford, 1993). For Soil A, K_i values increase significantly as slope increased from 9 % to 45 %. This result shows that a slope adjustment factor is a function of soil type and antecedent moisture content.

Kinnell (1991) suggests that, the I^2 term in Model III be replaced by the product of I and q (flow). According to the author, the product of I and q provides a better measure of the raindrop impact and flow interactions occurring in rain-impacted flows. As shown in Table 9, using the same slope steepness factor, for most of the treatment combinations, the rainfall intensity-flow discharge models (Models IV and V) were proven to be better for determining the interrill soil loss than Model III (based on R^2 values). However, Models IV and V, with slope steepness factor and with slope steepness in percent respectively, provided similar R^2 values.

3.6 Soil erodibility

Erodibility was calculated using two models (Model III and Model V) (Table 10). The values for each soil, slope steepness, and moisture content combination are given in Table 10. The table indicates that for both models, the highest average soil erodibility was observed for Soil C and the lowest was observed for Soil B. However, the erodibility values were not the same for all soil conditions. The other interesting result observed was the variation in erodibility values with changes in slope steepness. Even though it was expected to be constant, for most observations, erodibility values decreased with increases in slope. However, for Soil B, the erodibility values increased as slope increased from 9 to 25 % and decreased as slope increased from 25 to 45 %.

Table 10. Soil erodibility values for the three soils at different slope and initial moisture content interactions.

Soil type	Slope (%)	Moisture content	Erodibility ($\times10^6$)* (Kg s m^{-4}) (Model III)	Erodibility ($\times10^6$) Kg s m^{-4} (Model V)
Soil A	9	AD	1.22	1.59
		PW	0.78	1.67
	25	AD	1.07	1.56
		PW	0.60	0.96
	45	AD	0.92	1.53
		PW	0.36	0.93
Average erodibility for Soil A			0.83	1.37
Soil B	9	AD	0.92	1.59
		PW	0.64	0.88
	25	AD	0.63	1.19
		PW	0.55	0.91
	45	AD	0.08	1.18
		PW	0.23	0.82
Average erodibility for Soil B			0.51	1.10
Soil C	9	AD	0.86	1.07
		PW	0.57	1.17
	25	AD	0.97	1.30
		PW	0.85	1.45
	45	AD	0.92	1.63
		PW	0.92	4.78
Average erodibility for Soil C			0.85	1.90

* Column 4 and column 5 erodibility values were calculated based on Model III and V, respectively.

4 Conclusions

In general, the results obtained from this study support the findings of Foster and Martin (1969) that for steeper slopes more than (33 %), such as 45 %, splash detachment decreases. However, slope independent of soil type and initial moisture content may not determine or explain the actual detachment process of a soil. Though slope was assumed to have a positive effect on soil erosion (Wischemier and Smith 1965), the investigation made in this study indicated a decline in an average soil loss for steep slopes. Moreover, the actual effect was dependent on soil type and moisture content.

The experimental investigation somewhat supported the conceptual model that was suggested by Foster and Meyer (1975). However, as they suggested, the limiting process was not necessarily be detachment, rather, it is the soil type, the available detached sediment and transporting capacity of the transporting agent.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci.net/15/2367/2011/ hess-15-2367-2011-supplement.pdf.

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