RAINFALL DIRECTION AND ITS RELATIONSHIP TO EROSIVITY SOIL LOSS AND RUNOFF

Hans Hurni

ABSTRACT

Rainfall direction, defined as average inclination and compass direction of falling raindrops of a storm, is not normally monitored in standard soil erosion process studies. However, rainfall erosivity and runoff amounts may be influenced by rainfall direction in relationship to a sloping surface area, and may result in considerably differing soil loss and runoff rates according to slope exposure.

In a large research catchment in Ethiopia, differences in soil erosion damages can be attributed to uniform rainfall directions during several centuries. Slopes exposed towards the rain are much more damaged than slopes exposed towards the opposite direction (leeward effect).

A simple theoretical model to determine the influence of rainfall direction on Wischmeier erosivity values of normally recorded storms is developed in this paper. A method for measuring and calculating average strom directions using four gauges inclined towards the four main compass directions is presented. Finally, the model is validated with actual field data under natural rainfall conditions and a set of specifically directed and inclined continuous fallow micro-plots.

However, the correlation between erosivity and measured soil loss does not clearly increase with the data used in this paper if rainfall direction is included for erosivity calculation. Reasons for this may be found in inaccurate data collection and analysis, and the limited number of storms used for this test. Better results may be obtained if more values are compared. This is under way for about 500 more storm soil loss and rainfall inclination data collected throughout the Ethiopian highlands, but cannot be presented at this stage.

It is generally recommended to include rainfall direction measurements for soil erosion process studies as well as for climatic monitoring, especially in areas where rainfall direction is uniform over longer periods of time. Detailed procedures for assessing rainfall directions and erosivity adjustments are given in the paper.

INTRODUCTION

Rainfall direction, defined as inclination a (in degrees) and compass direction b (in degrees) of falling raindrops of a storm, is normally perceived as a possible factor influencing soil loss and runoff (cf. Lal, 1977). However, except for few studies (e.g. Ferreira et al., 1985), no quantitative assessments of the relationship between rainfall direction, erosivity, soil loss and runoff have been made so far. The downslope component of splash, on the other hand, has been studied more intensively (Hudson, 1971), but this has more to do with slope gradient than with rainfall direction. Little is known about the physical impact of raindrops on a soil in situations where this impact is not vertical. It is also not known whether inclined raindrops have stronger erosivity effects than vertical ones. None of the existing soil loss and runoff models include a rainfall inclination parameter as input value. Finally, little is known on the effective amounts of rainfall on slopes.

Based on a field survey of erosion damages in the Simen mountains in Northern Ethiopia (13° 16' N, 38° 06' E), this problem was taken up in 1975, and some measurements initiated in the following year in view of verifying a simple model. The results, however, do not allow significant statements at this stage. This is partly due to measurement problems, but may also have to be attributed to the simplicity of the model used. This paper is intended to present the methods used and the results obtained, and to stimulate more tests and experiments in this field of research.

FIELD EVIDENCE

Detailed mapping and subsequent analysis of soil erosion damages in the 30 km^2 Jinbar valley in Simen showed significant differences between eastern and western facing slopes (Hurni, 1975). These differences could not be attributed to topography, geomorphology, or soil parameters, and could also not simply be explained by different periods of intensive crop cultivation on the damaged slopes. The dominant soil type in the valley are Andosols of originally great uniformity, derived from volcanic ash deposits (Frei, 1978). Using about 500 soil depth samples on undisturbed Andosols in the eastern, uncultivated part of the valley, and comparing them with about 300 soil depth samples in the western, cultivated and damaged part, it was possible to quantify the differences of soil loss due to different degrees of damage between the two major exposures (Hurni, 1979, cf. Table 1).

Table 1 Total soil loss in t/ha (cm soil depth) since the inception of agriculture in the Jinbar valley, Simen, Ethiopia. The assessment was made in 1979 based on a field survey of 1974

Location in valley (age of cultivation)	Slope exposure E-facing	W-facing
Old cultivation, North of main river, (several centuries)	2,000 (16.0 cm)	800 (6.4 cm)
Recent cultivation, South of main river, (1-2 centuries)	1,100 (8.8 cm)	600 (4.8 cm)

Observations during the rainy seasons of 1974 and 1975 of rainfall directions showed very regular rainfall patterns with storms dominantly originating from east-northeastern directions. This led to the hypothesis that rainfall direction may be primarily responsible for the observed differences. A simple set-up of four inclined daily raingauges was used during the 1976 rainy season to prove the observed general rainfall direction pattern (Table 2). Methods for rainfall direction measurement and analysis are described in Section 4.

Table 2 shows that the dominant rainfall directions are E to NW which bring adjective storms to the Simen mountains. 94% of the rainfall and 96% of the respective erosivity originated from these compass directions. Note the difference in percentage between rainfall and erosivity for the eastern compass direction as compared to the NE-N-NW directions. Storms originating from eastern directions obviously have stronger erosivities than the ones from northerly directions. Obviously, there seems to be a strong, although maybe not direct correlation between the field evidence results presented in Tables 1 and 2, implying that slopes facing towards major storm directions are more damaged than slopes on the leeward side of the storms. Not yet presented are the rainfall inclinations of the storms, an additional factor to include for a more detailed analysis.

Table 2 Amounts and percentage of rainfall and erosivity (metric R; Wischmeier and Smith, 1978) according to compass directions from where the storms originated. Gich Camp climatic station, 3,600 m asl; May - November 1976.

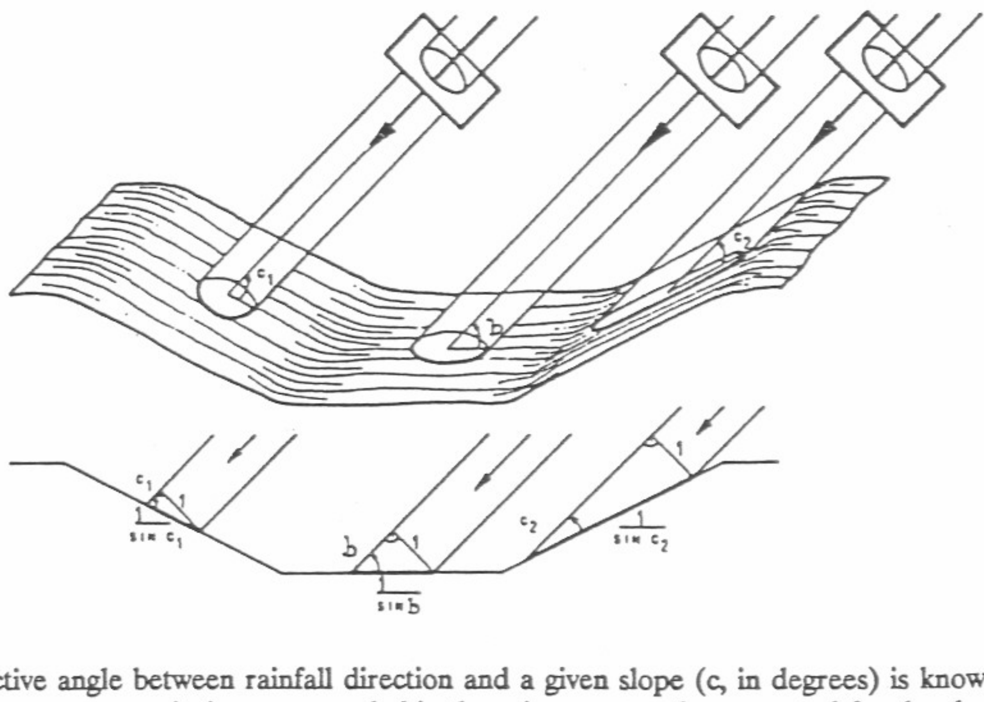
Compass direction	Rainfall (mm)	(%)	Erosivity (metric R)	(%)
W	12.3	1	3.12	1
SW	26.9	2	4.12	1
S	51.5	4	7.28	2
SE	-	-	-	-
E	268.1	20	163.47	34
NE	607.7	45	216.32	45
N	202.1	15	54.98	11
NW	189.8	14	29.26	6
Total	1,358.4	101	478.55	100

A SIMPLE THEORETICAL MODEL

Based on the field observations in Simen, rainfall direction may be brought in direct relationship to soil loss and runoff for differently exposed slopes. The model developed here is based on the assumption that rainfall direction basically affects storm erosivity. According to

Wischmeier and Smith (1978), erosivity is primarily a function of rainfall amounts falling in variable time units (intensities), used as input values to derive rainfall energy and maximum 30 minute intensity. The erosivity values obtained this way can be linearly correlated to soil loss from a continuous fallow plot of standard size. Amounts of rain, however, are assumed to fall on a certain area unit, i.e. the cylinder of the raingauge. If the rain is inclined, this unit area becomes variable and affects the rainfall amounts. Figure 1 shows uniform rain falling on slopes exposed in different compass directions. Similar quantities of rain falling on slopes on the leeward side of a valley obviously cover larger areas than on slopes exposed towards the rain. Hence, intensities will be less on the former than on the latter, because in the former case, less rainfall is received on a unit ground area of equal size.

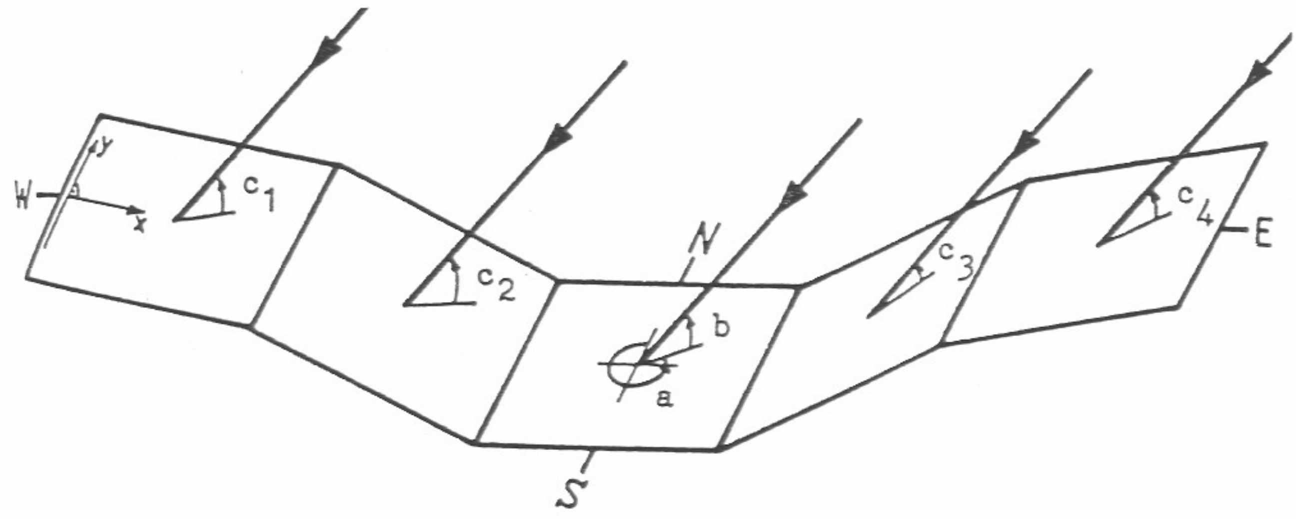
Figure 1 Rainfall direction and its relationship to slope exposure. A mathematical relationship is given below to describe the three situations and the modification factors used to correct amounts per time and area unit (intensities per slope)



If the respective angle between rainfall direction and a given slope (c, in degrees) is known, the rainfall amount per unit time as recorded in the raingauge can be corrected for the slope (see Formula 2 below). Rainfall amount and intensity, as a consequence, will be variable according to rainfall direction and slope exposure. Hence, erosivity will also be dependent on these two variables. The model can be validated by correlating soil loss and runoff with the adjusted values for rainfall amount and erosivity for a given testplot. Correlations should be significantly better than for non-adjusted erosivities and rainfall amounts, if rainfall direction is to be included in erosion models.

Practically, it will be necessary to measure the average rainfall compass direction a (in degrees) and inclination b (in degrees) for level ground, i.e. in the vicinity of the raingauge (Figure 2 and Section 4). With these two values measured per storm, the angle of rainfall direction, c, on any given slope, which itself is defined as inclination x (abscissa, in degrees) and compass direction y (ordinate, in degrees), can be expressed with the following trigonometric formula (or alternatively, with vector calculation) for each storm and that slope:

Figure 2 Rainfall direction (given with a; b on a level area; and respective rainfall direction (c_1, ..., c_4) for any given slope



$$c = \arcsin \frac{(\cos b \cos a \sin y \, tg \, x) - (\cos b \sin a \cos y \, tg \, x) + \sin b}{(\cos^2 b \cos^2 a + \cos^2 b \sin^2 a + \sin^2 b)^{0.5} \, (Sin^2 y \, tg^2 x + \cos^2 y \, tg^2 x + 1)^{0.5}} \qquad (1)$$

where:

c = Angle between rainfall direction and slope (in degrees)

a = Compass direction of rainfall (in degrees, e.g. N = 0°, W =9 0°, S = 180°, E = 270°)

b = Inclination of rainfall on level ground (in degrees, e.g. 90° is vertical, 0° is horizontal rainfall)

x = Slope gradient (orientation as abscissa, downslope direction, in degrees)

y = Compass direction of slope contour (orientation as ordinate, in degrees, same orientation as rainfall direction)

As a consequence, true rainfall amounts, P_t (in cm height), can be calculated for any given period measured with amounts measured in a rainfall recorder, P_p (in cm height), with the formula:

$$P_t = \frac{\sin c}{\sin b} \, . \, P_p \qquad (2)$$

where:

P_t = True amount of rain falling on a given slope (in cm)

P_p = Amount of rainfall measured with a pluviometer (in cm)

b,c = As above

Hence, rainfall amounts per any time unit (such as for uniform intensity classes in erosivity calculations) can be adjusted with Formulas 1 and 2 for any given slope for which the compass direction is defined by x and y, if a and b are known. The same applies for I_{30} adjustments. A storm example is given below for non-adjusted and adjusted erosivity calculations.

Example 1Conventional erosivity calculation

Time (Min)	Rainfall (in cm) Pp	Intensity (cm/h) I'	Energy per unit rain, Y'[1]	Total Energy of interval, E'[2]
65	0.25	0.23	150.5	37.6
45	2.8	3.73	255.7	716.0
55	0.4	0.44	175.0	70.0

Sum E:	I_{30}	Erosivity R:
823.6	3.7	30.5 [3]

1 Formula $Y' = 206 + 87 \log I'$ (Joules m^{-2} cm^{-1})

2 Formula $E' = Pp\ Y'$ (Wischmeier and Smith, 1978)

3 Formula $R = E\ I_{30}\ 10^{-2}$

Example 2 Erosivity calculation with rainfall direction adjusted (samestorm)

Assuming $a = 270^{\circ}$ (rainfall from E)
$b = 75^{\circ}$ (rainfall inclination)
$x = 18^{\circ}$ (slope inclination)
$y = 225^{\circ}$ (SE exposed slope)

With Formula 1:
$c = 60^{\circ}$ (rainfall inclination on slope)

With Formula 2:
$P_t = 0.89\ Pp$

Time (Min)	Rainfall (in cm) P_t	Intensity (cm/h) I_t'	Energy per unit rain, $Y_t'^{1}$	Total Energy of interval, $E_t'^{2}$
65	0.22	0.20	145.2	39.1
45	2.49	3.32	251.3	625.7
55	0.36	0.39	170.4	61.3

Sum E_t:	I_{30t}:	Erosivity R_t:
718.9	3.3	23.7

As is seen from examples 1 and 2, storm erosivities may considerably change if rainfall direction and slope exposure are included in calculation.

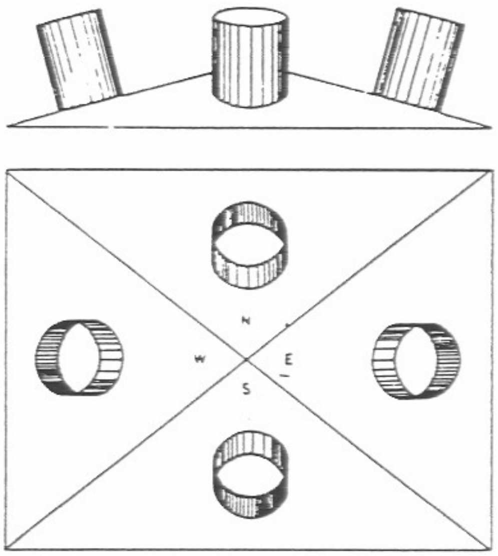
Obviously, there are many other parameters not included in this simple model, such as the impact of the raindrops varying according to the inclination of the impact; turbulence of storm winds; changing rainfall directions during the storm; and as for the USLE, variable soil parameters dependent on erosivity (moisture, aggregation, etc.).

METHODS TO MEASURE RAINFALL DIRECTION SOIL LOSS AND RUNOFF

Rainfall Inclinometer

Based on the field observations and qualitative analyses in Simen, it was tried to install a simple measuring device to validate the model. Rainfall direction was measured using four tins inclined towards the four main compass directions N, E, S, W (Figure 3).

Figure 3 Cross-section and top view of a simple rainfall inclinometer



Rainfall amounts are measured daily from the four inclined tins (in milliliter) as well as recorded with the automatic recorder for erosivity calculations. The mean weighed rainfall direction could be calculated from the four amounts in the tins (N, E, S, W) using the formula following below:

(1) $$a^* = \text{arc tg} \left\{ \left[\frac{(E - W)}{(E + W)} : \left[\frac{(S - N)}{(S + N)} + 0.00001 \right] \right] \right\}$$

(2) $$P_p = \frac{N + E + S + W}{3.14 \ d^2 \ \cos e}$$

(3) If $f = \left(\frac{S - N}{S + N} + 0.0001 \right) >= 0$ Yes : Go to (4)
No : Go to (5)

(4) If $g = \frac{E - W}{E + W} >= 0$ Yes : $a = 180^o + a^*$
No : $a = 180^o - a^*$

(5) If $\frac{E - W}{E + W} >= 0$ Yes : $a = 360^o - a^*$
No : $a = a^*$

(6) $$b = \text{arc tg} \left(\text{tg } e : (f^2 + g^2)^{0.5} \right)$$

where :

P_P = Rainfall measured in a normal recorder

N = Rainfall in northern exposed gauge (in ml)

E = Rainfall in eastern exposed gauge (in ml)

S = Rainfall in southern exposed gauge (in ml)

W = Rainfall in western exposed gauge (in ml)

a^* = Intermediate compass direction angle (in °)

a = Final compass direction angle (in °; N=0°, W=90°, S=180°, E=270°)

b = Final rainfall inclination (in °)

d = Diameter of inclinometer tins (in cm)

e = Inclination of inclinometer tins (in °)

Microplot Soil Loss and Runoff Assessment

During the rainy season 1976, six microplots were installed in a small valley near Gich Camp. Their local setup is given in Figure 4. They had two different slope gradients of 18% (10°) and 47% (25°), and were exposed towards east (Microplots A1 and A2) and west (A3 and A4). Four had a continuous fallow treatment and two were covered with vegetation (natural grass).

Figure 4 Illustrative view of a rainfall inclinometer consisting of four tins inclined towords the four major compass directions, with a rainfall recorder in front. Abbo Ager, Wello region, Ethiopia. H. Hurni, October 1987

Figure 5 Local setup of microplots at Gich Camp, 3,600 m asl, Simen Ethiopia, for the 1976 rainy season. Shaded: Continuous fallow treaments

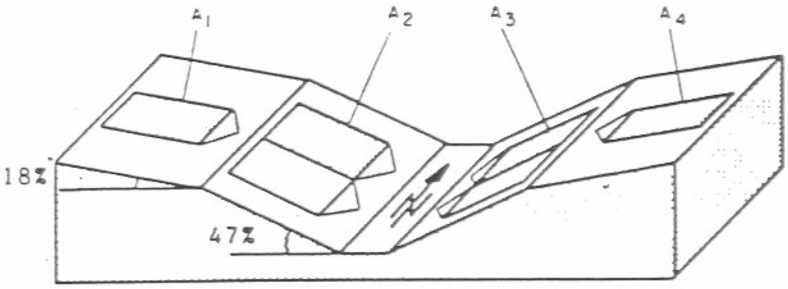
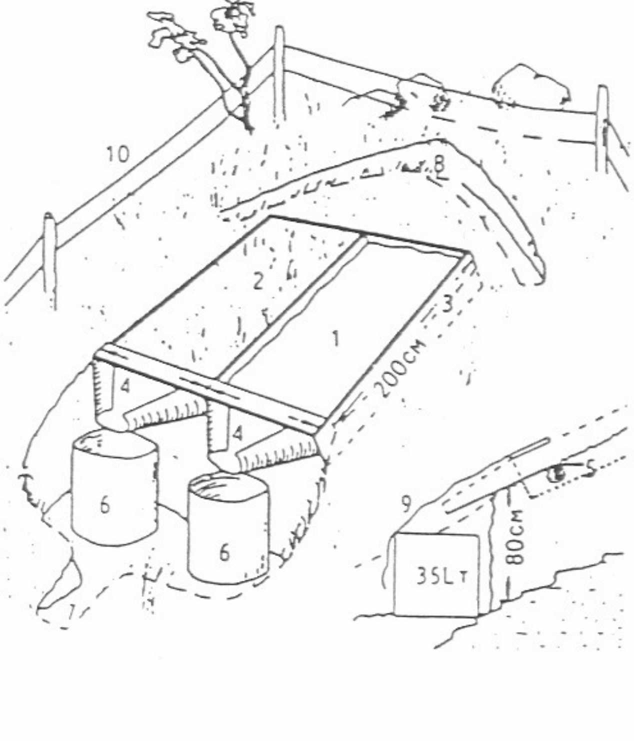


Figure 6 gives specifications for A2 microplots (47% gradients). Here, twin plots were used, one being covered with natural grass and one in continuous fallow. During the measuring process a number of problems occurred, both due to the design and the measuring methods of the plots. For example, the collection tanks were clearly underdesigned, just allowing for smaller storm runoff measurement. Soil loss was assessed with 1 liter samples only, whereby the solution of sediment and runoff was thoroughly mixed and the sample taken immediately thereafter. This resulted in rather large inaccuracies in data sampling, hampering the analysis considerably. However, due to logistic problems (the station being 50 km from motorable roads), no changes could be made during the measuring period.

Figure 6 Twin mocroplots at Gich Camp, Simen. 1: Continuous fallow plot 1 m by 2 m; 2: natural grass plot; 3: wooden border; 4: collection funnel; 5: immersion of funnel into ground; 6: collection tanks (35 lt capacity); 7: outlet ditch; 8: protection drain; 9: plastic cover of funnel and tanks; 10: protection fence



VALIDATION OF MODEL

Erosivity adjustments should only be made if the correlation between erosivity and soil loss measurements from continuous fallow plots significantly improves. This was not the case with the data used in this study. Tables 3-6 below show correlation coefficients between rainfall amount, I_{30}, erosivity on one hand, and soil loss and runoff on the other hand. The first parameters were then adjusted according to the procedures outlined in Sections 3 and 4 using rainfall inclinations measured on storm basis, and correlations made again (see index $_t$ in Tables).

Table 3 Coefficient matrix of linear correlations for rainfall, erosivity and 30-minute intensity for microplot A1 in Simen, Ethiopia, May-October 1976 (40 storms measured)

N=40	P_P	I_{30}	R	P_t	I_{30t}	R_t
Runoff	0.305	-.002	0.047	0.308	0.004	0.049
Soil loss	0.293	0.611	0.504	0.311	0.628	0.516

Table 4 Coefficient matrix of linear correlations for rainfall, erosivity and 30-minute intensity for the continuous fallow microplot A2 in Simen, Ethiopia, May-October 1976 (47 storms measured)

N=47	P_P	I_{30}	R	P_t	I_{30t}	R_t
Runoff	0.557	0.327	0.374	0.558	0.336	0.378
Soil loss	0.423	0.824	0.851	0.455	0.829	0.866

Table 5 Coefficient matrix of linear correlations for rainfall, erosivity and 30-minute intensity for the continuouss fallow microplot A3 in Simen, Ethiopia, May-October 1976 (47 storms measured)

N=47	P_p	I_{30}	R	P_t	$I_{30}t$	R_t
Runoff	0.547	0.340	0.388	0.534	0.334	0.391
Soil loss	0.298	0.450	0.365	0.252	0.389	0.331

Table 6 Coefficient matrix of linear correlations for rainfall, erosivity and 30-minute intensity for microplot A4 in Simen, Ethiopia, May-October 1976 (40 storms measured)

N=40	P_p	I_{30}	R	P_t	I_{30t}	R_t
Runoff	0.566	0.709	0.804	0.558	0.711	0.804
Soil loss	0.480	0.749	0.864	0.470	0.753	0.864

As is seen from Tables 3-6, there are none to slight increases in coefficients between normally recorded rainfall inputs and rainfall inputs where inclination was adjusted. Microplot A3 even showed slightly decreasing coefficients. All differences, however, are insignificant. Generally, the coefficients are low, indicating inaccuracies in measurements and high erodibility variations.

CONCLUSION

Although no clear improvements in correlations between soil loss and erosivity were observed when rainfall inclination was included for erosivity calculations in Simen (Ethiopia), the approach described in the paper should be tested further with more data available. At present, about 500 more storm data on continuous fallow plots are being prepared by the Soil Conservation Research Project in Ethiopia for a more detailed analysis following the procedures described in this paper. The measuring device for assessing rainfall storm direction as well as for including slope exposure for the calculation of true rainfall amounts for a given area is presented here to stimulate further research on the topic, and to include such data in climatic data monitoring.

REFERENCES

Ferreira, M.M., Russell Ferreira, A.J., and Sims, D.A., 1985: New orientation and erosivity factor added to the USLE makes sense in Portugal. IV ISCO Conference, Venezuela.

Frei, E., 1978: Andepts in some high mountains of east Africa. Geoderma 21: 119-131

Hudson, N., 1971: Soil Conservation. Ithaka-New York, 320 p.

Hurni, H., 1975: Bodenerosion in Semien-Aethiopien (mit Karte 1:25,000). Geographica Helvetica (Heft 4, 157-168)

Hurni, H., 1979: Semien - Aethiopien: Methoden zur Erfassung der Bodenerosion. Geomethodica 4, Veroff. 4 BGC (151-182)

Lal, R., 1977: Analysis of factors affecting rainfall erosivity and soil erodibility. Soil Conservation and Management in the Humid Tropics, Wiley, Chichester: 49-56

Wischmeier, W.H., and Smith, D.D., 1978: Predicting rainfall erosion losses - a guide to conservation planning. U.S. Department of Agriculture, Agriculture Handbook No. 537.