Original Research

Developing Empirical Relationship between Interrill Erosion, Rainfall Intensity, Slope Gradient and Soil Types in Highlands of Salale, Ethiopia

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Abstract	Article Information
In order to develop an empirical relationship for interrill erosion based on rainfall intensity, slope steepness and soil types, an interrill erosion experiment was conducted using laboratory rainfall simulator on three soil types (Vertisols, Cambisols and Leptosols) for the highlands of North Shewa Zone of Oromia Region. From simulation work done using 450 x 320 x 100 mm erosion test pan; splashed soils, runoff and washed soils were collected at 5 minute interval for each 15 minutes simulation run at various combinations of design rainfall intensities of 25.67, 52.14, 73.50, and 99.20 mmhr^{-1}, slope steepness of 5, 20, 35, and 50% and the three soil types. Runoff rate, splash and wash loss were measured to obtain a total soil loss from the test pan. Different models relating interrill erosion with rainfall intensity and runoff rate were considered and their coefficients and parameters were estimated. From the models, those with highest prediction potential (R^2) were selected to be incorporated into models consisting soil properties and used to form six basic models of which three of them had shown average R^2 values of more than 0.95. Accordingly, five slope factor equations were combined with the three selected models and thus 15 models were formed. Out of these models, three of them had shown $R^2 > 0.90$ and were further compared with each other using the graph plotted for observed versus predicted interrill erosion. This showed that model incorporating rainfall intensity, runoff rate, median soil particle diameter, % clay and quadratic form of slope factor carried higher prediction potential than the other two models and selected as the final model for predicting interrill erosion. As this model incorporates more factors than those previously developed models, it ensures more accurate estimation of interrill erosion.	 ***Corresponding Author:** **Habtamu Adenew** **E-mail:** sinanhaw29@gmail.com

INTRODUCTION

Ethiopia is among the Sub-Saharan African countries where soil erosion by water constitutes the most widespread and damaging process of land degradation (Gete and Hurni, 2001). As suggested by Soil Conservation Research Projects (SCRP, 1990), this process has been accelerated by population growth (due to deforestation and expansion of agricultural production into marginal lands) and due to intense tropical rainfall and the dissected nature of the terrain with nearly 70% of the highlands having slopes in excess of 30% over which erosion by water is dominant.

Interrill erosion is one form of water erosion that seriously affects the most productive top soil of cultivated lands. It occurs on an area where detachment of soil particles is caused mainly by raindrop impact, and simultaneously, transportation takes place by splash and raindrop- induced shallow overland flow. According to Bradford *et al.* (1987), in interrill area, the flow alone can transport only the smallest particles, but raindrop impact on this flow entrains larger particles and significantly increase the thin flow transport capacity so that transportation of detached soil particles can be carried by raindrop induced interrill flow.

The relationship existing between interrill erosion and factors affecting it were previously evaluated by several researchers (Libenow *et al.,* 1990; Fox and Bryan, 1999). However, these relationships were empirically driven and affected by the levels of factors considered and their interactions. Several equations relating rainfall intensity, runoff rate and slope gradient to interrill erosion were also evaluated in previous studies (Zhang *et al.*, 2003; Jayawardena and Rezaur, 2006) and the results revealed that these relationships were empirically derived and were characterized as unique functions of soil properties, rainfall intensity, surface soil conditions and erosion processes. Most of the empirical equations which were developed so far between interrill erosion and major factors affecting it consider only few factors and are also dependent on local situations. Hence, for proper management of interrill area, there is a need to consider several factors and develop an empirical relationship that better relates interrill erosion with factors influencing it under a wide range of situations. Therefore, the study was conducted to develop appropriate models relating interrill erosion with rainfall intensity, runoff rate, slope steepness and major soil types and to estimate coefficients and parameters for the empirical equations.

MATERIALS AND METHODS

Description of the Study Area

The study was carried out in the highlands of North Shewa Zone of Oromia Region, which is situated between $9^0 09'$N to $10^0 39'$N latitude and $38^0 85'$E to $39^0 52'$E longitude. The study area has an altitude of 1500 to 3480 m.a.s.l., the mean annual rainfall of 1500 mm and the mean annual temperature of 16^oC. The major soils include Vertisols, Cambisols, Leptosols and Luvisols in widely diversified distribution and the dominant land use types are cultivable land and a parcel of grazing land.
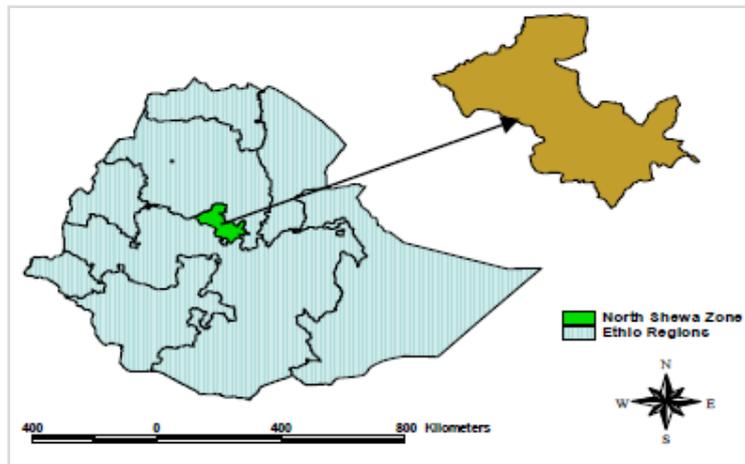

Figure 1: Location Map of the Study Site

Site and Treatment Selection

Of the 14 *Woredas* in the Zone, mainly, nine of them (*Grar-Jarso*, *Dagam, Kuyu, Wachale, Jidda, Shano, Aleletu, Yaya-Gulele,* and *Mulo*) fall partially or fully under the highland agro-climate from where the soil samples were taken. Soils with a wide range of physico-chemical properties, large areal coverage and higher agricultural importance were selected from the cultivated lands in the highlands of the Zone as Vertisols, Cambisols and Leptosols. The treatments for this study consisted of three soil types (Vertisols, Cambisols and Leptosols), four rainfall intensities (25, 50, 75 and 100 mmhr^{-1}), and four slope gradients (5, 20, 35 and 50%) with three replications.

Soil Sampling and Analysis

Samples were collected for simulation test and analysis of some soil physical properties. During sampling, 10 m x 10 m plot size was equally divided by rods into 5 equal parts giving 25 grids from where the samples were collected in a systematic way from the surface layer of 20 cm. The selected soil physical property with their respective method of analysis includes: soil texture (hydrometer), soil bulk density (core method), aggregate stability (wet sieving), D_{50} (Sieve analysis) and soil shear strength (Swedish fall-cone penetro-meter).

Interrill Erosion Experiment in the Laboratory using Simulated Rainfall

The interrill erosion experiment was conducted in a laboratory using FEL-3 rainfall simulator and erosion test pans with dimension of 450 mm x 320 mm x 100 mm (used by Le Bissonnais (1996)) with a splash shield on the four sides and a gutter on down slope side to collect washed soil loss and runoff. Accordingly, for the proposed intensities of 25, 50, 75 and 100 mm hr^{-1}, actual intensities of 25.67, 52.14, 73.50 and 99.20 mm hr^{-1} with coefficients of uniformity of 83, 83, 84 and 82% were used for the actual erosion experiment. For interrill erosion experiment, the soil sample was packed in erosion test pan and by keeping the moisture content at field capacity, the simulation started with desired intensity by adjusting the plot to the desired slope. The simulation was done for 15 minutes during which 3 splash and runoff yields were collected at 5 minute interval.

The runoff collected in the cylindrical container at the interval of 5 minutes at each run was measured to obtain the runoff volume. The dry mass of the soil washed was obtained from sediment in the container after decantation and oven dry at 105^oC. The amount of soil splashed during the run was also oven dried, weighed separately and combined with dry mass of washed soil and finally interrill erosion rate (g m^{-2} hr^{-1}) and runoff rate (cm^3 min^{-1} per cm width of the test pan) was estimated.

RESULTS

Selected Soil Physical Properties

The analysis results of some of the soil physical properties (Table 1) show that the textural classes of the soils were clay, clay loam and sandy clay loam for Vertisols, Cambisols and Leptosols, respectively. The bulk density for the three soils range from 1.21 to 1.46 g cm^{-3}.

Table1: Analysis results for selected soil physical properties

Soil type	Particle size distribution (%)			Textural classes	Water stable aggregate (WSA %)	Bulk density (gcm^{-3})	d_{50} (µm)	τ (KN/m^2)
	Sand	Silt	Clay					
Vertisols	11.08	25.20	63.72	Clay	61	1.21	1.45	5.413
Cambisols	26.28	35.60	38.12	clay loam	54	1.33	2.25	2.995
Leptosols	49.63	21.48	28.89	Sandy clay loam	37	1.46	9.03	2.034

d_{50}= median soil particle diameter, τ = shear strength of the soil, WSA= Water Stable Aggregates (%).

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The result from aggregate stability analysis as expressed in percent water stable aggregates was indicated as Vertisols (61%), Cambisols (54%) and Leptosols (37%). Median soil particle diameters (d_{50}) and the shear strength of the soils were found to be 1.45, 2.25, 9.03 μm and 5.413, 2.995, 2.034 KN/m^2 respectively, for the three soils.

Runoff Rates & Soil Losses from the Three Soil Types at Different Slope Steepness and Rainfall Intensities
The comparison of runoff rate in terms of soil types indicated that, under a given rainfall intensity; runoff rate

was generally high for Cambisols and low for Leptosols while an intermediate for Vertisols implying that Cambisols are more erodible relative to the other two. The rate of soil loss for the three soils varied with variation in slope steepness and rainfall intensities. The result of average soil loss rate (Table 2) showed that under each rainfall intensity, average soil loss rate tends to increase with an increase in slope steepness. Likely, under all rainfall intensities, average soil loss rate seems to increase.

Table 2: Average runoff rate (cm^3 min^{-1}cm^{-1}) and soil loss rate (g m^{-2}hr^{-1}) for the three soils at different slope steepness and rainfall intensities

Soil types	Slope (%)	Rainfall intensities *							
		$I_{25.67}$		$I_{52.14}$		$I_{73.50}$		$I_{99.20}$	
		Q	SL	Q	SL	Q	SL	Q	SL
Leptosols	5	0.297	41.08	0.415	58.55	0.601	86.08	2.990	427.60
	20	0.534	75.17	1.273	181.80	4.614	658.23	4.097	584.29
	35	1.351	192.40	1.485	211.01	6.082	868.37	5.259	750.73
	50	2.430	346.92	2.374	339.42	5.613	722.78	6.214	887.58
	average	1.153	163.89	1.386	197.69	4.227	583.86	4.640	662.55
Vertisols	5	0.705	93.01	1.76	280.09	3.881	554.18	3.335	476.01
	20	0.843	120.30	1.919	253.94	4.157	592.44	6.514	929.72
	35	4.276	569.09	5.056	672.59	6.372	1237.55	6.081	1539.14
	50	4.127	549.57	5.067	673.81	5.651	1236.36	5.934	1288.69
	average	2.487	412.98	3.450	470.10	5.015	905.13	5.466	1058.39
Cambisols	5	1.676	222.70	2.436	324.69	3.530	503.70	6.210	887.38
	20	3.221	500.48	3.405	486.03	6.753	965.02	6.664	951.94
	35	3.206	460.04	3.854	686.61	8.381	1072.14	7.721	1102.20
	50	3.751	570.89	6.391	913.19	7.519	1197.74	10.763	1537.38
	average	2.701	394.40	4.021	602.63	6.221	934.65	7.839	1119.72

* $I_{25.67}$=25.67 mm hr^{-1}rainfall intensity, $I_{52.14}$=52.14 mm hr^{-1} rainfall intensity, $I_{73.50}$=73.50 mm hr^{-1} Rainfall intensity, $I_{99.20}$= 99.20 mm hr^{-1} rainfall intensity, Runoff rate (Q)= (cm^3 min^{-1}cm^{-1}) and Soil loss rate (SL) (g m^{-2} hr^{-1}).

DISCUSSION

Relationship between Interrill Erosion and Rainfall Intensity
To estimate the empirical constants of the power equation that relates interrill erosion and rainfall intensity (Model 1), the experimental data from the simulation for the duration of 0 – 15 minutes were grouped by soil types and slope steepness, and parameters *a* and *b* were estimated by linear regression of log transformed data.

$$E_i = aI^b ....(I)$$

Where, E_i = Interrill erosion rate (g m^{-2} hr^{-1}), I = intensity (mm hr^{-1}) and *a* & *b* are best fit local constants.

This power equation was used by several researchers like Goff *et al.* (2000), Mengistu (2003), and Agarwal and Dickinson (2005), and recommended that it best relate interrill erosion and rainfall intensity. In this study also, the values of parameter *a* and *b* were estimated to be in the range of 0.37 to 97.36 and 0.01 to 4.53 for the three soils, respectively and the results agree with the one explained by Fox and Bryan (1999) after conducting an experiment on two soils (Vertisols and Nitosols). Averaged values of *b* for the three soils were found to be in the range of 1.29 to 2.14. This result agrees with the suggestion given by Meyer (1994) as the power equation with a value of *b* = 2 could describe the process of interrill erosion mainly for Leptosols and Cambisols. For the three soils, R^2 value has an average value of 0.90, 0.92 and 0.95 for Leptosols, Vertisols and Cambisols, respectively. It

consistently increased with an increase in slope steepness only for Vertisols.

Table 3: Estimated values of coefficients and exponents for the model I. Model I ($E_i = aI^b$) *

Soil type	Slope (%)	*a*	*b*	R^2
Leptosols	5	0.58	1.98	0.79
	20	0.37	1.78	0.95
	35	9.35	2.59	0.87
	50	95.60	0.56	0.99
	Average	**26.48**	**1.48**	**0.90**
Vertisols	5	0.81	0.01	0.83
	20	0.90	1.98	0.89
	35	58.11	1.53	0.97
	50	74.66	1.65	0.98
	Average	**33.62**	**1.29**	**0.92**
Cambisols	5	12.32	0.85	0.87
	20	64.65	1.70	0.98
	35	94.84	1.48	0.95
	50	97.36	4.53	0.99
	Average	**67.29**	**2.14**	**0.95**

*E_i (g m^{-2} hr^{-1}), I (mm hr^{-1}), *a* and *b* are parameters of best fit, R^2 = Coefficient of determination.

The average R^2 value for the three soils showed that this power equation could describe interrill erosion better on both soils though it has high prediction potential for Cambisols with R^2 value of 0.95.

Relationship between Rainfall Intensity, Runoff Rate and Interrill Erosion

In order to incorporate runoff rate, models with non-linear and linear terms of rainfall intensities were considered for interrill erosion processes as presented below:

$$E_i = aI^b Q^n \qquad (II)$$

$$E_i = aIQ^n \qquad (III)$$

Where, E_i = interrill sediment delivery per unit area per unit time (g m^{-2} hr^{-1}), I is rainfall intensity (mm hr^{-1}), Q is Runoff rate (cm^3 min^{-1} cm^{-1}) and a, b and n are best fit local constants.

For estimating coefficient and exponent values of these empirical equations, the data from duration of 5 – 15 minutes were grouped by soil type and slope, and linear regression of log transformed data was used to estimate the parameters. From the analysis results (Table 4), it could be observed that the values of *a* for models II

and III varied from 0.017 to 7.052 and 0.256 to 3.092 respectively

The estimated values of *b* for model II ranged from 0.071 to 5.847 and for each soil types, it had an increasing trend with increase in slope steepness. This could be in agreement with the values reported by Grosh and Jarret (2004) after conducting an experiment on disturbed silty clay loam. Estimated values of *n* for model II has variable values and it agrees with the results reported by Agarwal and Dickinson (2005) as an average values of *n* ranging from -2.86 to 2.88 and suggested that the average value of *n* for model with linear term of rainfall intensity was increased with slope steepness. Coefficients of determination for model II were found to be more than 0.87 with average values of 0.92, 0.95 and 0.98 for Leptosols, Vertisols and Cambisols, respectively. These values of R^2 showed that this model could predict interrill erosion on all three soils in a better way. Meyer (1994) reported values of R^2 greater than 0.90 for similar models by confirming that it better predicted interrill erosion for their study condition.

Table 4: Estimated values of the parameters for model II and III

Soil types	Slope (%)	Model II ($E_i = aI^b Q^n$)*				Model III ($E_i = aIQ^n$)*		
		a	b	n	R^2	a	n	R^2
Leptosols	5	0.943	0.256	-0.046	0.87	2.923	1.087	0.79
	20	0.997	1.253	-0.052	0.91	1.171	0.365	0.73
	35	1.018	1.459	0.234	0.96	1.263	0.955	0.91
	50	3.615	3.615	0.405	0.94	1.086	1.572	0.86
	Average	**1.643**	**1.645**	**0.135**	**0.92**	**1.610**	**0.994**	**0.82**
Vertisols	5	0.035	0.299	-0.397	0.92	2.186	-2.225	0.83
	20	1.027	1.405	-0.096	0.97	1.201	0.444	0.91
	35	1.058	3.161	-0.423	0.94	7.086	1.482	0.86
	50	3.033	5.847	0.965	0.99	11.09	1.445	0.87
	Average	**1.288**	**2.678**	**0.012**	**0.95**	**5.390**	**0.287**	**0.86**
Cambisols	5	0.017	0.071	-0.325	0.97	0.256	-1.843	0.84
	20	0.994	1.663	-0.535	0.98	1.031	1.532	0.85
	35	0.998	3.349	1.186	0.99	9.005	0.405	0.92
	50	7.052	4.154	2.727	0.99	13.092	1.463	0.91
	Average	**2.265**	**2.309**	**0.170**	**0.98**	**5.846**	**0.389**	**0.88**

* E_i (g m^{-2} hr^{-1}), I (mm hr^{-1}) and Q (cm^3 min^{-1} cm^{-1}), R^2 is coefficient of determination

For model III, R^2 have average values of 0.82, 0.86 and 0.88 respectively, for the three soils showing that model III has lower potential than model II in predicting interrill erosion on the three soils.

From the average values of R^2 at each slope steepness, it could be possible to observe that, since the R^2 values of model II were greater than that of model III, generally model with non-linear intensity term ($E_i = aI^b Q^n$) described the interrill erosion process better than that with linear intensity term ($E_i = aIQ^n$) at each slope steepness for the three soils. Likely, Le Bissonnais and Singer (2003) tried to incorporate the model with non-linear term of rainfall intensity in their experiment and found that it better described interrill erosion than model with linear rainfall intensity term with R^2 greater than 0.88. Therefore, from the three models (model I, II and III), comparison of their respective average R^2 values for the three showed that the first two models had relatively higher R^2 values than the last model implying that they could better describe interrill erosion on the three soils, and were selected to be further incorporated into other models.

Relationship between Rainfall Intensity, Runoff Rate, Soil Physical Properties and Interrill Erosion

Among others, Sheridan *et al.* (2007) had conducted experiments to see the effects of some soil physical properties on interrill erosion and finally reported that, soil shear strength, % clay content and median soil particle diameter mainly influence the nature of interrill erosion. Similarly, in the present study as well, these soil properties were selected and models which relate them with interrill erosion were incorporated into the above selected models (model I and II), and formed six basic models that would be further evaluated to select an appropriate model that best describes interrill erosion. The data collected were grouped for slope steepnesses and the parameters were estimated by non-linear regression analysis. The models obtained were of the form:

$$E_i = aI^b \tau^y d_{50}^z \qquad (IV)$$
$$E_i = aI^b \tau^y (\%clay)^x \qquad (V)$$
$$E_i = aI^b d_{50}^z (\%clay)^x \qquad (VI)$$
$$E_i = aI^b Q^n \tau^y d_{50}^z \qquad (VII)$$
$$E_i = aI^b Q^n \tau^y (\%clay)^x \qquad (VIII)$$
$$E_i = aI^b Q^n d_{50}^z (\%clay)^x \qquad (IX)$$

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Where, E_i is interrill erosion rate (g m^{-2} hr^{-1}), I is rainfall intensity (mm hr^{-1}), Q is runoff rate (cm^3 min^{-1} cm^{-1}), τ is soil shear strength (KN m^{-2}), d_{50} is median soil particle diameter (μ m), a, b, n, x, y, z are parameters to be estimated.

Based on the estimated values of parameters for the six models (Table 5), the value of a,b, and n ranged from 0.474 to 21.042, 0.248 to 2.911 and 0.009 to 1.043 respectively. For these three models there was a general tendency of increase in n with increase in slope steepness showing that as slope steepness increases, runoff rate also increases, which in turn increases soil loss rate. Similarly, researchers like (Fan and Wu, 2001) reported that runoff rate increases with an increase in slope steepness.

The values of x in the models relating clay percentage to soil loss by interrill erosion has an average values of -

0562, -0.669, -0.417 and -0.595, respectively. No consistent trend was observed between estimated values of x and slope steepness though the negative values shows that the higher the clay contents, the lower would be the interrill erosion. For the models containing shear strength, the estimated values of y, in the case of this study, ranged from -1.058 to -0.046 in which the negative values show that there is an inverse relationship between soil shear strength and soil loss. This result was in agreement with results reported by Sheridan et al., (2007) who found values of y ranging from -0.43 to -0.40 under variable slope steepness and rainfall intensity. Likely, the estimated values of z in model relating median soil particle diameter with interrill erosion rate has an average values of -0.386, -1.106, -0.903 and -0.617, respectively indicating that as d_{50} increases soil loss rate decreases due to the fact that the higher the particle sizes the lower would be the ease of transport.

Table 5: Estimated values of the parameters for the selected six models

Models	Slope(%)	a	b	n	x	y	z	R^2
Model IV $E_i = aI^b \tau^y d_{50}{}^z$	5	1.691	1.032	-	-	-0.046	-0.007	0.71
	20	0.474	1.457	-	-	-0.262	-0.083	0.83
	35	13.455	1.944	-	-	-0.417	-0.513	0.87
	50	21.042	1.993	-	-	-0.901	-0.942	0.90
	Ave.	**9.165**	**1.607**	**-**	**-**	**-0.406**	**-0.386**	**0.83**
Model V $E_i = aI^b \tau^y (\%clay)^x$	5	3.721	0.248	-	-0.674	-0.921	-	0.92
	20	0.545	0.871	-	-0.596	-0.743	-	0.99
	35	2.972	2.053	-	-0.505	-0.931	-	0.98
	50	1.074	2.911	-	-0.473	-1.058	-	0.96
	Ave.	**2.078**	**1.521**	**-**	**-0.562**	**-0.913**	**-**	**0.96**
Model VI $E_i = aI^b d_{50}{}^z clay)^x$	5	1.931	0.738	-	1.073	-	-1.337	0.85
	20	1.952	0.966	-	-0.902	-	-1.391	0.87
	35	2.017	1.062	-	-0.347	-	-0.805	0.92
	50	0.573	1.719	-	-0.352	-	-0.892	0.90
	Ave.	**1.618**	**1.121**	**-**	**-0.669**	**-**	**-1.106**	**0.88**
Model VII $E_i = aI^b Q^n \tau^y d_{50}{}^z$	5	4.071	2.381	0.058	-	-0.066	-0.843	0.87
	20	7.151	1.942	0.692	-	-0.583	-0.807	0.89
	35	3.094	0.731	0.921	-	-0.147	-0.917	0.86
	50	16.01	0.897	1.043	-	-0.803	-1.045	0.91
	Ave.	**7.582**	**1.487**	**0.678**	**-**	**-0.399**	**-0.903**	**0.88**
Model VIII $E_i = aI^b Q^n \tau^y (\%clay)^x$	5	1.094	1.944	0.031	-0.392	-0.074	-	0.95
	20	5.173	2.817	0.031	-0.104	-0.536	-	0.98
	35	2.037	2.201	0.647	-0.463	-0.773	-	0.97
	50	2.572	1.504	0.593	-0.709	-0.944	-	0.99
	Ave.	**2.719**	**2.116**	**0.325**	**-0.417**	**-0.581**	**-**	**0.98**
Model IX $E_i = aI^b Q^n d_{50}{}^z (\%clay)^x$	5	2.249	1.913	0.009	-0.964	-	-0.185	0.94
	20	1.981	2.579	0.025	-0.913	-	-0.408	0.98
	35	1.542	2.841	0.377	-0.255	-	-0.904	0.96
	50	1.353	0.901	0.246	-0.247	-	-0.971	0.97
	Ave.	**1.781**	**2.059**	**0.164**	**-0.594**	**-**	**-0.617**	**0.96**

At 5 and 20% slope steepness, models V, VIII and IX describe interrill erosion better than the other models (with their R^2 values greater than 0.90), while the other models has the least potential with their R^2 value less than 0.90 (Table 5). Still at slope steepness of 35%, model V, VIII and IX have higher coefficient of determination. From the comparison of the average efficiencies for each of the models, R^2 value for model V, VIII and IX were greater than that of the others showing that these three models had higher potential to predict interrill erosion at all slope steepness's. Therefore, model V, VIII and IX were

selected and used in the complete statistical modeling in which slope factors were incorporated.

Relationship between Slope Steepness and Interrill Erosion

To investigate the effect of slope steepness on interrill erosion, the rate of interrill soil loss for duration of 15 minutes and slope steepness for the three types of soils with four different intensities were plotted as shown in figures 2 to 5. From figure 2, the soil loss rates for Vertisols and Cambisols initially increased at a decreasing

rate with an increase in slope steepness and above 35% slope steepness it increased on both soils with the same fashion. This might be due to the nature of the soil with high clay content as it initially swells and holds water and difficult to be detached (Mc Cool *et al.*, 1997). Under a rainfall intensity of 52.14 mm hr^{-1} (Figure 3), soil loss rate for Vertisols and Cambisols generally tends to increase with higher rate for Cambisols under all slope steepnesses. For 73.50 mmhr^{-1} rainfall intensity (Figure 4) and 99.20 mm hr^{-1} rainfall intensity (figure 5), soil loss rate for the three soils generally increased with slope steepness. Similarly, Huang (2001) had also found that soil loss rate for both soils increased gradually with slope steepness. Similar results were also reported by Fan and Wu (2001) as well as Meyer (1994).
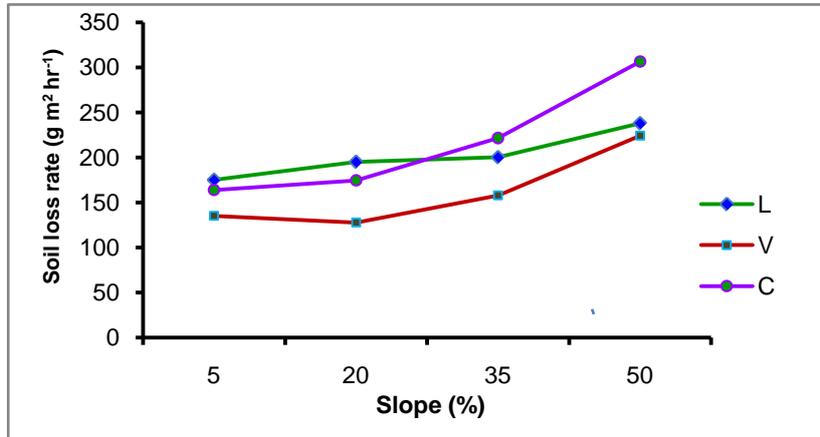
Figure 2: Interrill erosion Vs slope steepness at rainfall intensity of 25.67mm hr^{-1} (Where, L= Leptosols, V = Vertisols, C = Cambisols
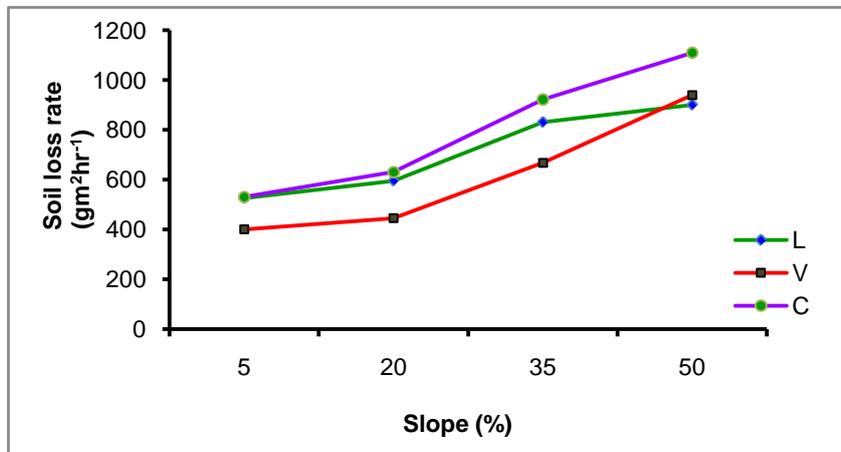
Figure 3: Interrill erosion Vs slope steepness at rainfall intensity of 52.14mm hr^{-1} (Where, L= Leptosols, V = Vertisols, C = Cambisols)
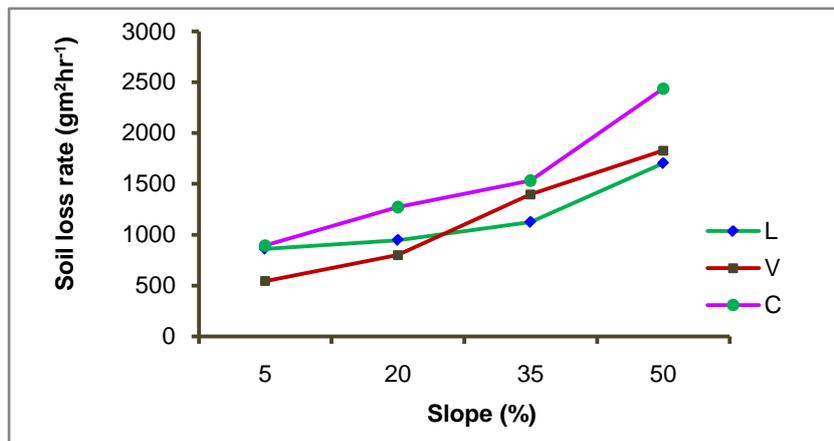

Figure 4: Interrill erosion Vs slope steepness at rainfall intensity of 73.50 mm hr^{-1} (Where, L= Leptosols, V = Vertisols, C = Cambisols)
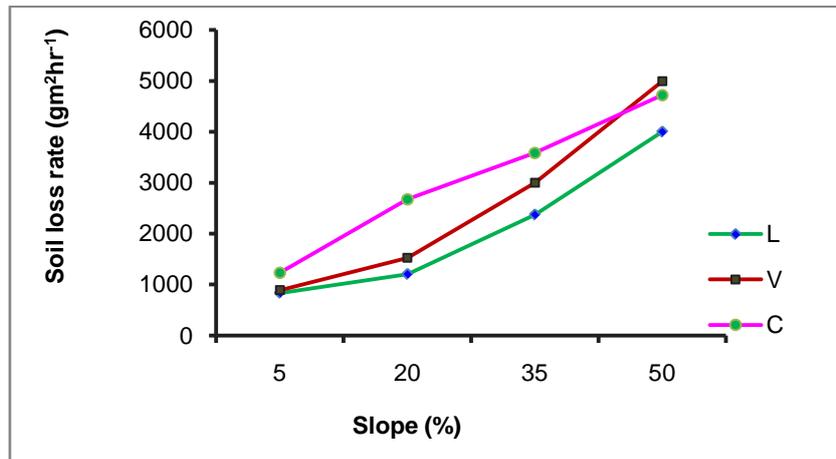
Figure 5: Interrill erosion Vs slope steepness at rainfall intensity of 99.20 mm hr^{-1} (Where, L= Leptosols, V = Vertisols, C = Cambisols)

A closer observation of figures *2* to *5* revealed that soil loss mainly increased with an increase in slope steepness. At higher slope steepness, the erosion rate was mainly increased at a decreasing rate. This could be attributed to the reduction in the raindrop impact on soil surface due to higher surface inclination (Fan and Wu, 2001). After investigating the effect of slope steepness on interrill erosion, it is worth considering some of the models relating interrill erosion and slope steepness that better describes the above relationships and incorporate it into other models to come out with an appropriate model encompassing all parameters under consideration. Some of the slope steepness factor equations selected for describing the effect of slope steepness on interrill erosion include:

$S_{f1} = h + d\sin\theta + m\sin^2\theta$ (Fox and Bryan,1999)

$S_{f2} = h + \sin^d\theta$ (Huang, 2001)

$S_{f3} = 1.05 - 0.85\exp(-4\sin\theta)$ (Liebenow *etal.*, 1990)

$S_{f4} = S^d$ (Van Liew and Saxton,2006)

$S_{f5} = 3.0(\sin\theta)^{0.8} + 0.56$ (Mc Cool *et al.*, 1997)

Where, S_f = Slope factor,q θ = Slope angle (%), h, d and m are the best fit constants and exponents.

The above equations were tested for their ability to describe the effect of slope steepness on interrill erosion. A total of 15 models (5 slope factor equations * 3 models in which soil properties, rainfall intensity and runoff rates were included) were fitted to the experimental data and coefficients and exponents were estimated using a non-linear regression analysis and the parameters estimated for the models were presented in Table 6.

Table 6: Estimated parameters for the models including soil properties and slope factor

Models*		Parameters								
	S_f	a	b	n	x	y	h	d	m	R^2
Model X $E_i = aI^b \tau^y (\%clay)^x * S_f$	S_{f1}	2.150	1.836	-	-0.675	-0.088	4.598	0.520	0.036	0.87
	S_{f2}	0.974	1. 308	-	-0.627	-1.492	9.745	0.580	-	0.91
	S_{f3}	0.451	1.502	-	-0.432	-0.094	-	-	-	0.71
	S_{f4}	0.912	1.385	-	-0.033	-0.632	1.424	-0.180	-	0.86
	S_{f5}	0.064	1.009	-	-0.007	-0.047	-	-	-	0.66
Model XI $E_i = aI^b Q^n \tau^y (\%clay)^x * S_f$	S_{f1}	2.606	0.594	0.217	-0.318	-0.933	4.639	-1.803	0.585	0.94
	S_{f2}	6.073	1.056	1.268	-5.246	-4.787	0.467	-6.865	-	0.88
	S_{f3}	1.702	0.021	0.079	-0.251	-0.044	-	-	-	0.72
	S_{f4}	1.834	0.732	0.967	-0.829	-0.397	-5.770	2.449	-	0.81
	S_{f5}	0.907	0.006	0.281	-0.407	-0.039	-	-	-	0.67
Model XII $E_i = aI^b Q^n d_{50}^y (\%clay)^x * S_f$	S_{f1}	5.272	0.599	0.836	-0.194	-0.751	7.305	4.165	1.903	0.95
	S_{f2}	1.901	0.562	0.966	-0.475	-1.096	-17.35	0.590	-	0.88
	S_{f3}	0.927	3.401	0.009	0.437	-1.208	-	-	-	0.76
	S_{f4}	11.480	1.469	0.995	-0.656	-6.402	20.880	-0.561	-	0.81
	S_{f5}	5.019	2.307	0.081	-0.057	-2.904	-	-	-	0.69

*E_i (g m^{-2}hr^{-1}), I (mm hr^{-1}), Q (cm^3 min^{-1} cm^{-1}), d_{50} (µ m), τ (KNm^{-2}), Slope steepness, S (mm^{-1}), θ = Slope angle (%), Sf represents Slope factors

Results of parameter estimation for the models (Table 6) showed that the R^2 value for each of the models varies. For a given model combined with different slope factor, variation in R^2 value was mainly due to variability in the potential of slope factor to predict interrill erosion under the concerned situation. The R^2 values revealed that the potential effect of S_{f1}, except S_{f2} in the first model, on interrill erosion process was very high relative to the other slope factor equations in all the three models, while models incorporated into S_{f3} and S_{f5} had the lowest prediction potential.

The Complete Empirical Equation for Interrill Soil Erosion

To develop the final empirical equation relating interrill erosion with rainfall intensity, soil properties, runoff rate and slope steepness, it could be feasible to select the model that best predicts interrill erosion. Accordingly, several models relating rainfall intensity, runoff rate and soil properties were tested and only three of them were selected depending on their prediction potential (R^2 value). Parameters were estimated for empirical equations relating slope factors and other interrill erosion models selected to develop a powerful model for predicting interrill erosion as done by previous researchers (Fan and Wu, 2001). Models incorporated with slope factor of the form S_{f5} and S_{f3} had low R^2 values implying low prediction potential.

Models incorporated with slope factor equation of the form S_{f4} gave better R^2 value for model X ($R^2 = 0.86$) than for models XI and XII for which the R^2 value was equal (0.81). Models incorporated with slope factor of the form S_{f2} gave equal prediction power for models XI and XII with $R^2 = 0.88$, while it has the highest R^2 value for model X with ($R^2 = 0.91$). For models XI and XII, interrill erosion models with slope factor of quadratic form ($S_{f1} = h + d \sin\theta + m \sin^2\theta$) have R^2 values which were sufficiently higher than that of the other models with R^2 of 0.94 and 0.95 for models XI and XII respectively. Therefore, for the final model of interrill erosion, models which have the highest prediction potential (with highest R^2 values) were selected for further comparison and accordingly from the models

presented in Table 6, the following three models were selected. Finally the three models were of the form:

$$E_i = aI^b \, \tau^y \, (\%clay)^x \, * \, (h + \sin^d\theta) \qquad (R^2=0.91) \quad (X)$$

$$E_i = aI^b Q^n \, \tau^y \, (\%clay)^x * (h+d \sin\theta + m \sin^2\theta) \quad (R^2=0.94) \quad (XI)$$

$$E_i = aI^b Q^n \, d_{50}{}^y \, (\%clay)^x *(h+d\sin\theta + m \sin^2\theta) \quad (R^2=0.95) \quad (XII)$$

When the coefficients and exponents estimated for these models (Table 6) were substituted for each parameter, the final empirical equations become:

$$E_i = 0.974 I^{1.308} \tau^{-1.492} (\%clay)^{-0.627} * (9.745 + \sin^{0.58}\theta) \quad (XIII)$$

$$E_i = 2.606 I^{0.594} Q^{0.217} \, \tau^{-0.933} (\%clay)^{-0.318} *(4.639 - 1.803\sin\theta + 0.585\sin^2\theta) \quad (XIV)$$

$$E_i = 5.272 I^{0.599} Q^{0.836} \, d_{50}{}^{-0.751}(\%clay)^{-0.194} *(7.305 + 4.165\sin\theta + 1.903\sin^2\theta) \quad (XV)$$

Even though the above models have high prediction potentials, it is still possible to select one model that will enable us to best predict interrill erosion at the study area. This could be done by comparing the models in terms of interrill erosion rates estimated from each of the models with the actual interrill erosion rates.
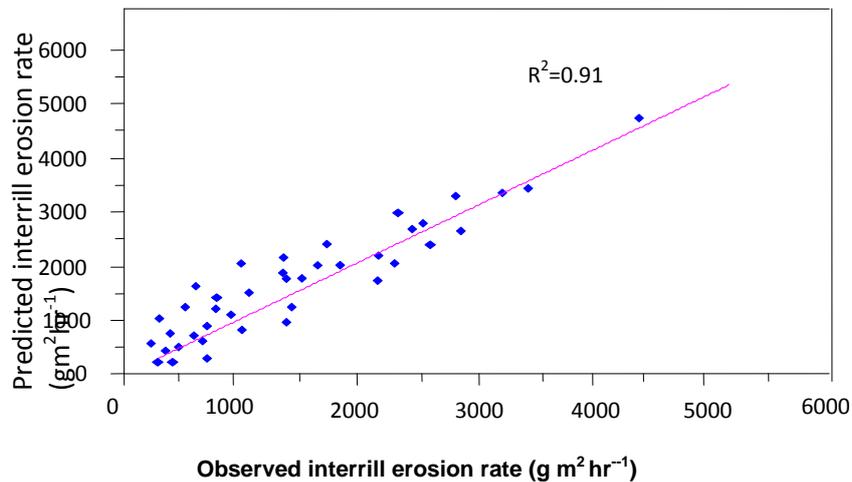

**Figure 6:** Predicted Vs observed interrill erosion rate for model X
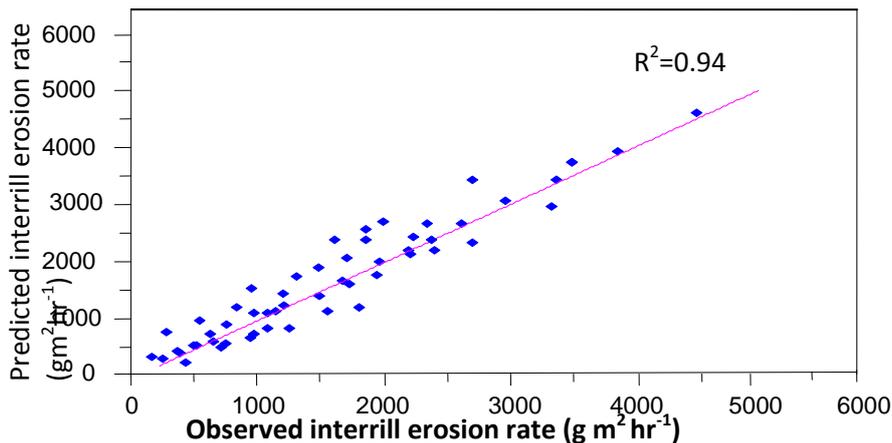
Figure 7: Predicted Vs observed interrill erosion rate for Model XI
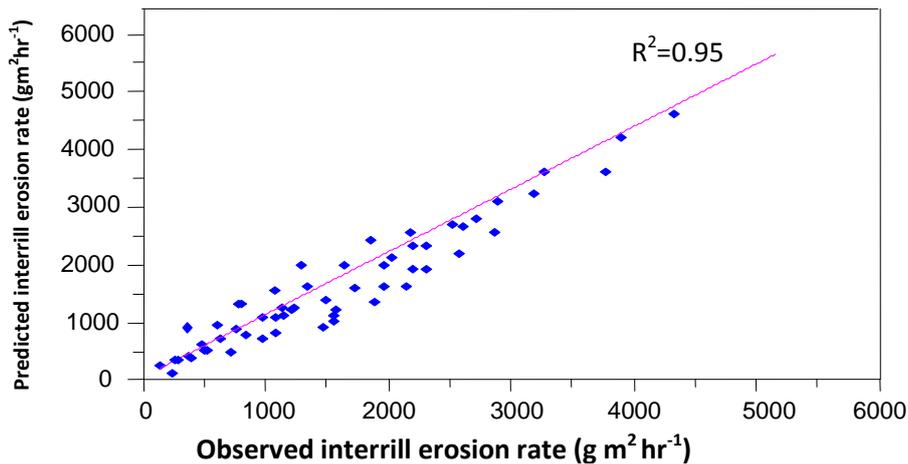

Figure 8: Predicted Vs observed interrill erosion rate for model XII

It could be seen that in case of model X, it nearly over estimated interrill erosion with R^2 value of 0.91 (Figure 6). Most of the dots are above the 1:1 line indicating that for a given observed value, the model has over prediction of lower values. Besides, the line 1:1 is almost far to pass through the origin so that the observed and predicted values are not too much approaching each other. Similarly, in the case of model XI (Figure 7), most of the dots were above 1:1 line indicating that the model has a tendency of over predicting middle to higher values. But, the line 1:1 relatively tends to pass through the origin than in case of model X.

In the case of model XII, most of the dots were below the 1:1 line (Figure 8), indicating that the model has under predicted lower values. Grosh and Jarrett (2004) reported that, models that nearly under predicted interrill erosion could be better recommended even though it has limitation than models that over estimate the soil loss. Therefore, from the three models, model XII (R^2= 0.95) has higher tendency to predict interrill erosion to the maximum of expected values as the 1:1line tends to pass through the origin than the rest two models implying that the predicted and observed values are nearly equal. So, it could be feasible using model XII to predict interrill erosion from crop lands of the study area, estimating environmental impacts and to account for land preparation methods in soil and water conservation efforts. Therefore, the empirical model selected for further recommendation could be of the form:

$$E_i = 5.272I^{0.599}Q^{0.836} d_{50}^{-0.751}(\%clay)^{-0.194} *(7.305+ 4.165sin\theta + 1.903sin^2\theta) \qquad (XVI)$$

Where, E_i = interrill erosion rate (g m^{-2} hr^{-1}), I = rainfall intensity (mm hr^{-1}), Q = runoff rate (cm^3 min^{-1} cm^{-1}), % clay = Percentage clay content, d_{50} = median soil particle diameter (μ m), θ = slope angle (%).

CONCLUSIONS

To obtain the complete empirical model that better describes interrill erosion in which the considered factors such as rainfall intensity, runoff rate, soil properties and slope were incorporated, different models were considered. The models are initially the one that better describes interrill erosion better even though they are from only limited factors that affects interrill erosion.

By using the data from runoff volume, runoff rate and some soil physical properties, coefficients and parameters were estimated for different combinations of the models. These models were compared in terms of their R^2 values and models with highest R^2 values that better describes interrill erosion in the study area were selected. Later, models with highest performance were compared with each other in terms of interrill erosion rates estimated from each of the models with the actual interrill erosion rates and finally an empirical equation that better predicted interrill erosion was suggested as the final empirical relationship for quantifying interrill erosion. Unlike the previously developed models, this model incorporates several factors that affect interrill erosion which enable us to critically estimate soil loss rate by interrill erosion. This model can be applied for any environment with the estimation of the local constants.

Conflict of Interest

None declared.

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