Hydrol. Earth Syst. Sci. Discuss., 7, 6447–6489, 2010
www.hydrol-earth-syst-sci-discuss.net/7/6447/2010/
doi:10.5194/hessd-7-6447-2010

Hydrology and
Earth System
Sciences
Discussions

Interrill erosion, runoff and sediment size distribution as affected by slope steepness and antecedent moisture content

M. B. Defersha[1], **S. Quraishi**[2], **and A. Melesse**[1]

[1]Department of Earth and Environment, Florida International University, FL, USA
[2]Haramaya University, Haramaya, Ethiopia

Received: 27 May 2010 – Accepted: 6 August 2010 – Published: 31 August 2010

Correspondence to: M. B. Defersha (dejetnumeng@yahoo.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Soil erosion is a two-phase process consisting of the detachment of individual particles and their transport by erosive agents such as flowing water. The rate at which erosion occurs depends upon the individual as well as interactive effects of different parameters responsible for soil erosion. The study discusses results of a laboratory analysis and evaluates the effect of slope steepness and antecedent moisture content on sediment yield (wash) and runoff rate. Interrill sediment yield, splash detachment, runoff, and sediment size distribution were measured in laboratory erosion pans under simulated total duration of 90 min. Rainfall intensity at 120 mm/hr, 70 mm/hr, and 55 mm/hr were applied sequentially at 9, 25, and 45% slope steepness for three soils (Alemaya Black soil, Regosols, and Cambisols) varied from clay to sandy clay loam in texture with wet and dry antecedent water contents. As slope steepness increased from 9 to 25% splash increased for five treatments and decreased for the remaining treatment; washed sediment increased for all treatments. As slope increased from 25 to 45% splash decreased for five treatments but increased for one treatment, and washed sediment increased for three treatments but decreased for the other three treatments. Pre-wetting decreased splash detachment for all soil treatments and rate of reduction was high for the highly aggregated soil, Alemaya Black soil and low for the less aggregated soil Regosols. Splash sediment and sediment yield was not correlated. Change in splash with increase in slope steepness was also not correlated with change in sediment yield. Change in runoff rate with increase in slope steepness was correlated ($r = 0.66$) with change in sediment yield. For Alemaya Black soil and Regosols, splashed sediment size distribution was correlated with washed sediment size distribution. Interrill erosion models that include runoff and rainfall intensity parameters were a better fit for these data than the rainfall intensity based model. The exponent term, b, values in ($E = a\,I^b$) model did not approach 2.00 for all treatments. For the same slope steepness factor, both rainfall and rainfall-runoff based models provided different erodibility coefficients at different levels of slope and moisture contents.

1 Introduction

Most regions of sub-Saharan Africa suffer from several forms of environmental degradation with its detrimental impact on food and agricultural productivity and production (Fekadu, 2000). Of all countries in this region, Ethiopia has the greatest land degradation problems (Hurni, 1985). According to Constable (1985), soil erosion continues to be a major agricultural problem in this country, particularly in the highlands (defined as area above 1500 m a.s.l.), which constitute 43% of the total area of the country. The Ethiopian highlands contain 88% of the country's population, 67% of livestock population, and over 90% of permanently cultivated area. Because of population pressure, all possible arable land, steep slopes as high as 60% have been under cultivation. Thus to prevent soil erosion which means to reduce the rate of soil loss to approximately that which would occur under natural conditions, an appropriate soil conservation measures may be required, and in turn, it needs a thorough understanding of the mechanics of erosion and quantifying the current rate of erosion. However, in Ethiopia and especially in Alemaya watershed very little research work has been done on the mechanisms of soil erosion and almost no information are available to design sound conservation structures and in turn to reduce erosion to the tolerable limit.

Detachment, transport, and deposition are basic processes of soil erosion that occur on upland areas. Detachment occurs when the erosive forces of raindrop impact and flowing water exceed the soil's resistant to erosion (Kinnell, 2005). Transport of detached particles takes place by raindrop splash and flow. Deposition occurs when sediment load of a given particle size exceeds the transport capacity. The relative importance of these fundamental processes depends on whether the processes are occurring on interrill or rill areas and on the level of the controlling variables (Foster, 1982).

Interill erosion occurs on an area where all detachment is due to the forces of raindrop impact and, transport is primarily by over land flow (Bradford and Huang, 1996). Different factors affects rate of soil erosion from interrill areas. Most of the time rainfall intensity, topography, and soil properties are taken as the important parameters to determine interrill erosion. Several models have been proposed by different researchers to explain the effects of one or more of those factors on rate of soil erosion in interrill areas.

Currently available interrill erosion models varies from a simple intensity-erosion relationship to those that incorporate the interaction effects of soil properties, intensity, runoff, and slope steepness relationships on rate of erosion. According to (Meyer, 1981; Foster, 1982) the effect of rain intensity (I) on erosion rate (E) for a range of soil and cropping conditions mostly expressed as:

$$E = a \; I^b \tag{1}$$

Meyer (1981) found the exponent, b decreases as clay content of the soil increases. The change approximates b=2.1–clay fraction. And the exponent, b, is near 2 for soils with low clay contents (less than about 20%). Other relationships have been also proposed to describe the interaction effect of soil characteristics, rainfall intensity, and slope on interrill erosion. Foster (1982) suggested an equation of the form:

$$D_i \equiv K_i \; I^p S_f \tag{2}$$

Where, D_i=interrill erosion rate; K_i=interrill soil erodibility factor; I=rainfall intensity,; S_f=interrill slope steepness factor; θ=slope angle, and p, b, a, and c are fitted constants.

The WEPP (Water Erosion Prediction Project) model for interrill erosion for instance is similar to Eq. (2) and in this case the value of the exponent "p" is equal to 2 and slope steepness factors that was developed by Liebenow et al. (1990) was used (Watson and Laflens, 1986). The WEPP interrill erosion component model is expressed as:

$$D_i = K_i \times I^2 \times S_f \tag{3}$$

Where, D_i = interrill erosion, Kg/m^2- S; K_i=interrill erodibility, Kg S/m^4; I=rainfall intensity, m/S and S_f = Slope steepness factor, dimensionless Neal (1938) suggested yet another equation, which is similar to Eq. (1) but here slope gradient is used instead of slope steepness factor.

$$Di \equiv K_c I^p S^q \tag{4}$$

Where: I and P are rainfall intensity and exponent, respectively; S is the slope gradient; q is a fitted exponent, and K_c is a coefficient reflecting soil, intensity, and slope effects.

Several researchers such as Watson and Laflens (1986); Kinnell (1991); Truman and Bradford (1993) suggested that the proposed model that give iterrill erosion (D_i) as a function of I^2 (rainfall intensity squared) as Eqs. (1), (2) and (3) may not hold for all soils and moisture conditions, which indicates that the value of the exponent may not be equal to 2 and may vary with initial soil moisture. In addition, the exponent term and coefficient (K_i) are dependent on each other; therefore, the exponent and interrill erodibility parameter (K_i) accordingly will change with changes in rainfall intensity and soil loss (Kinnell, 1991; Truman and Bradford, 1993).

Other researcher also suggested an interrill erosion model that includes a runoff rate parameter (q) in addition to the rainfall intensity parameter (Kinnell, 1993b). The proposed model by Kinnell (1993b) was expressed as follows:

$$E \equiv K_{iq} I \times q \times S_f \tag{5}$$

Where: K_{iq} is interrill erodibility parameter, q is flow discharge, I is rainfall intensity, and, S_f is slope steepness factor.

In the above models slope steepness factors are inputs that can be developed as a function of slope angle. Various researchers have developed slope steepness factor relationship on interrill erosion. Using data of Meyer et al. (1975) and Lattanzi et al. (1974), a slope factor term for interrill areas as a function of slope angle (θ) was derived by Foster (1982) and given as:

$$S_f = 2.96(\sin\theta)^{0.79} + 0.56 \tag{6}$$

The data were obtained from soil pans of 0.6 m×0.6 m exposed to simulated rainfall of 64 mm per hour intensity for two hours, and slope ranging from zero to 30 per cent. Liebenow et al. (1990) has proposed a similar equation for interrill areas:

$$S_f = 1.05 - 0.85e^{-4\sin\theta} \quad (7)$$

Where, θ=slope angle

Interrill erosion models that incorporate slope gradient and slope steepness factors (Eqs. 6 and 7) assumed a unique relationship between soil erosion and slope steepness as well as an increase in erosion with increase in slope steepness. The relationship between slope steepness and interrill soil loss were empirically derived and is characterized as a unique function, i.e., independent of soil properties, surface soil conditions, and erosion processes (Bradford and Foster, 1996). According to the authors these equations may not apply to a wide range of soils, or soil conditions and slope steepness, because the magnitude at which erosion processes of detachment and transport control sediment yield in interrill area could be different (Kinnell and Cummings, 1993).

Various researchers have observed variation in effect of slope steepness with soil conditions and the relationships of slope angle to rill and sheet erosion are also equivocal (Evans, 1980). Not all studies show an increase in erosion as slope angle increases (Lillard et al., 1941; Neal, 1938) though there is often a marked increase in erosion on slopes of 5–10% compared to erosion on gentler slopes. Nevertheless, on slopes steeper than this erosion is often less.

With such contradictory research results applying models that were developed with the assumption of increase in soil loss with increase in slope steepness, as well as a unique relationship of slope steepness independent of soil conditions may lead to over or under estimating the actual interrill erosion that in turn may mislead estimation of the gross soil erosion, which, may affect decision making and conservation measures design activities. Moreover for countries like Ethiopia, where cultivated lands as steep as 60% are common, applying such models that were developed using data on agricultural lands in which slope steepness less than 30%, without testing their effect at such slopes may exacerbate the problem.

Considering the above described limitations on the current knowledge of soil erosion processes as well as the very little research work that has been done in the area, the following paper was proposed to (1) determine the effect of slope steepness and antecedent soil moisture content on splash detachment, infiltration, runoff and soil loss using three major soils of Lake Alemaya watershed; (1) estimate the interrelation between various soil erosion and runoff parameters and evaluate the validity of different proposed rainfall intensity and rainfall intensity-runoff based soil erosion models and (2) test the hypothesis that slope steepness term as expressed in several interrill erosion models varies with soil conditions; and determine the soil erodibility factor (K) for the three major soils of Alemaya watershed.

2 Methodology

2.1 Description of the study area

The study area, Alemaya, is located in eastern Ethiopia. The Alemaya woreda (area between 1850 and 2200 m a.s.l. elevation) is classified as "Woina Dega" agro-ecological zone with its average annual rainfall of 870 mm (560–1260 mm range). There are six months (March to September) with more than the average monthly rainfall.

2.2 Experimental procedures

This experiment was conducted in the laboratory using a rotating disc nozzle type rainfall simulator and laboratory erosion pans with the main assumptions that; detachment by surface flow is negligible in interrill soil erosion and the splash detachment values are estimates of the amount of sediment made available for transport

2.2.1 Rainfall simulator

In this study, FEL 3-A (rotating disc type) rainfall simulator was used. The equipment consists essentially of two units, the rainfall simulator, and its service module, which stands along side. 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 and flexible PVC tube.

2.2.2 Soils

Three soil materials that varied in texture were taken from freshly plowed surface soils. These soil materials 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 soils occurring in Alemaya woreda. 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 long period. Each soil sample was air dried and sieved through a 10 mm sieve before simulation run. In each simulation run, a 60 mm thick layer of soil in the central area of erosion pan was packed over laying a 90 mm of gravel. Table 1 indicates, 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).

2.2.3 Soil erosion pan

Edge effect is one of the problems that influence study procedures on small plots. In addition to edge effect, the size and type of a pan may have effect on interrill erosion study. For the rectangular type pans, as the area increases, splash per unit soil area decreases because the central part of the box contributes less sediment than parts closer to the edge (Le Bissonnais, 1996). Eventhuogh, the different factors that affect the initiation of rill erosion are not well studied, obviously size of pan has effect on concentration (volume) of runoff; that may in turn has effect on rill initiation. In this study, an erosion pan similar in design to Bradford and Foster (1996) with slight modification was used. The test area of this pan used for experiment was 320 mm wide by 450 mm long with 150 mm depth. An additional component of 200 mm wide soil buffer, surrounding the central test area is 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 was provided to collect runoff and wash, and Drainage outlet at the bottom of each compartments were provided for percolation of water.

2.2.4 Selection of levels of treatments

The three soil types for the study were selected from Alemaya series eroded phase (Regosols), Godie soil series (Cambisols), and Alemaya black soil (Vertisols). Antecedent moisture content of two levels, i.e., air-dry and pre-wetted conditions were selected. Pre-wetting took place by applying water through the drain for 24 h. The pan was positioned at 9, 25, and 45 per cent slopes beneath the rainfall simulator that suspended above the test pan, and 15-min storms at three intensities (55, 70, and 120 mm/hr) were applied in two sequences. The two sequences of intensities were determined by a systematic random arrangement. The first sequence was determined randomly as (55, 70, 120, 70, 55, 120) and applied for total of 90 min. The second sequence of intensities determined based on the first sequence following a similar method as Meyer (1981), who used 15 min storm at four intensities ranging from 10 mm/hr to 105 mm/hr. Based on this study; with this sequence, each of the 15-min storms at three intensities followed both of the other an equal number of times. Thus, although erosion rates generally decreased somewhat with additional rainfall, the sequence did not bias the analyses.

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2.2.5 Splash detachment, runoff and wash sediment

Splash detachment, runoff, and wash sediment were measured within 5 min intervals from splash collector and runoff, and wash collector respectively throughout the 90 min rainfall. The collected samples were oven dried at 105 °C for 24 h; for further analysis.

2.2.6 Sediment size distribution

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 suspension sampled at fixed depths after allowing settling times.

2.2.7 Surface soil strength and soil erodibility

Surface shear strength were measured in each post rainfall application following procedures adopted by various researchers such as Al-Durrah and Bradford (1981); Bradford et al. (1987) and Truman and Bradford (1993). In this study, erodibility was determined using an equation that was best fits the specific data collected.

2.2.8 Statistical analysis

The study was a four factor factorial experiment in a complete randomized design with two replication of each combination. Each of the factors i.e., slope steepness at three levels; antecedent soil moisture content at two levels; rainfall intensity at three level, and soil types at three level were tested. Using the obtained data analysis of variance was made following the standard procedures, and means were separated by using a protected least significance difference method at 0.05 probability level. The significance of factors influencing splash, soil loss, shear strength, runoff, and sediment size distribution were evaluated. Using the appropriate statistical tests, the correlations between erosion variables were calculated and significance of the correlation coefficients were tested. Regression analyses were conducted to identify or estimate the fitted constants of five selected interrill erosion models.

2.2.9 Interrill erosion models and Slope steepness factor

In this study, slope steepness factor and five interrill erosion models were tested using regression analyses. For each model the related erodibility coefficients for the three soils were evaluated at air-dry and pre-wetted conditions. The five models that were evaluated are discussed below. From the five interrill erosion models, two of them are rainfall intensity, runoff rate, and slope steepness based models, while the other two are rainfall intensity and slope based models, and the remaining one is rainfall intensity based model

Model I: $E \equiv aI^b$

Where: E, is sediment yield from interrill area, b is the exponent term, usually taken as 2, I is the rainfall intensity, and a is the fitted coefficient. In this study the objective was to test the exponent term that assumed by various researchers equal to 2. Meyer and Wischmeier (1969) deduced that soil detachment by rainfall was proportional to I^2. Subsequent work by Meyer (1981) related interrill erosion with the square of intensity. In this study, it was assumed that interrill erosion is a function of rainfall intensity (I^2).

Model II: $E \equiv K_i I^2$

This model is the WEPP interrill component and is well adopted worldwide. In WEPP model, E is sediment yield from interrill area, K_i is the erodibility parameter, and I is rain fall intensity.

Model III: $\frac{E}{S_f} \equiv K_i I^2$

This model is similar to model two except that additional parameter of slope steepness factor (S_f). S_f factor that is used in this model is the one that proposed by Liebenow et al. (1990), and is used in this study. The slope steepness factor, given as:

$S_f \equiv 1.05 - 0.85^{-4\sin\theta}$; Where, θ = slope angle.

Model IV: $E \equiv K_i \times I \times Q \times S$; Where, K_i is interrill erodibility coefficient, I rainfall intensity, Q is runoff rate, and S is slope steepness in percent.

Model V: $\frac{E}{S_f} \equiv K_i \times I \times Q$

This model is similar to model IV, but instead of the slope steepness, here slope steepness factor, which is already discussed above, is used

3 Results and discussion

3.1 Splash detachment

Splash values are only an estimation of the amount of air borne soil material during a 15-min sampling period. Splash detachment was determined as the amount of soil splashed from a 320-mm-wide by 450-mm-long plot with soil buffer area.

Aggregates containing important particles of clay, such as Soil A, may suffer from swelling of the oriented clays resulting in breakdown and a negative correlation occurs between the degrees of clay orientation and aggregate stability (Imerson and Jungerius, 1977). The measured values of splash detachment in the sampling periods ranged from a low of 2.25 Kg m^{-2} h^{-1} for a weakly aggregated soil (Soil C) to a high of 5.23 Kg m^{-2} h^{-1} for the strongly aggregated soil (Soil A) (Table 2).

Soil type significantly affected the magnitude of splash detachment at a significance level of (p =0.0206). High splash detachment was observed for highly aggregated soil, Soil A, with high percentage of clay content; and low for a weakly aggregated soil, Soil C, with high percentage of silt content. The magnitude of the mean splash detachment from Soil A was significantly higher than that of Soil C. The amount of mean splash detachment values between Soil A and Soil B, and Soil B and Soil C, were not significantly varied. Numerically, the splashed sediment from Soil B was greater than the splashed sediment from Soil C.

Soil that is highly susceptible to surface sealing, such as Soil C, increase strength rapidly with time (Bradford and Huang, 1992), resulting in lower splash after a prolonged periods of rain. The reduced splash detachment for Soil B compared to that of Soil A was probably due to its high organic matter content. Organic matter is one of the well-known aggregate stabilizing agents in soils (Le Bissonnais, 1996).

This study revealed that, high clay content has better correlation with degree of aggregation than with aggregate stability. However, Gollany et al. (1991) found high aggregate stability and low splash detachment with increase in clay content. On the other hand, Le-Bissonais and Singer (1993), as well as Pierson and Mulla (1990) did not find significant correlation between clay content and aggregate stability. Rose (1960) and Epstein and Grant (1967) found greater detachment of soil particles by raindrop as clay content of soil increased.

Antecedent moisture contents of soils significantly affected the mean splash detachment values. Close observation of Table 3 indicate that less splash detachment took place when the soil was initially wet. However, the percentage by which splash detachment decreased varied with soil types. Highly aggregated soils resist aggregate breakdown upon wetting, and splash detachment is lower (Le-Bissonnais, 1996). Due to wetting, Soil A, the highly aggregated soil, increased resistance by 26.6%, and splash detachment decreased by 28%. The moderately aggregated soil, Soil B, and the weakly aggregated soil, Soil C, increased resistance by 20.81% and 6.581%, and splash detachment decreased by 25 and 21% respectively, in comparison with initially dry surfaces (Table 2). The tendency for the three soils to had lower splash detachment than air-dry soils was probably due to the reduction in slaking forces with slower wetting. In initially dry soil, both slaking and raindrop impact forces act on the soil simultaneously and result in aggregate breakdown rapidly (Torri, 1996).

The interactive effects of soil and slope steepness were highly significant, at (p =0.0035). For Soil A, the average detachment values significantly varied with the level of slope steepness, and the highest mean values of 4.23 $\mathrm{Kg\,m^{-2}\,h^{-1}}$ was measured at 25% slope steepness (Table 2). For Soil B, there was no significant difference between the mean values of splash detachment at each levels of slope steepness. For Soil C, the mean detachment increased with increasing slope steepness from 9% to 25%. As slope increased from 25 to 45%, the mean splash detachment values were significantly decreased for Soil A and Soil C. Foster and Martin (1969) had found a similar result to this study. According to them, as slope increased detachment by raindrop rose to a maximum and then decreased again on steeper slopes, steepness greater than 33%.

However, the actual effect of slope steepness on splash detachment varied with the initial moisture content of the soil (Table 3). Thus, the slope steepness effect on splash was positive or negative depending on the relative magnitude of the driving and resisting stresses on the soil surface.

As slope steepness increased from 9 to 25%, splash detachment increased for all soil treatments except for Soil B wet. When slope steepness increased from 25 to 45%, splash detachment decreased for all treatments except for Soil B-wet. The increase in splash with increase in slope steepness was a result of the decreasing in soil resistance. As shown in Table 2, strength values for this group of soils show a weaker surface strength or seal at 25% slope steepness than at 9% slope. The reduction in strength over rides reduction in raindrop normal impact forces. However, for Soil B wet the reduction in splash as slope increased from 9 to 25% was not due to the increased in shear strength, the possible reason may be due to the reduction in raindrop normal impact forces. Different in final strength was not evident for Soil A dry, and thus strength difference was not a probable cause. Also as evidenced by the higher runoff rate at 9% slope than at 25% slope steepness, slaking effect due to suction was not a probable cause. Thus, the probable cause for the lower splash detachment at 9% than at 25% was possibly due to depth of water poundings, as evidenced by the runoff rate measured at the two slopes. Pounded water deeper than a critical depth of water cushions the impact of raindrops and diminishes the rate of detachment. For Soil A, wet high depth of water pounding was not a probable cause. The greater increase in splash detachment at 25% slope was possibly due to the less water depths of pounding less than the critical depth. The other possible reason was slaking of aggregates, as evidenced by the measured runoff rate at the two slopes. Slaking involves the distribution of aggregates due to compression of air in the dry soil.

3.2 Runoff and infiltration rates

Here, it is assumed that variation in the amount of rainfall intercepted at different slope steepness is negligible. Runoff rate during the last three 15-min sampling periods ranged from a low of 5.76 mm h^{-1} for Soil B, (soil with high organic matter, high percentage of sand particles, and low percentage of silt content) to 68.45 mm h^{-1} for Soil C, (soil with high silt, high sand, and low organic matter content) (Table 4).

Soil types have a highly significant effect on runoff rate. The mean runoff rate observed on Soil C, 54.08 mm h^{-1}, was significantly greater than the mean runoff rate value of 38.06 mm h^{-1} that was observed on Soil B (Table 5). Even though, high sand content implies a high infiltration rate, that reduce the amount of runoff; in this study high runoff rate (low infiltration rate) was observed with Soil C, soil that has the highest percentage of sand particles than the others. The probable reason for the highest runoff observed on Soil C could be the development of high sealing due to clogging effect of silt particles, as evidenced by the high silt contents and high shear strength values observed for this soil. The probable reason for lowest runoff rate observed with Soil B was might be due to the high infiltration capacity of the soil containing high organic matter and high sand particle. In addition to this, the low seal formation, as evidenced by the low shear strength value measured, might enable the soil to continue infiltration at its capacity rate.

Slope steepness had a highly significant effect on runoff rate at $p = 0.0001$. As slope steepness increased from 9% to 25%, the mean runoff rate numerically decreased from 51.53 mm h^{-1} to 51.32 mm h^{-1}. However, there was no statistically significant variation between these values. When slope steepness increased from 25% to 45%, the mean runoff rate significantly decreased from 51.32 mm h^{-1} to 37.25 mm hr^{-1} respectively.

The effect of antecedent moisture content on runoff rate was not significant. However, numerically the mean runoff rate was higher for initially dry treatments than wet treatments. The interaction effect of moisture content with soil types and moisture content with slope steepness was highly significant. For Soil A, the mean runoff rate value was higher for initially dry surface than for initially wet surface. As shown in Table 4 the mean runoff rate observed from initially dry condition of Soil A was 1.41 times higher than the mean runoff rate that was observed from pre-wetted surface. The mean runoff rate value was significantly higher for initially wet condition than initially dry condition of Soil B. For Soil C, the magnitude of the mean runoff rate that was observed from initially dry condition and initially wet condition did not vary significantly. The probable cause of the higher mean runoff rate for initially dry surface than initially wet surface of Soil A was due to the reduction in dispersion upon wetting. For Soil B, the higher mean runoff rate was observed for initially wet surface than initially dry surface due to decreased infiltration capacity with increased moisture content. For Soil C, even if pre-wetting decreased surface sealing, due to its lower water holding capacity, high runoff rate was observed on wet treatment. Furthermore, the magnitude of runoff rate within the levels of initial moisture conditions varied with the levels of slope steepness. As slope steepness increased from 9% to 25%, runoff rate decreased for initially dry treatments and increased for initially wet treatments. However, as slope increased from 25% to 45%, runoff rate decreased for both initially dry and wet treatments.

The interactive effect of slope steepness and soil type on the magnitude of runoff was highly significant at P=0.0001. Except for Soil B, runoff rate numerically increased as slope steepness increased from 9% to 25%. For Soil B, runoff rate decreased as slope increased from 9% to 25%. As slope increased from 25% to 45%, runoff rate significantly decreased for all treatments. Surprisingly, for Soil B the mean runoff rate at 45% slope steepness was much lower than the mean runoff rate at 25% slope steepness.

3.3 Sediment yield

It is assumed that the splash detachment values are estimates of the amount of sediment made available for transport and sediment yield increases as slope steepness increases, independent of soil type and moisture content. The gross effects of the main factors (slope steepness, soil type, and antecedent moisture content and rainfall intensity) were highly significant at the probability levels of $p<0.0001$. Results of the significant tests also indicate that there are highly significant soil type-slope steepness, soil type-moisture content, as well as soil type-slope steepness-moisture content interactions, but no slope steepness-moisture content interaction.

Sediment yield during the sampling periods ranged from 0.137 Kg m^{-2} hr^{-1} for air-dry treatment of Soil B at 25% slope to 1.51-Kg m^{-2} hr^{-1} for air-dry treatment of Soil A at 45% slope (Table 6). On average the highest amount of sediment was washed out from Soil C, however for the least erodible soil, Soil B, sediment yield was at average rate of 0.57 Kg m^{-2} hr^{-1}. As indicated in Table 6 Soil A was less erodible than Soil C and highly erodible than Soil B. The actual magnitude of sediment yield for all soil treatments varied with moisture content, slope steepness, and combined effect of slope steepness and moisture content was considerable.

The rate of sediment yield was significantly varied with moisture contents (Table 7). For Soil A, sediment yield from initially air-dry surface was significantly higher than that of initially wet surface. Wetting, decreased erodibility of Soil A by 48.6%. For Soil B, pre-wetting did not significantly decrease soil loss, but magnitude of soil loss from initially wet surface was higher than air-dry surface. For Soil C wetting significantly decreased soil loss by 11.62% on average. The reason for the low sediment yield from wet surfaces of Soil A and C compared to dry surfaces of Soil A and C could be due to the less available detached sediment (for both soils) and less available transporting agent (for Soil A) that were observed from initially wet surfaces than initially dry surfaces.

As slope steepness increased from 9% to 25%, sediment yield increased for all three soils. However, as slope increased from 25% to 45%, sediment yield decreased for Soil A and Soil B, but it increased for Soil C. For Soil A, the mean sediment yield increased significantly as slope increased from 9 to 25%. However, as slope increased from 25% to 45%, the sediment yield reduction was not statistically significant. Thus, the effect of slope steepness, especially at 45%, on sediment yield was dependent on soil type. For Soil A and Soil B, lower mean sediment yield was observed at 25% than at 45% slope. For Soil C, sediment yield increased even for slope steeper than 25%. Even if little works have been done on steeper slopes, previous works indicate a similar result. Lillard et al. (1941) and Neal (1938) found a decreased in soil loss for steeper slopes. The reason for lower soil loss to be observed at 45% than at 25% slope for Soil A and Soil B were probably due to the less available transporting agent (limited transporting capacity) at 45%, than at 25%.

Figure 1 shows the effect of slope steepness on sediment yield, for each level of soil type and initial moisture content. For Soil A-dry, Soil C dry and wet treatments the mean rate of sediment yield increased as slope steepness increased. Sediment yield increased at a higher rate as slope increased from 9% to 25%, and then rate of increment decreased when slope increased from 25% to 45%. For Soil A-wet and Soil B dry and wet treatments sediment yield increased as slope steepness increased from 9% to 25%. For Soil A wet and Soil B dry and wet treatments sediment yield decreased as slope increased from 25% to 45%. Especially, for air-dry treatment of Soil B, sediment yield reduced at a higher rate, relative to the rate of reduction that was observed for other treatments.

For Soils A, B, and C dry treatments, the reason for increased sediment yield as slope increased from 9% to 25% was not due to the availability of high runoff rate. Also depth of flow may not be a probable cause. The possible reason may be the higher stream power available at 25% slope steepness than at 9%. Slope steepness has the most direct effect on the erosivity of over land flow by determining its stream power, which is a product of hydraulic shear stress and average flow velocity (Nearing et al., 1991), both of which in turn are a function of slope. The other possible reason could be the availability of high-detached sediment at 25% than at 9% slope as evidenced from the measured values of detachment for both slopes. For Soils A and C wet treatments, the availability of high runoff, high velocity, and high detached sediment at 25% than at 9% slope may be the reason for increased sediment yield. For Soil B, wet, high detached sediment and high runoff availability were not the reason for increased sediment yield as evidenced from the measured splash and runoff rate values at both slopes. The probable reason for this soil may be reduction in raindrop impact due to high flow depth as evidenced from the high runoff rate observed at 9% slope steepness. Kinnell (1991), showed that transport rate of particles declines linearly with flow depth when flows are deeper than a break point depth, according to him the breaking point is about 2–3 mm.

Moreover, for Soil B, wet and dry treatments the decreased sediment yield as slope increased from 25% to 45% was due to the extreme reduction in runoff rate as slope increased from 25% to 45%. For Soil A, wet treatment, the reason for reduced sediment yield at 45% than at 25% was due to the low runoff rate and detached sediment available at 45% than at 25%. The reason for increased sediment yield as slope increased from 25% to 45% for Soil A and C dry treatments were not due to the high detached sediment and runoff rate availability as evidenced from the measured values of splash and runoff rate for both slopes. The possible reason may be due to the less drop impact at flows deeper than the break point as stated by Kinnell (1991).

As slope steepness increased from 9% to 25%, the percentage of splash transported as sediment yield increased for both moisture conditions of Soil C and for initially wet conditions of Soil B, but it decreased for initially dry condition of Soil A and Soil B (Table 6). As slope increased from 25% to 45%, the percentage of splash transported as sediment yield increased for Soil A dry and decreased for both moisture conditions of Soil B and wet condition of Soil A. The increase in percentage of splash transported in overland flow due to slope steepness was greater for the highly erodible soil, Soil C-wet (0.64/0.37=1.73) and slight decrease, for the less erodible soil, Soil B-dry (0.05/0.20–0.25). This result may show how the effect of slope steepness on sediment yield was varied with soil type and initial moisture condition. The percentage of splash transported in over land flow, due to increase slope from 25% to 45%, was less than one (0.25) for Soil B, which shows the negative effect of slope steepness.

According to (Table 10), there was poor degree of association between splash detachment and sediment yield values $r = 0.399$, at $p = 0.110$. However, the correlation was improved when the analysis was done excluding data at 45% slope $r = 0.71$, at $p = 0.009$. This shows that, higher splashed sediment availability does not mean necessarily higher sediment yield. The improvement that was found for data excluding 45% slope may show how the relationships between these variables was slope dependent.

Change in splash with increase in slope steepness was not significantly correlated with change in sediment yield $r = 0.426$, at $p = 0.077$. However, when the analyses were done for each soil types, better degree of association was found for Soil C than Soils A and B. Correlation coefficients of $r = 0.97$, at $p = 0.038$, $r = 0.79$, at $p = 0.214$ were obtained for Soils C and A respectively. For Soil B poor correlation between these variables was observed. The higher correlation coefficient for Soil C may show a significant detachment limiting case, and the poor correlation coefficient observed for Soil B may be due to the decreased in runoff rate as slope increased (due to less transport capacity of the transporting agent with increased in slope steepness). Runoff rate was correlated with sediment yield $r = 0.66$, at $p = 0.003$. When the analysis was done excluding data at 45% slope, in contrast to the result for splash detachment, the correlation was poor $r = 0.40$, at $p = 0.096$. Splash detachment was an important process up to 25% slope. However, when slope increases further runoff rate was the more limiting process than splash, as evidenced from the observed significant different between the correlation coefficients when the analysis were done with and with out data at 45% slope.

Change in runoff rate with increase in slope steepness was highly correlated with change in sediment yield $r=0.826$, at $p=0.001$ (Table 10). When the correlations between these variables were analyzed for each soil highest correlation coefficient was observed for Soil B ($r=0.96$, $p=0.008$). For Soil A and Soil C, poor correlation coefficients of $r=0.47$, at $p=0.420$, and $r=0.45$, at $p=0.44$, respectively were observed. The poor correlation coefficients observed for Soil C, show that detachment was the basic process that determined sediment yield than runoff rate; as evidenced from the high correlation coefficients observed for the relationship between change in sediment yield and change in splash. However, the high correlation coefficient observed for Soil B, may show the limiting process was sediment transport than detachment.

3.4 Sediment size distribution

In this study, it was assumed that the characteristics of particles available for interrill transport depend on the sizes produced by interrill detachment (Foster, 1982). It was also assumed that detachment and transport on interrill areas are size selective.

As evident from Table 8, the size distributions of splashed sediments were numerically varied with soil type. For Soil A, the highest fraction of the total averaged size splashed sediment was enclosed by silt-sized particles (47.82%). For this soil medium sand and fine sand sized particles contributed the least percentage by mass, (4.14% and 4.48%), of the total averaged splashed sediment, respectively.

For Soil B, similar to Soil A, the splashed sediment was highly enriched with silt (42.36%) and deficient in fine sand (6.32%), and medium sand (6.78%). For Soil C, the splashed sediment was highly enriched in coarse sand (33.54%) and deficient in fine sand (8.24%).

The fraction of the primary particles that had been observed in the splashed sediment has somewhat relations with the availability of these particles in the original soil materials. As shown in Table 1, Soil A was highly enriched in silt and correspondingly the splashed sediment was highly enriched in silt, and both the original soil and the splashed sediment were deficient with fine and medium sand. For Soil C, the original soil material and the splashed sediment had high coarse sand, silt, and clay sized particles and small amounts of fine sand and medium size sand particles. Thus for these soils one of the possible reasons for the observed splashed sediment characteristics was possibly the availability of the primary particles in the original soil materials. However, for Soil B, the original soil material was highly rich in clay, medium sand, and coarse sand, but the splashed sediment was deficient in medium size sand particles, and highly rich in silt, clay and coarse size sand particles. Both the original soil material and the splashed sediment were deficient in fine sand.

After scrutiny of Table 9, it was observed that the magnitudes of average sediment size distributions were varied with slope steepness. As slope increased the fraction of clay-sized sediment decreased. At 9% slope, at average (35.50%) by mass of clay sized particles were observed from the total mass of the splashed sediment. The, fraction of silt-sized sediment increased as slope increased, and the highest silt fraction (47.03%) was observed at 45% slope steepness. The fraction of coarse sand and medium sand in the splash sediment were decreased as slope increased from 25% to 45%. The splashed sediment distributions were varied for pre-wetted and air-dry treatments. The clay sized fractions increased as the initial moisture content increased; but others decreased as the initial moisture content of soil increased (Table 9).

3.5 Soil loss, rainfall intensity, and slope steepness factors

To test the capability of the assumption that $b=2$, in model-I ($E=aI^2$), values for each treatment combinations were determined on the log transformed data (Table 11). For each slope steepness, b, values for model I, was varied between the two antecedent water contents. At 9% and 25% slope, the exponent term increased with moisture content, excluding Soil B but at 45% slope, the exponent term, b, decreased with increased initial moisture content, except for Soil C.

Values of b-ranged from, 0.46 for Soil A-dry at 9% slope, to 1.75 for Soil B-wet at 45% slope, although most b-values were between 0.95 and 1.75. In model I, the exponent term, b, did not approach to 2.0, and as indicated in Table 11, b values varied with slope steepness, soil type and moisture content. For Soil A, b values were less than

1.0 except for pre-wetted condition at 25% and air-dry at 45% slope steepness. For Soil B the exponent values were greater than 1.0, except for pre-wetted treatment at 25% slope. For Soil C it was less than 1.0 for air-dry treatments and greater than 1.0 for pre-wetted conditions.

Meyer (1981) found similar results. The author reported that *b* values were not close to 2.0 for all soils and showed that the influence of rainfall intensity on erosion to be greater for low clay soils. Meyer (1981) suggests that the lesser effect of rainfall intensity on soils with higher clay contents may be due to greater soil cohesiveness and larger sediment sizes, which limit detachment and transport; for soil A, the result tend to support the idea that was suggested by Meyer (1981). However, for soil B, the larger b values compared to soil C that has lower clay content indicate effect of other parameters.

Effect of initial moisture content on the erodibility coefficients, Model II ($E = K_i I^2$) were determined for each soil at the three levels of slope steepness. For Soil A, at 9% and 25% slope, pre-wetting had little effect; however, there was highly significant difference between the erodibility values of air-dry and pre-wetted treatments. For this soil, pre-wetting decreased the erodibility coefficient by 73%. Similarly for Soil B, the effect of pre-wetting on K_i, was little, but numerically pre-wetting decreased the erodibility coefficient at 9% and 25% slope steepness and increased the coefficient at 45% slope steepness by 27.8%. For Soil C, the effect was little and numerically it decreased or increased depend on slope steepness.

K_i values were determined from the equation $E/S_f = K_i\ I^2$ (Model III). There were significant different between calculated values of the erodibility coefficients (K_i) at the three levels of slope steepness. At 45% slope steepness, there was a significant difference between these coefficients at different initial moisture contents. An appropriate slope steepness factor should result an equal K_i values for a range of slope steepness (Truman and Bradford, 1993). For Soil A, K_i values increased significantly, as slope increased from 9% to 45%. At 45% slope the K_i values were significantly varied with moisture content, and a coefficient (0.47×10^6) for air-dry condition and (0.12×10^6) for pre-wetted condition were observed. However, numerically K_i values were higher for air-dry conditions than pre-wetted conditions. For Soil C, the K_i values were less for initially wetted treatments than initially dry treatments. Furthermore K_i values increased as slope steepness increased from 9% to 25%, and decreased as slope increased from 25% to 45%. This result shows that a slope adjustment factor is a function of soil type and antecedent moisture content, and as shown in this section and preceding sections slope steepness greater than 25% has a negative effect.

3.6 Soil loss, rainfall intensity, and runoff rate relationships

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 11, using same slope steepness factor, for most of the treatment combinations the rainfall intensity-flow discharge model (Model V) prove to be better means of determining the interrill soil loss than model III and model II (based on R^2 values). However, model IV and model V provided similar R^2 values. Nonetheless K_i values were varied with slope steepness and initial moisture content. The probable reason for this variation can be the slope steepness adjustment factor for model V and IV that were included to these models. Especially these models (model V and IV) are well fitted for data greater than 45% slope.

3.7 Soil erodibility

Interrill soil erodibility is not a fundamental property of the soil but is defined by the specific equation and the period of time that rainfall occurs (Bradford and Foster, 1996). As shown in the above section erodibility coefficients of the interrill erosion models were varied with initial moisture contents and slope steepness. However, to estimate relative erodibility values of the three soils, based on the average rainfall intensity, the actual average soil loss was divided by the product of erosivity parameter and slope steepness factor. Erodibility was then calculated using two models, and the values for each soil, slope steepness, and moisture content combinations are given in Table 12. The table indicated that for both models the highest average soil erodibility was observed for Soil C and the least was observed for Soil B. However, the erodibility values were not the same for all soil conditions, except for Soil B at 45% increase in moisture content reduced erodibility of soils. The other interesting result observed was variation in erodibility values with variation in slope steepness, even though it was expected to be the same, almost for most observations erodibility values decreased with increases in slope steepness. However, for Soil B the erodibility values increased as slope increased from 9 to 25% and decreased as slope increased from 25 to 45%.

4 Conclusions

Based on this study, high clay content had positive relationships with degree of aggregation than with aggregate stability. It was observed that a soil that had highly stabilized aggregates would be less susceptible for splash detachment. Initially wetted surface had high resistance and low detachability than air-dry surfaces. Effect of pre-wetting was high for a highly aggregated soil than for moderately and weakly aggregated soils.

In general the results obtained from this study support the idea of Foster and Martin (1969) that for steeper slopes more than 33%, such as 45%, splash detachment decreased. However, slope steepness independent of soil type and initial moisture content, may not determine, or explain the actual detachment process of a soil. Similarly high clay content of soil not mean that high aggregate stability and low detachability, unless the interactive effect of clay content with other primary particles, initial moisture and organic matter contents are considered.

Runoff rate was high for soils that were weakly aggregated and was low for soil that was moderately aggregated and had high organic matter, and clay content. This result shows that, for the weakly aggregated soil with high silt content, runoff rate was high possibly due to the sealing effect of high silt fractions; but for soil with high organic matter content runoff rate was low due to high infiltration. Past research works have indicated a negative correlation between silt content and infiltration rate (Bradford et al. 1987; Bradford and Huang, 1992). However, in this study even if high runoff rate was observed for soils with high silt content; its effect was higher for less aggregated soils and for soils that had low fraction of clay.

Sediment yield was observed to depend on slope steepness, soil type, and initial moisture content. For all soil treatments, sediment yield increased with increasing slope steepness from 9% to 25%, and decreased thereof. Though slope steepness was assumed to have a positive effect on soil erosion (Wischemier and Smith, 1965), the investigation made indicated decline in average soil loss for steeper slopes more than 25%. However, the actual effect was dependent on soil type and moisture content. Though little work has been done on steeper slopes, past experiences indicate a similar trend. Lillard et al., 1941 and Neal, 1938 found a decreased in soil loss for steeper slopes.

The experimental investigation some what supported the conceptual model that was suggested by (Foster and Meyer, 1975). However, as they suggested, the limiting process was not necessarily detachment, rather it is the soil type, the available detached sediment and transporting capacity of the transporting agent. As indicated in the above sections for Soil B, the responsible factor for the observed low soil loss at 45% slope was the low transporting capacity. Magnitude of sediment yield was not correlated with magnitude of splash. However, the correlation was improved when the analysis was done without the 45% slope set for. In addition, there was poor correlation between change in splash and change in sediment yield with increase in slope steepness. Nevertheless, when the analysis was done unconnectedly for each soil treatment, the correlation was significant for Soil C. The high correlation implies a detachment limited condition for this soil. However, for all treatments an increase in splash resulted in an increase in sediment yield showing the importance of detachment process to sediment yield. The splash proportion increased as slope steepness increased for detachment limiting condition (Soil C). However, for the other two soils the proportion increased or decreased depending on the limiting process. Sediment yield was significantly correlated with runoff rate. Moreover, change in sediment yield was significantly correlated with change in runoff. However, when the analysis was done for each soil, highly significant correlation was observed for Soil B implying highly significant transport limited condition; and poor correlation coefficient was obtained for Soil C.

Data of splashed and washed sediment size distribution indicate, sediment characteristics are a function of soil characteristics and size selectivity of the detachment and transport processes. Moreover, the size distributions of washed sediment are dependent on the characteristics of the available detached sediment. The effect of slope steepness on sediment yield is dependent on soil type, moisture content and the limiting processes. In general, the effect is positive for low slopes; for slopes steeper than 25%, such as 45%, the effect can be positive or negative depend on soil type and the actual process that takes place. For detachment, limiting condition slope has a positive effect independent of soil type. However, for transport limiting condition means for soils that has high infiltration capacity, such as Soil B, the effect of slope steepness may be negative for steeper slopes, slope steeper than 25%. The effect of moisture content on sediment yield also varies with soil type and degree of aggregation.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/7/6447/2010/ hessd-7-6447-2010-supplement.pdf.

Acknowledgements. We would like to thank the academic and non-academic staffs of the department of Agricultural Engineering, Haramaya University for facilitating us to use the laboratory and shop facility of the Department as well as for their valuable advice, comments and support during the study periods.

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Table 1. Particle size distribution (%) of soils studied.

Soil	Major soil classifications	Coarse	Sand sand	Fine sand	Silt	Clay	Organic matter
Soil A	Alemaya black soil (Vertisol)	7.91	9.04	6.78	41.20	35.07	5.6*
Soil B	Godie soil series (Cambisols)	18.07	22.89	11.45	15.66	31.93	13.67*
Soil C	Alemaya series eroded phase (Regosols)	21.39	17.11	10.70	32.09	18.71	4.21*

* Percent taken from the total soil material.

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Table 2. Shear strength and splash detachment values for each combination of soil types, slope steepness, and initial moisture contents.

Soil types	Slope Steepness (%)	Initial moisture condition	Shear strength (Kilo Pascal)	Splash detachment (Kg m^{-2} h^{-1})
Soil A	9	Air-dry	6.95	2.56
		Pre-wetted	7.43	2.41
	25	Air-dry	8.30	5.23
		Pre-wetted	7.61	3.23
	45	Air-dry	9.53	3.97
		Pre-wetted	16.33	2.79
Soil B	9	Air-dry	7.75	3.48
		Pre-wetted	9.94	2.62
	25	Air dry	6.03	4.23
		Pre-wetted	8.21	2.25
	45	Air dry	9.14	2.91
		Pre-wetted	9.96	3.08
Soil C	9	Air-dry	14.67	3.13
		Pre-wetted	14.46	2.25
	25	Air dry	12.96	3.74
		Pre-wetted	12.75	3.09
	45	Air dry	16.68	2.85
		Pre-wetted	17.01	2.34

Table 3. Effect of the different combinations and levels of antecedent moisture contents and slope steepness on splash detachment.

Slope steepness (%)	Antecedent moisture content splash kg/m^2/hr		
	Air-dry	Pre-wetted	Mean
9	3.06	2.42	2.74
25	4.40	2.86	3.63
45	3.24	2.74	2.99
Mean	3.57	2.67	
	Slope	Initial moisture content	Slope x initial moisture
SEM	0.114	0.093	0.162
LSD	0.323	0.264	0.458

Table 4. Effect of the different combinations and levels of antecedent moisture content, soil type, and slope steepness on runoff rate.

soil type	Slope Steepness (%)	Initial moisture content	Runoff rate (mm h^{-1})
Soil A	9	air dry	62.74
		pre-wetted	37.64
	25	air dry	56.14
		pre-wetted	50.56
	45	air dry	49.35
		pre-wetted	31.39
Soil B	9	air dry	47.34
		pre-wetted	59.95
	25	air dry	43.10
		pre-wetted	49.59
	45	air dry	5.76
		pre-wetted	22.60
Soil C	9	air dry	62.16
		pre-wetted	39.39
	25	Air-dry	61.22
		Pre-wetted	47.30
	45	Air dry	45.97
		Pre-wetted	68.45

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

	Soil type			
	Soil A	Soil B	Soil C	Mean
Moisture content		(mm-hr^{-1})		
Air-dry	56.08	32.06	56.45	48.20
Pre-wetted	39.87	44.05	51.71	45.21
Mean	47.97	38.06	54.08	46.70
	Soil type	Moisture content	Moisture-Soil interaction	
SEM	1.5369	1.2548	2.1740	
LSD	4.3579	3.5581	6.1627	

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Table 6. The different combinations and levels of soil type and slope steepness effect on sediment yield.

Soil type	Slope steepness (%)	Initial Moisture content	Sediment yield (soil loss) (Kg m^{-2} hr^{-1})	Splash detachment (Kg m^{-2} hr^{-1})	Proportion of sediment transported by runoff
Soil A	9	Air-dry	1.03	2.56	0.40
		Pre-wetted	0.66	2.41	0.28
	25	Air-dry	1.45	5.23	0.28
		Pre-wetted	0.81	3.23	0.25
	45	Air-dry	1.51	3.97	0.38
		Pre-wetted	0.59	2.79	0.21
Soil B	9	Air-dry	0.78	3.48	0.22
		Pre-wetted	0.55	2.62	0.21
	25	Air-dry	0.85	4.23	0.20
		Pre-wetted	0.74	2.25	0.34
	45	Air-dry	0.14	2.91	0.05
		Pre-wetted	0.372	3.08	0.12
Soil C	9	Air-dry	0.72	3.13	0.23
		Pre-wetted	0.48	2.25	0.21
	25	Air-dry	1.31	3.74	0.35
		Pre-wetted	1.15	3.09	0.37
	45	Air-dry	1.50	2.85	0.53
		Pre-wetted	1.50	2.34	0.64

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

Moisture content	Soil type			
	Sediment yield (Kg $m^{-2} hr^{-1}$)			
Air-dry	1.33	0.59	1.18	1.03
Pre-wetted	0.68	0.55	1.04	0.76
Mean	1.01	0.57	1.11	
	Soil	Moisture condition	Soil X moisture	
SEM±	0.034	0.028	0.048	
$LSD_{0.05}$	0.096	0.078	0.068	

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

Soil	Slope	Initial	Fraction by weight in size class (%)				
type		moisture content	Coarse sand (2.0–0.60 mm)	Medium sand 0.6–0.212 mm	Fine sand 0.212–0.075 mm	Silt 0.075–0.002	Clay < 0.002
Soil A	9%	Air-dry	0.1300	0.0408	0.0332	0.4940	0.3020
		Pre-wetted	0.1374	0.0392	0.0392	0.3921	0.3921
	25%	Air-dry	0.1522	0.0436	0.0511	0.4345	0.3188
		Pre-wetted	0.1247	0.0421	0.0452	0.4060	0.3820
	45%	Air-dry	0.1243	0.0415	0.0569	0.6702	0.1071
		Pre-wetted	0.1098	0.0413	0.0433	0.4723	0.3334
Soil B	9%	Air-dry	0.1550	0.1053	0.0650	0.3548	0.3199
		Pre-wetted	0.1900	0.0351	0.0309	0.2690	0.4750
	25%	Air-dry	0.1409	0.1046	0.0864	0.3500	0.3182
		Pre-wetted	0.2473	0.0538	0.0538	0.4301	0.2151
	45%	Air-dry	0.2344	0.0503	0.1119	0.4500	0.1534
		Pre-wetted	0.1255	0.0576	0.0314	0.6880	0.0975
Soil C	9%	Air-dry	0.1209	0.0569	0.1600	0.3620	0.3002
		Pre-wetted	0.3182	0.1009	0.1364	0.1036	0.3409
	25%	Air-dry	0.4383	0.1250	0.0200	0.2084	0.2083
		Pre-wetted	0.3750	0.1000	0.0250	0.2500	0.2500
	45%	Air-dry	0.4043	0.1064	0.0638	0.3191	0.1064
		Pre-wetted	0.3556	0.1111	0.0889	0.2222	0.2222

Table 9. Size distribution of the washed sediment for the three soils.

Soil type	Slope (%)	Fraction by weight in size class (%)					
		moisture content	Coarse sand (2.0–.60 mm)	Medium sand 0.6–0.212	Fine sand 0.212–0.075 mm	Silt 0.075–0.002	Clay < 0.002
Soil A	9%	Air-dry	0.1141	0.0712	0.0721	0.4782	0.2644
		Pre-wetted	0.0833	0.0417	0.0417	0.3937	0.4396
	25%	Air-dry	0.0968	0.0674	0.0989	0.5104	0.2265
		Pre-wetted	0.0828	0.0580	0.0592	0.3296	0.4703
	45%	Air-dry	0.0809	0.0630	0.0617	0.3972	0.3972
		Pre-wetted	0.0513	0.0367	0.0437	0.2895	0.5788
Soil B	9%	Air-dry	0.1142	0.1020	0.1024	0.3620	0.3194
		Pre-wetted	0.0959	0.0711	0.0911	0.4400	0.3019
	25%	Air-dry	0.1356	0.1343	0.1260	0.3021	0.3020
		Pre-wetted	0.2292	0.0521	0.0937	0.4167	0.2083
	45%	Air-dry	0.1888	0.0281	0.0281	0.3775	0.3775
		Pre-wetted	0.0941	0.0389	0.0435	0.1176	0.7059
Soil C	9%	Air-dry	0.0862	0.0254	0.1500	0.3098	0.4286
		Pre-wetted	0.1209	0.0330	0.1319	0.2747	0.4396
	25%	Air-dry	0.1289	0.0960	0.0750	0.3164	0.3837
		Pre-wetted	0.3333	0.1100	0.0435	0.2233	0.2899
	45%	Air-dry	0.2258	0.1129	0.0968	0.3226	0.2419
		Pre-wetted	0.1836	0.1532	0.1020	0.2041	0.3571

Table 10. Correlation between erosion variables.

Variables	Correlation coefficient	Probability level
Change in runoff rate Vs change in sediment yield (with increase in slope: among Soil A and antecedent moistures)	0.47	0.420
Change in runoff rate Vs change in sediment yield (with increase in slope: among Soil B and antecedent moistures)	0.96	0.008
Change in runoff rate Vs change in sediment yield (with increase in slopes: among Soil C and antecedent moistures)	0.45	0.440
Runoff rate Vs sediment yield (among all treatments; soils, slopes, and antecedent moistures)	0.66	0.003
runoff rate Vs sediment yield (among all soils, slopes with out 45%, and antecedent moistures)	0.40	0.096
Change in runoff rate Vs change in sediment yield (with increase in slopes: among all soils, and antecedent moistures)	0.83	0.001
Change in splash Vs change in sediment yield (with increase in slope: among Soil A and antecedent moistures)	0.79	0.214
Change in splash Vs change in sediment yield (with increase in slope: among Soil B and antecedent moistures)	0.36	0.419
Change in splash Vs change in sediment yield (with increase in slopes: among Soil C, and antecedent moistures)	0.97	0.038
Change in splash Vs change in sediment yield (with increase in slopes: among all soils, and antecedent moistures)	0.426	0.077
Splash Vs sediment yield (among all treatments; soils, slopes, and antecedent moistures)	0.399	0.110
Splash Vs sediment yield (among all soils, slopes with out 45%, and antecedent moistures)	0.71	0.009

Table 11. 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	$K_{iq} \times 10^6$	R^2	$K_{iq} \times 10^6$	R^2
Soil A	9	air-dry	0.46	0.65	0.10	0.580	0.21	0.610	1.73	0.660	0.34	0.730
		pre-wetted	0.57	0.99	0.86	0.970	0.19	0.980	2.05	0.990	0.41	0.990
	25	air-dry	0.72	0.81	0.22	0.800	0.30	0.810	1.43	0.800	0.49	0.830
		pre-wetted	1.16	0.88	0.20	0.900	0.28	0.910	1.29	0.950	0.44	0.950
	45	air-dry	1.14	0.99	0.41	0.999	0.47	0.999	1.56	1.000	0.79	1.000
		pre-wetted	0.79	0.997	0.11	1.000	0.12	0.999	0.57	0.990	0.29	0.990
Soil B	9	air-dry	1.24	0.850	0.25	0.940	0.54	0.940	5.53	0.910	1.09	0.910
		pre-wetted	1.58	0.999	0.21	1.000	0.45	0.840	3.03	0.996	0.60	0.996
	25	air-dry	1.30	0.950	0.09	0.970	0.35	0.970	1.54	0.950	0.53	0.950
		pre-wetted	0.98	0.990	0.06	0.990	0.24	0.990	1.04	0.985	0.36	0.990
	45	air-dry	1.48	0.907	0.13	0.960	0.14	0.960	1.37	0.985	0.70	0.990
		pre-wetted	1.75	0.870	0.18	0.960	0.24	1.000	0.34	0.940	0.43	1.000
Soil C	9	air-dry	0.71	0.960	0.12	0.960	0.26	0.960	2.00	0.990	0.39	0.990
		pre-wetted	1.72	0.640	0.13	0.720	0.17	0.980	1.09	0.980	0.22	0.980
	25	air-dry	0.93	0.980	0.30	0.995	0.41	0.990	1.85	0.990	0.64	0.990
		pre-wetted	1.03	0.997	0.29	0.999	0.40	0.999	1.89	0.990	0.65	0.990
	45	air-dry	0.82	0.990	0.30	0.999	0.34	0.999	1.28	0.997	0.65	0.997
		pre-wetted	1.47	0.600	0.34	0.640	0.23	0.910	0.67	0.960	0.33	0.96

Table 12. Soil erodibility values for the three soils at different slope and initial moisture content interactions.

Soil type	Slope (%)	Moisture content	Erodibility ($\times 10^6$) (Kg S m^{-4})	Erodibility ($\times 10^6$) Kg S m^{-4}
Soil A	9	Air-dry	1.22	1.59
		Pre-wetted	0.78	1.67
	25	Air-dry	1.07	1.56
		Pre-wetted	0.60	0.96
	45	Air-dry	0.92	1.53
		Pre-wetted	0.36	0.93
Average erodibility for Soil A			0.83	1.37
Soil B	9	Air-dry	0.92	1.59
		Pre-wetted	0.64	0.88
	25	Air-dry	0.63	1.19
		Pre-wetted	0.55	0.91
	45	Air-dry	0.08	1.18
		Pre-wetted	0.23	0.82
Average erodibility for Soil B			0.51	1.10
Soil C	9	Air-dry	0.86	1.07
		Pre-wetted	0.57	1.17
	25	Air-dry	0.97	1.30
		Pre-wetted	0.85	1.45
	45	Air-dry	0.92	1.63
		Pre-wetted	0.92	4.78
Average erodibility for Soil C			0.85	1.90

Column 4: Erodibility calculated based on $E \equiv K_i I^2 S_f$ and Column 5: Erodibility calculated based on $E = K_i I Q S_f$

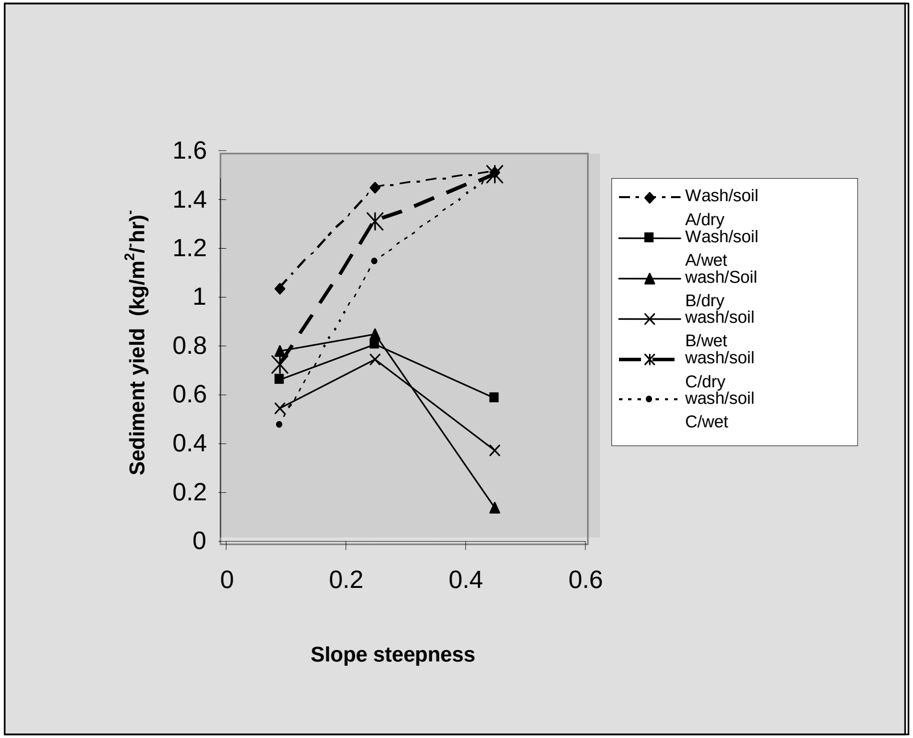

Fig. 1. Effect of the different levels of slope steepness on sediment yield for the three soils and at two levels of initial moisture contents.