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IIASA Collaborative Paper
November 1982

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STABILITY OF AGRICULTURAL ECOSYSTEMS: VALIDATION OF A SIMPLE MODEL FOR SOIL EROSION ASSESSMENT

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November 1982
CP-82-76

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PREFACE

Beginning in 1982, IIASA's "Land and Landcover Resources" task within the Resources and Environment Area (REN) initiated the investigation of the problem "Stability of Ecosystems". Four main topics were developed:

1. Methodological problems of estimating the stability of the ecosystems;
2. Regional stability of landscapes and the ecological optimization of landscape use;
3. Stability of agroecosystems;
4. Stability of water ecosystems as a result of the environmental consequences of land use which influence the quality of a water system.

The research institutes of Bulgaria, Canada, Czechoslovakia, England, Hungary, USA and USSR collaborated in this field of research. The investigation of the problem of agroecosystems stability was done in cooperation with the English researchers from the National College of Agricultural Engineering (Silsoe, Bedford). They suggested a model for assessing the stability of soil erosion component of an agricultural ecosystem. This model was implemented at IIASA in 1982 and the documentation of this model was described in IIASA's Collaborative Paper (CP-82-59). Using this model, the stability of agroecosystems for 67 sites in 12 countries was investigated later on as a consequence of the different management agricultural policies for a range of soil and crop conditions. The analysis of these investigations is given in this paper.

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ACKNOWLEDGEMENTS

Mr. D.D.V. Morgan (National College of Agricultural Engineering) contributed many ideas in discussion on the development and testing of this model and commented on a draft of this paper.

ABSTRACT

Validation trials of the model described by Morgan, Morgan and Finney (1982) for assessing the stability of the soil erosion component of an agricultural ecosystem were carried out using data from published studies of soil loss for 67 sites in 12 countries. Correlation coefficients of 0.74 and 0.58 were obtained between predicted and observed values of runoff at 56 sites and soil loss at 67 sites respectively. If two poor predictions of very high erosion rates in China are omitted, the value of the correlation coefficient for soil loss rises to 0.67 and the slope of the reduced major axis regression line is not significantly different from unity. The success of the model was also evaluated against the criteria that it should predict whether or not there was likely to be an erosion problem and if there was, that it should predict the magnitude of the problem. Against these criteria, the model was successful on 59 per cent of the tests for runoff and 70 per cent of the tests for soil loss. Considering only those sites for which high quality input data were available, the success rate for soil loss rose to 90 per cent. Guidelines are presented for the selection of parameter values for rainfall intensity, weathering rates, soil renewal rates and rooting depth.

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STABILITY OF AGRICULTURAL ECOSYSTEMS: VALIDATION OF A SIMPLE MODEL FOR SOIL EROSION ASSESSMENT.

R.P.C. Morgan and Hilary J. Finney

INTRODUCTION

Within the context of the research programme on the stability of ecosystems being carried out at the International Institute for Applied Systems Analysis by the Resources and Environment Section, a simple model has been developed for a reconnaissance or initial assessment of the stability of the soil erosion system as expressed in terms of changes in soil depth through time. A previous paper (Morgan, Morgan and Finney, 1982) has presented documentation of the model dealing with its basic format, governing equations, selection of input parameter values, output files and a listing of the computer program. Only limited validation of the model has been published so far covering sites in the United Kingdom (Morgan, Morgan and Finney, 1982) and Malaysia (Morgan, Hatch and Sulaiman, 1982). This paper presents the results of a more extensive evaluation in which runoff volumes and soil loss rates predicted by the model are compared with measured data from hillslope erosion plots in Tanzania (Staples, 1936; Mitchell, 1965; Temple, 1972; Lundgren, 1980), Ivory Coast (Roose, 1977), Senegal (Roose, 1967), Thailand (Kraayenhagen, Watnaprateep and Nakasthien, 1981; Sheng, Jackson, Kraayenhagen, Nakasthien and Watnaprateep, 1981), Italy (Caroni and Tropeano, 1981), Belgium (Bolline, 1978), Federal Republic of Germany (Richter and Negendank, 1977), Taiwan (Liao, 1981), Zimbabwe (Hudson and Jackson, 1959) and China (Gong and Jiang, 1977; Mou and Meng, 1980). Because of the simplicity of the model a relatively simple system is presented to assess the goodness of fit of the predicted values. Further comments are also made on the selection of input parameter values.

TEST SITES

Sites were selected from published journal articles, reports and monographs describing measurements of erosion made on hillslopes using erosion plots. The publications had to contain information on annual rates of soil loss, slope steepness, land use, crop management practices including any soil conservation measures, soil texture and location. Ideally, data on annual rainfall and runoff volumes, the physical properties of the surface soil and a description of the soil profile are needed to operate the model. Where details of the annual rainfall and the number of rain days were not provided, data for the nearest climatic station were taken from Müller (1979). In these instances which make up the majority of the test sites, it was only possible to use mean annual data. This means that the model is then predicting a mean annual erosion response to mean rainfall inputs. When assessing the validity of the model it should be remembered that the mean annual prediction may not conform to the measured value for a given year because the rainfall inputs for that year may be higher or lower than the mean rainfall values. A further problem is that the climatic conditions of the nearest climatic station listed in Müller (1979) may differ from those of the test site. An example is Lyamungu, Tanzania, where a value of 1660 mm is obtained for the mean annual rainfall from the work of Mitchell (1965) but no information is available on the number of rain days. The nearest climatic station listed in Müller (1979) is Tabora where the mean annual values are only 892mm for the rainfall and 99 for the number of rain days. The ratio of the two rainfall totals was applied as an arbitrary adjustment factor to the number of rain days at Tabora to provide an estimate of the number of rain days at Lyamungu. A similar adjustment was also used to estimate the number of rain days at Tuanshangou, China, where the climatic station taken from Müller (1979) is Taiyuan which has mean values of 396 mm for the annual rainfall and 55 for the number of rain days. The mean annual rainfall at the test site is 500 mm.

It was frequently necessary to make judgements, using the guidelines given in Morgan, Morgan and Finney (1982), on the values for the moisture storage at field capacity, the bulk density and the rooting depth of the soil. Details of these were rarely available in the sources consulted.

The need to use rainfall and soil data which may differ from those of the test sites means that good predictions of runoff and erosion may not be obtained because the model is sensitive to a 1 per cent change in the values of these parameters (Morgan, Morgan and Finney, 1982). Because of this the test sites are classified into two groups: those for which high quality information is available and those where the quality of the information is only moderate.

INPUT FILES

Input files were prepared to the format presented in Table 1. The files for the sites with high quality data are shown in Table 2 and those for the sites with moderate quality data in Table 3.

Table 1 Input File

CARDS 1-3: Title cards up to 60 characters each

CARD 4: MS, BD, RD, SD, K, W, RN, SLP, NY

CARDS 5-n: YEAR, RAIN, RDAY, INTENS, INCEP, ETEO, CFAC

(a separate card is required for each year of simulation for the input parameters on card 5)

All data are read in fields of six columns. NY, YEAR, RAIN and RDAY must be in integer form (I6), the other parameters are in floating point form.

MS	Soil moisture content at field capacity (% w/w)
BD	Bulk density of top soil layer (Mg/m^3)
RD	Rooting depth (m)
SD	Total soil depth (m)
K	Soil detachability index (g/J/m^2)
W	Weathering rate (mm/y)
RN	Top soil renewal rate (mm/y)
SLP	Sine of slope angle
NY	Number of years of simulation
YEAR	Year of simulation
RAIN	Annual rainfall total (mm)
RDAY	Number of rain days in the year
INTENS	Typical intensity of erosive rain (mm/h)
INCEP	Percentage rainfall contributing to permanent interception and stem flow
ETEO	Ratio of actual to potential evapotranspiration
CFAC	Crop management factor (CP factors of the Universal Soil Loss Equation)

Table 2 Input files and predicted and measured rates of annual runoff and erosion for sites with high quality field data

Input file									Runoff (mm)		Soil loss (kg/m^2)	
									Observed	Predicted	Observed	Predicted
LUSHOTO, TANZANIA												
Clay Maize beans intercropping												
0.35	0.89	0.10	0.60	0.02	0.01	0.20	0.191	2				
1974	628	96	25.0	25.0	0.90	0.20			0.3- 1.0	6.85	0.0012-0.0013	0.0018
1975	643	112	25.0	25.0	0.90	0.20			0.2- 1.0	3.74	0.0005-0.0010	0.0005
Sandy clay loam gentle slope Evergreen forest ferns mosses												
0.37	0.95	0.15	0.60	0.35	0.01	0.20	0.208	2				
1974	971	115	25.0	23.0	0.90	0.004			2.6- 5.6	2.59	0.0006-0.0015	0.0000
1975	1261	135	25.0	21.0	0.90	0.004			4.2- 5.7	5.96	0.0012-0.0030	0.0000
Sandy clay loam steep slope Evergreen forest ferns mosses												
0.52	0.65	0.15	0.60	0.35	0.01	0.20	0.404	2				
1974	971	115	25.0	23.0	0.90	0.004			8.5-12.7	3.25	0.0013-0.0057	0.0000
1975	1261	135	25.0	21.0	0.90	0.004			10.4-14.8	7.31	0.0105-0.0129	0.0001
Clay steep slope Maize beans intercropping												
0.35	0.89	0.10	0.60	0.02	0.01	0.20	0.407	2				
1974	628	96	25.0	25.0	0.90	0.20			0.4- 0.8	6.85	0.0007-0.0013	0.0038
1975	643	112	25.0	25.0	0.90	0.20			0.4- 0.8	3.74	0.0008-0.0010	0.0011

Source: Lundgren (1980)

Table 2 continued

Input file	Runoff (mm)		Soil loss (kg/m^2)	
	Observed	Predicted	Observed	Predicted
ADIOPODOUME, IVORY COAST				
Sandy loam Secondary tropical forest				
0.40 0.99 0.15 1.00 0.30 0.01 0.20 0.233 1 0001 2144 116 25.0 25.0 1.00 0.002	15.0	85.9	0.001- 0.02	0.003
Sandy loam Bare ground				
0.28 1.55 0.10 1.00 0.30 0.01 0.01 0.070 1 0001 2144 116 25.0 0.00 0.05 1.00	707-1415	1268.1	6.9- 15.0	15.5 (DET)
Sandy loam Oil palm				
0.28 1.45 0.15 1.00 0.30 0.01 0.20 0.070 1 0001 2144 116 25.0 30.0 1.20 0.10	43-172	57.8	0.001- 0.05	0.02
Sandy loam Banana with mulch				
0.28 1.45 0.15 1.00 0.30 0.01 0.20 0.070 1 0001 2144 116 25.0 50.0 0.85 0.002	11-86	102.4	0.004-0.005	0.002
Sandy loam Maize				
0.28 1.45 0.10 1.00 0.30 0.01 0.15 0.070 1 0001 2144 116 25.0 25.0 0.67 0.40	643-1608	355.0	3.5- 13.1	3.53
Sandy loam Groundnut				
0.28 1.45 0.10 1.00 0.30 0.01 0.15 0.070 1 0001 2144 116 25.0 25.0 0.50 0.50	579-1565	452.7	5.9- 12.0	7.17

Source: Roose (1977) DET=Detachment-limited erosion rate. Value for MS under secondary tropical forest is an estimate for a soil of a bulk density of 0.99 Mg/m^3. RAIN, RDAY from Müller (1979)for Abidjan.

Table 3 Input files, predicted and measured rates of annual runoff and erosion for sites with moderate quality field data

Input file	Runoff (mm)		Soil loss (kg/m^2)	
	Observed	Predicted	Observed	Predicted
SEFA, SENEGAL Loam soil Secondary tropical forest				
0.28 1.20 0.15 1.00 0.30 0.01 0.20 0.020 1 0001 1626 80 25.0 25.0 0.90 0.002	1.6-19.2	154.8	0.002-0.02	0.0009
Loam soil Groundnut				
0.28 1.20 0.10 1.00 0.30 0.01 0.15 0.020 1 0001 1626 80 25.0 25.0 0.80 0.50	130-699	370.8	0.29-1.63	1.38
Loam soil Cotton				
0.28 1.20 0.10 1.00 0.30 0.01 0.15 0.020 1 0001 1626 80 25.0 15.0 0.65 0.50	15-699	429.0	0.05-1.85	1.84
Loam soil Maize with mechanization				
0.28 1.20 0.10 1.00 0.30 0.01 0.15 0.020 1 0001 1626 80 25.0 25.0 0.67 0.20	504	420.3	1.03	0.71
Loam soil Sorghum				
0.28 1.20 0.10 1.00 0.30 0.01 0.15 0.020 1 0001 1626 80 25.0 25.0 0.62 0.40	390-683	442.5	0.33-1.24	1.57

Source: Roose (1967) RAIN, RDAY from Müller (1979) for Ziguinchor.

Table 3 continued

Input file	Runoff (mm) Observed	Runoff (mm) Predicted	Soil loss (kg/m^2) Observed	Soil loss (kg/m^2) Predicted
PONG KHRAI, THAILAND Clay Loam Upland Rice				
0.40 1.30 0.10 1.00 0.40 0.02 0.15 0.300 1 0001 1217 108 25.0 30.0 0.60 0.20	22-32	34.4	1.40-2.40	0.07
Clay Loam Upland rice bench terraces				
0.40 1.30 0.10 1.00 0.40 0.02 0.15 0.300 1 0001 1217 108 25.0 30.0 0.60 0.03	16-53	34.4	1.1-1.3	0.011
Sources: Kraayenhagen, Watnaprateep and Nakasthien (1981); Sheng, Jackson, Kraayenhagen, Nakasthien and Watnaprateep (1981). RAIN, RDAY from Müller (1979) for Chiangmai.				
MARCHIAZZA BASIN, ITALY Loamy sand Bare soil tufted grass				
0.23 1.30 0.10 1.00 0.25 0.02 0.22 0.310 1 0001 843 85 23.0 1.00 0.25 0.30	201-261	186.7	2.7-3.1	3.25
Loamy soil Dense Molinia moor grass				
0.23 1.30 0.10 1.00 0.25 0.02 0.22 0.190 1 0001 843 85 23.0 25.0 0.80 0.01	51-58	56.9	0.05-0.09	0.0062
Loamy soil Chestnut and oak trees, ferns				
0.23 1.30 0.10 1.00 0.25 0.02 0.22 0.310 1 0001 843 85 23.0 20.0 0.90 0.002	36-38	48.3	0.009-0.018	0.0014

Source: Caroni and Tropeano (1981). RAIN, RDAY from Müller (1979) for Parma.

Table 3 continued

Input file	Runoff (mm) Observed	Runoff (mm) Predicted	Soil Loss (kg/m^2) Observed	Soil Loss (kg/m^2) Predicted
HESBAYE, BELGIUM Sand derived from loess Sugar beet				
0.08 1.50 0.10 10.00 0.7 0.01 0.15 0.110 1 0001 817 206 11.0 20.0 0.74 0.25	n/a	60.7	0.13-2.95	0.10
Sand derived from loess Winter wheat				
0.08 1.50 0.10 10.00 0.7 0.01 0.15 0.110 1 0001 817 206 11.0 43.0 0.60 0.15	n/a	78.6	0.045-0.10	0.10
Sand derived from loess Bare soil				
0.08 1.50 0.10 10.00 0.7 0.01 0.15 0.110 1 0001 817 206 11.0 0.0 0.05 1.00	n/a	415.6	0.6-8.25	12.01 (DET)

Source: Bolline (1978) RAIN, RDAY from Müller (1979) for Brussels (Uccle)
DET = Detachment-limited erosion rate

Input file	Runoff (mm) Observed	Runoff (mm) Predicted	Soil Loss (kg/m^2) Observed	Soil Loss (kg/m^2) Predicted
TRIER, FEDERAL REPUBLIC OF GERMANY Sandy loam Vines				
0.28 1.20 0.10 1.00 0.3 0.01 0.15 0.342 1 0001 719 163 11.0 15.0 0.40 0.60	n/a	5.8	0.0027-0.0044	0.0046

Source: Richter and Negendank (1977). RAIN, RDAY from Müller (1979) for Trier.

Table 3 continued

Input File	Runoff (mm)		Soil Loss (kg/m^2)	
	Observed	Predicted	Observed	Predicted
TAIWAN				
Clay loam				
Citrus clean cultivation				
0.40 1.30 0.05 1.00 0.4 0.01 0.15 0.280 1 0001 1812 108 20.0 10.0 0.54 0.30	1268	580.2	15.64	10.25 (DET)
Clay loam				
Citrus bench terracing				
0.40 1.30 0.05 1.00 0.4 0.01 0.15 0.280 1 0001 1812 108 20.0 10.0 0.54 0.05	344	580.2	0.50	4.71
Clay loam				
Citrus with grass and mulch				
0.40 1.30 0.05 1.00 0.4 0.01 0.20 0.280 1 0001 1812 108 20.0 50.0 0.85 0.003	109	517.9	0.094-0.28	0.22
Clay loam				
Banana clean cultivation				
0.40 1.30 0.05 1.00 0.4 0.01 0.15 0.230 1 0001 2100 188 20.0 20.0 0.75 0.30	1113-1449	279.7	3.94-6.37	5.40
Clay loam				
Banana with mulch				
0.40 1.30 0.05 1.00 0.4 0.01 0.20 0.230 1 0001 2100 188 20.0 50.0 0.85 0.003	189	245.6	0.009	0.042
Clay loam				
Banana with contour bunds				
0.40 1.30 0.05 1.00 0.4 0.01 0.15 0.230 1 0001 2100 188 20.0 20.0 0.75 0.03	483-1029	279.7	0.11-0.39	0.54

Source: Liao (1981) RAIN, RDAY from Müller (1979) for Tainan (citrus sites) and Taipeh (banana sites).
DET = Detachment-limited erosion rate.

Table 3 continued

Input file	Runoff (mm)		Soil loss (kg/m^2)	
	Observed	Predicted	Observed	Predicted
HENDERSON, ZIMBABWE Clay Good maize crop				
0.45 1.10 0.10 1.00 0.02 0.01 0.15 0.044 1 0001 868 73 25.0 25.0 0.70 0.40	8- 61	26.7	0.2-0.3	0.013
Clay Cropped grass				
0.45 1.10 0.10 1.00 0.02 0.01 0.15 0.044 1 0001 868 73 25.0 40.0 0.85 0.008	8- 26	18.6	0.05-0.1	0.0000
Sources: Hudson and Jackson (1959); Temple (1972); Lundgren (1980). RAIN, RDAY from Müller (1979) for Harare				
MPWAPWA, TANZANIA Clay loam Bare soil				
0.40 1.30 0.10 1.00 0.40 0.01 0.01 0.061 1 0001 892 110 25.0 0.0 0.05 1.00	446	212.7	14.7	2.78
Clay loam Sorghum and millet				
0.40 1.30 0.10 1.00 0.40 0.01 0.15 0.061 1 0001 892 110 25.0 25.0 0.62 0.40	80-259	5.72	5.5-9.0	0.0007
Clay loam Tufted grass 50% cover				
0.40 1.30 0.10 1.00 0.40 0.01 0.15 0.061 1 0001 892 110 25.0 25.0 0.80 0.10	8-65	2.9	0-0.07	0.0000
Clay loam Savanna secondary growth				
0.40 1.30 0.10 1.00 0.40 0.01 0.20 0.061 1 0001 892 110 25.0 40.0 0.90 0.01	3-4	2.04	0.0	0.0000

Sources: Staples (1936); Temple (1972); Lundgren (1980). RAIN, RDAY from Müller (1979)for Morogoro.

Table 3 continued

Input file	Runoff (mm)		Soil Loss (kg/m^2)	
	Observed	Predicted	Observed	Predicted
LYAMUNGU, TANZANIA Clay loam Coffee clean cultivation				
0.40 1.30 0.10 1.00 0.40 0.01 0.15 0.165 1 0001 1660 184 25.0 20.0 0.50 0.30	15-232	28.18	4.3	0.04
Clay loam Coffee with cover crops				
0.40 1.30 0.10 1.00 0.40 0.01 0.20 0.165 1 0001 1660 184 25.0 25.0 0.80 0.10	10- 98	9.57	0.4	0.002
Clay loam Coffee with contour ridges				
0.40 1.30 0.10 1.00 0.40 0.01 0.15 0.165 1 0001 1660 184 25.0 20.0 0.50 0.03	36	28.18	0.3	0.004
Clay loam Coffee with cover crops and contour ridges				
0.40 1.30 0.10 1.00 0.40 0.01 0.20 0.165 1 0001 1660 184 25.0 25.0 0.80 0.01	27	9.57	0.1	0.0001

Sources: Mitchell (1965); Temple (1972); Lundgren (1980). RDAY value is estimated from the value for Tabora (Müller, 1979) with proportional adjustment for difference in rainfall totals between Tabora and Lyamungu.

Table 3 continued

Input file									Runoff (mm)		Soil loss (kg/m^2)	
									Observed	Predicted	Observed	Predicted
TUANSHANGOU, HUANG HE BASIN, CHINA												
Sand derived from loess												
Millet/mungbean, potato, millet/mungbean (2), alfalfa												
0.08	1.50	0.05	1.00	0.70	0.01	0.15	0.404	5				
0001	500	69	120.0	15.0	0.50	0.50			n/a	278.3	0.1	7.89 (DET)
0002	500	69	120.0	12.0	0.70	0.30			n/a	250.3	43.9	7.59 (DET)
0003	500	69	120.0	15.0	0.50	0.50			n/a	278.3	6.3	7.89 (DET)
0004	500	69	120.0	15.0	0.50	0.50			n/a	278.3	23.4	7.89 (DET)
0005	500	69	120.0	30.0	0.80	0.01			n/a	238.5	4.4	0.23
							Mean values		n/a		13.1	6.29

Sources: Gong and Jiang (1977); Mou and Meng (1980). RDAY value is estimated from the value for Taiyuan (Müller, 1979) with proportional adjustment for difference in rainfall totals between Taiyuan and Tuanshangou. DET = Detachment-limited erosion rate.

Table 4 Summary results of previous trials

Site			Runoff (mm)		Soil loss (kg/m^2)	
			Observed	Predicted	Observed	Predicted
MALAYSIA						
	Johor	Oil palm	263	294	0.77	0.29
			657	757	0.89	0.76
	Selangor	Bare soil	532-642	827	2.93-3.39	3.73
		Groundnut	273-328	273	0.64-1.01	1.04
		Maize	365-378	340	0.56-0.81	1.07
		Maize + mulch	73-80	298	0.04-0.06	0.06
		Bare soil	688-941	829	2.44-3.92	3.93
		Groundnut	241-388	266	0.51-0.97	0.99
		Cowpea	260-302	291	0.59-0.61	1.18
	Sarawak	Primary rain forest	n/a	181	0.004-0.024	0.027
Source: Morgan, Hatch and Sulaiman (1982)						
UNITED KINGDOM						
	Silsoe	Bare soil	66	341	3.9	8.0
	Silsoe	Grass	17	28	2.3	0.001
	Maulden	Woodland	9	2	0.001	0.00
	Pulloxhill	Spring barley	1	9	0.07	0.003
	Ashwell	Winter wheat	5	5	0.07	0.002
	Meppershall	Winter wheat, spring barley	6	5	0.05	0.001
	Woburn	Oats, wheat, beans	11	11	0.06	0.005
Source: Morgan, Morgan and Finney (1982)						

RESULTS

Predicted values of annual runoff and soil loss are given for each site (Tables 2 and 3) with the measured values for comparison. Results are also presented (Table 4) for previous trials with the model in Malaysia (Morgan, Hatch and Sulaiman, 1982) and the United Kingdom (Morgan, Morgan and Finney, 1982) where high quality data were available.

Generally the predicted values are closer to the measured values for runoff than for soil loss and the predictions are closer for the sites with high quality data than for those with moderate quality data. The soil loss predictions for Silsoe, United Kingdom, are an exception to this. Overall, the soil loss predictions are worst at very low rates of soil loss when they are often an order of magnitude out, as is the case for Silsoe, or at very high rates of soil loss, as at Tuanshuangou, China. Runoff predictions were often poor where mechanical soil conservation measures such as ridging and terracing were used as on the orchard sites in Taiwan and the coffee plantations at Lyamungu, Tanzania, or where mulching was adopted, as under banana in the Ivory Coast, citrus fruits in Taiwan, banana in Taiwan and maize in Malaysia. Under those conditions the model frequently, but not always, overpredicted. The model generally predicted erosion as being limited by the transport capacity of the runoff but where runoff rates were very high, erosion was detachment-limited. This occurred on bare soil in the Ivory Coast and Belgium, under clean-cultivated citrus in Taiwan and under cropped land in Tuanshuangou, China.

In devising a method for assessing the goodness of fit of the predictions it is important to keep in mind the objectives of using the model. These are to indicate whether or not the soil erosion system is stable under existing systems of agricultural production and, if the system is found to be unstable, to predict the degree of instability. Where instability is predicted the model can be used to determine guidelines for management to produce a stable erosion system but this aspect is beyond the scope of this paper.

In the analysis of the model predictions for Malaysia (Morgan, Hatch and Sulaiman, 1982), correlation and regression techniques were used to compare predicted and measured values of soil loss. Although there was a high value of the correlation coefficient ($r = 0.95$; $n = 26$) and the slope of the regression line was close to unity at 1.07, both desirable properties, this type of analysis is rather limiting because it gives equal weight to the differences between the predicted and observed values regardless of their magnitude whereas much greater differences may be acceptable in practice at very high and very low values of soil loss. If the objective is to determine whether the erosion system is stable and the system is stable and the model predicts this, accurate prediction of the rate of soil loss is of limited importance because the rate will be very low and there will be no erosion problem. If the erosion system is extremely unstable and erosion rates are catastrophic, it may be sufficient for the model to indicate the general condition without giving a close prediction of the actual rate of soil loss. More reasonable predictions are required for the range of conditions between erosion systems which are on the verge of becoming unstable and those where the level of instability could be reduced by the implementation of soil conservation measures.

With these points as background, the following criteria were established for assessing goodness of fit.

(a) An arbitrary value of 0.1 $kg/m^2/y$ was set as a threshold for soil loss. If the predicted and measured soil loss rates were both less than this value, the prediction was considered successful. It should be stressed that the value is rather conservative compared with the target of 1.1 $kg/m^2/y$ set by the United States Department of Agriculture as the maximum permissible rate of soil loss (McCormack and Young, 1981) and its selection should allow unstable conditions to be identified adequately even on very erodible soils. No threshold value was applied to the assessments of goodness of fit for the runoff predictions.

(b) For all runoff values and predicted or measured values of soil loss equal to or greater than 0.1 $kg/m^2/y$, the prediction was considered successful if the ratio of the predicted to either a single observed value or to the mid-point of a range of observed values was within the range of 0.5 to 2.0.

After rounding the predicted and observed values to two decimal places and applying the above criteria, the model was found to predict successfully runoff for 33 out of 56 test sites and soil loss for 47 out of 67 test sites, giving percentage success rates of 59 and 70 respectively. If only the sites with high quality input data are considered (Tables 2 and 4), the success rates are 57 and 90 per cent.

Despite the reservations expressed earlier, the validity of the model was also examined using correlation and regression analyses. Because of the likelihood of errors in the measured data as well as in the predicted values, regression lines were fitted to minimise dispersion about the reduced major axis (Kermack and Haldane, 1950; Till, 1973). The following relationships were obtained between predicted (Y) and observed (X) values:

$$Y = 19.776 + 0.755\,X \quad \text{for runoff, } r = 0.735,\ n = 56 \qquad (1)$$
$$Y = 0.427 + 0.503\,X \quad \text{for soil loss, } r = 0.583,\ n = 67 \qquad (2)$$

The lower value of the correlation coefficient (r) for soil loss is partly explained by the failure of the model to predict sufficiently closely two extremely high soil loss rates at Tuanshangou, China (Table 3). If these two cases with observed soil losses of 23.4 and 43.9 $kg/m^2/y$ are omitted, the relationship becomes:

$$Y = -0.090 + 0.896\,X \quad \text{for soil loss, } r = 0.671,\ n = 65 \qquad (3)$$

where the slope of the regression line is not significantly different from unity ($t = 1.112 < t_{0.05} = 2.00$).

From these results it is concluded that the model provides acceptable predictions of runoff and soil loss under most conditions for field-sized areas on hillslopes on an annual basis.

DISCUSSION

The need to obtain the best possible information on the more sensitive parameters, expecially the annual rainfall total (RAIN), the number of rain days (RDAY), the soil moisture storage at field capacity (MS), the bulk density of the soil (BD) and the rooting depth (RD) is emphasized by the improved performance of the model where good quality input data are available. This is illustrated by referring to the prediction for Lushoto, Tanzania, on the clay soil under intercropped maize and beans (Table 2). The bulk density of the soil as measured in the field is very low at 0.89 Mg/m^3 which, in terms of the model, results in a high soil moisture storage capacity and low rates of runoff and erosion. If the typical values of 0.45 and 1.1 had been used for the moisture content at field capacity and bulk density respectively (Table 4 in Morgan, Morgan and Finney, 1982), lower soil moisture storage capacity, higher runoff and higher erosion would have been predicted. The measured erosion rates are unusually low for a tropical agricultural site (Lundgren, 1980) and it is satisfying that the model is able to predict these.

The rainfall data must also be obtained from a recording station as close as possible to the study site. Where measured data were not available, the source of data being used (Müller, 1979) did not contain a sufficient density of recording stations in some countries to enable a representative station to be selected. The adjustment factor used to estimate the mean number of annual rain days for Lyamungu, Tanzania, seems to have worked reasonably well because satisfactory predictions of runoff were obtained. The cause of the poor soil loss predictions must be related to factors other than the rain day estimate. It was not possible to assess the effects of using the adjustment factor for Tuanshangou, China, because no runoff measurements were presented in the sources consulted (Gong and Jiang, 1977; Mou and Meng, 1980).

No field measurements were available for the rates of splash detachment, except for the sites in the United Kingdom and Belgium, so the detachment phase of the model could not be fully tested. The measured rates in these two countries are high at 2 to 37 kg/m^2/y on bare soils (Morgan, 1982; Bolline, 1978) and the model underestimates them by an order of magnitude. However, the model is predicting the rate over an area of 1 m^2 whereas the measured rates are based on target areas of 12 to 175 cm^2 and it is unlikely that they apply to an average figure over a larger area. The detachment phase of the model is only important when erosion is detachment-limited and this occurs only when runoff volumes are very high. In these cases the rate of detachment is either a satisfactory prediction of the measured soil loss or is a closer approximation to it than is the transport capacity of the runoff.

The rate of detachment is related to the value selected for a typical rainfall intensity. The model is not very sensitive to changes in the value of this parameter and so only approximations are needed. The experience of these validation trials indicates that values of 11.0 mm/h for temperate climates, 25.0 mm/h for tropical climates and 30 mm/h for strongly seasonal climates such as the Mediterranean are appropriate.

Where local information is available, however, it is helpful to use it in preference. For example, at Tuanshangou, China, as much as half of the annual rainfall can occur in one storm and intensities of 120 mm/h are common in such storms (Gong and Jiang, 1977). Using an intensity value of 120 mm/h produced better predictions of mean annual erosion rates than using a value of only 30 mm/h.

The poor runoff predictions obtained for sites where mulching, ridging or terracing are practised can be explained by the inability of the model to allow for surface depression storage. The model takes account of these practises in the erosion phase through the values selected for the crop management factor (CFAC) so that the soil loss predictions are often satisfactory when the runoff prediction is not.

The objective of the model is not simply to predict runoff and erosion but is to allow comparisons of the rates of erosion with rates of soil renewal over periods of 20 years or more in order to assess the stability of the erosion system. The success of the model therefore depends upon adequate characterization of the rates of weathering (W) and soil renewal (RN). Both rates are difficult to estimate and more research is required before they can be expressed with any precision. In preparing the data files for these validation trials, the values chosen for the weathering rates were based on measured rates of erosion under natural forest or grassland. These are very low and values of 0.01 or 0.02 mm/y are common. It is recommended that these values be used in future work with the model rather than the high value of 0.20 mm/y adopted in the previous trials of the model for sites in the United Kingdom (Morgan, Morgan and Finney, 1982)

The values for soil renewal rate were based on those listed in Table 5 in Morgan, Morgan and Finney (1982), selecting the value given there for the sites under forest or grassland or where crop residues are returned to the soil or organic matter is regularly applied. For most of the rooting depths pertaining to the test sites, a value of 0.20 mm/y was appropriate. This value was arbitrarily reduced to 0.15 mm/y for standard husbandry practices with the use of chemical fertilizers and to 0.10 mm/y for poor husbandry practices with little fertizer input. On the bare soil sites the soil renewal rate was set to equal the weathering rate, generally at 0.01 mm/y. A scale of values needs to be determined for the renewal rate which is related to the productivity of the agricultural system, perhaps expressed in terms of dry matter production, and the amount of crop residue returned to the soil.

A critical input parameter for both soil loss and runoff prediction is the rooting depth (RD). Experience from these validation trials indicates that it is easy to overestimate the value of this parameter which should be interpreted strictly as the depth at which the bulk of the root mat is found. Only rarely is it likely to exceed 1.0 m. Values of 0.10 m for cereals and vegetables and 0.15 m for tree crops such as rubber and oil palm appear to be generally appropriate. For very shallow sandy soils, low in organic matter, such as those derived from loess at Tuanshangou, China, a rooting depth of only 0.05 m was used because the extremely high rates of erosion measured there combined with the steep slope are indicative of a very shallow soil.

It is difficult to assess the success of this model in comparison with other models because similar analysis has not been carried out in respect of the CREAMS model (Knisel, 1980) or the Universal Soil Loss Equation (Wischmeier and Smith, 1978) for example. The validity of the CREAMS model has been tested for its component sub-models of hydrology, erosion and chemistry using only a few study sites and a descriptive interpretation of the results. The Universal Soil Loss Equation yields high correlations between predicted and observed erosion rates for the erosion plot data in the U.S.A. from which it was derived but it has received very limited testing with data from other countries. Neither model has been examined in relation to predetermined set of criteria. The criteria selected here for assessing the goodness of fit of the Morgan, Morgan and Finney (1982) model are those considered most relevant to an analysis of the stability of the erosion system. Against these criteria, the model's performance is extremely promising. Other users of the model should set their own criteria relevant to their own investigations and judge the model accordingly. In order to avoid applying the model in situations for which it was not designed, it should be stressed that it is intended to predict annual soil loss rates from field-sized areas on hillslopes where erosion results from raindrop impact, overland flow and rills. It is not intended for use in other spatial, temporal or process conditions.

CONCLUSIONS

The model has proved satisfactory in validation trials involving 67 sites in twelve countries for predicting whether or not the erosion system is stable and, if it is not, for predicting the magnitude of the instability. It does not, however, predict soil loss with acceptable accuracy at very low and at very high erosion rates.

The basic documentation of the model is set out in Morgan, Morgan and Finney (1982) but the following guidelines supplement those contained in that paper.

(a) Rainfall intensity values of 11.0, 25.0 and 30.0 mm/h can be used for humid temperate, humid tropical and strongly seasonal (monsoon and Mediterranean) climates respectively. Where local information is available it should be used in preference to these values.

(b) Local field data on rainfall amount, number of rain days, bulk density and moisture storage at field capacity should always be used when available.

(c) Weathering rates are generally about 0.01 to 0.02 mm/y.

(d) The term rooting depth should be applied literally; depths are normally shallow, about 0.10 m for cereals and vegetables and 0.15 m for tree crops.

(e) For rooting depths up to 0.25 m, recommended soil renewal rates are 0.20 mm/y for forest, grassland or where crop residues are returned to the soil; 0.15 mm/y for standard husbandry and 0.10 mm/y for poor husbandry. More research is needed to enable these values to be defined more precisely.

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