J. agric. Engng Res. (1984) 30, 245–253

A Predictive Model for the Assessment of Soil Erosion Risk

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A model is developed for predicting annual soil loss from field-sized areas on hillslopes. The model comprises a water phase and a sediment phase. In the sediment phase erosion is taken to result from the detachment of soil particles by rainsplash and their transport by runoff. Splash is related to rainfall energy and rainfall interception; runoff transport capacity depends upon the volume of runoff, slope steepness and crop management. Rainfall energy and runoff volume are estimated from annual rainfall amount in the water phase. The predicted rate of soil loss is compared with a topsoil renewal rate to determine changes in topsoil depth over time. Model validation was carried out by comparing predicted and observed values of annual runoff and erosion for 67 sites in 12 countries. As an example of how the model can be used, a 100-year simulation exercise is presented for soil erosion under shifting cultivation in Peninsular Malaysia.

1. Introduction

The need to predict the rate of soil erosion, both under existing conditions and those expected to occur following soil conservation practice, has led to the development of the Universal Soil Loss Equation[1] and the CREAMS model.[2] These techniques require considerable inputs of data and are generally too complicated for initial assessments of erosion in reconnaissance surveys. This paper presents an alternative procedure for soil loss prediction, bringing together the results of research by geomorphologists and agricultural engineers into a model which, although empirical, has a stronger physical base than the Universal Soil Loss Equation and is simpler and more flexible than CREAMS. Although it is an amalgam of existing operating functions and, in that sense, is not new, the model was developed with the specific objective of seeing to what extent existing work could be combined in a simple format to predict annual soil loss from field-sized areas on hillslopes.

2. Approach

The model[3] separates the soil erosion process into a water phase and a sediment phase (*Fig. 1*). The structure of the sediment phase is a simplification of the soil loss model described by Meyer and Wischmeier.[4] It considers soil erosion to result from the detachment of soil particles from the soil mass by raindrop impact and the transport of those particles by overland flow. The energy of rainfall for splash detachment and the volume of overland flow are estimated in the water phase. Operating functions (Table 1) were selected from the geomorphological and engineering literature according to their predictive ability, simplicity, and ease of determination of their input parameters (Table 2).

In the water phase annual rainfall (R) is used to determine the energy of the rainfall for splash detachment and the volume of runoff. Rainfall energy (E) is modelled empirically by extending the relationship between energy and intensity (I) developed by Wischmeier and Smith[1]

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Received 3 November 1983; accepted in revised form 29 August 1984

Paper presented at AG ENG 84, Cambridge, U.K., 1–5 April 1984

0021-8634/84/070245+09 $03.00/0

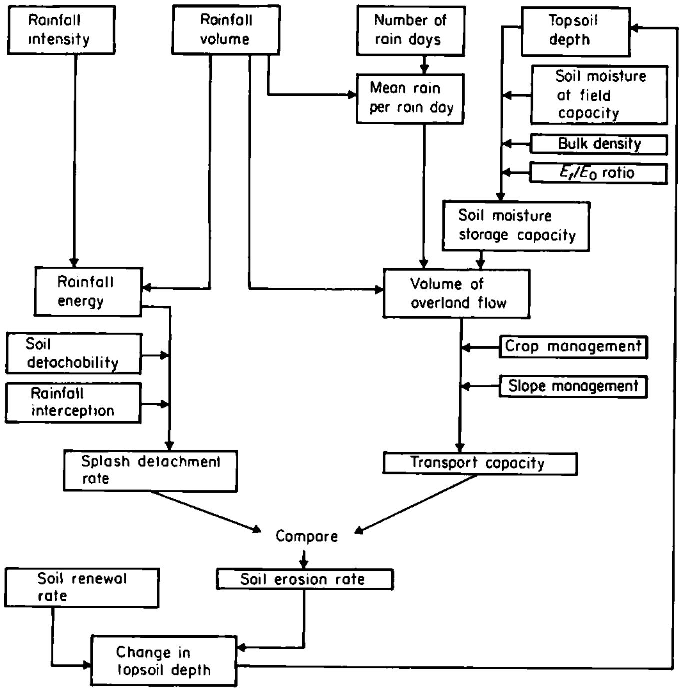

Fig. 1. Flowchart of the model.

TABLE 1
Operating functions

Water phase

$$E = R(11{\cdot}9 + 8{\cdot}7 \log_{10} I), \qquad \ldots(1)$$

$$Q = R \exp(-R_c/R_0), \qquad \ldots(2)$$

where $R_c = 1000\, M\gamma D_r\, (E_t/E_0)^{0{\cdot}5}$ and $R_0 = R/R_n$.

Sediment phase

$$F = K(E\mathrm{e}^{-aP})^b \times 10^{-3} \qquad \ldots(3)$$

$$G = CQ^d(\sin S) \times 10^{-3} \qquad \ldots(4)$$

E = Kinetic energy of rainfall (in J/m^2); Q = volume of overland flow (in mm); F = rate of splash detachment (kg/m^2); G = transport capacity of overland flow (kg/m^2)

Values of exponents: $a = 0{\cdot}05$;[8,9] $b = 1{\cdot}0$;[7] $d = 2{\cdot}0$[5,10,11]

to an annual basis using the annual rainfall and an estimate of the typical hourly intensity of erosive rain [eqn (1) in Table 1]. Runoff volume is predicted from eqn (2) in Table 1, as given by Carson and Kirkby,[5] which assumes that runoff occurs whenever the daily rainfall exceeds a critical value (R_c) representing the moisture storage capacity of the soil–crop complex and that the daily rainfall amounts approximate an exponential frequency distribution. The value of R_c depends upon the soil moisture storage at field capacity (M), the bulk density of soil (γ) and the topsoil rooting depth (D_r) (Withers and Vipond[6]) after allowing for the crop cover effect through evapotranspiration (E_t/E_0) using the empirical relationship adopted by Kirkby.[7]

The sediment phase is divided into two components: splash detachment and runoff transport. Splash detachment is modelled using the widely accepted power relationship with rainfall energy (Meyer[8]) modified to allow for the rainfall interception effect of the crop. Rainfall energy at the

TABLE 2
Input parameters

M	Soil moisture content at field capacity or 1/3 bar tension, % w/w
γ	Bulk density of the top soil layer, Mg/m^3
D_r	Topsoil rooting depth (in m), defined as the depth of soil from the surface to an impermeable or stony layer, to the base of the A horizon, to the dominant root base or to 1·0 m, whichever is the shallowest. Reasonable values are 0·05 for grass and cereal crops and 0·1 for trees and tree crops
D_s	Total soil depth (in m), defined as the depth of soil from the surface to bedrock
K	Soil detachability index (in g/J), defined as the weight of soil detached from the soil mass per unit of rainfall energy
W	Rate of increase in soil depth by weathering at the rock–soil interface, mm/a
V	Rate of increase of the topsoil rooting layer (mm/a) as a result of crop management practices and the natural breakdown of vegetative matter into humus
S	Steepness of the ground slope expressed as the slope angle
R	Annual rainfall, mm
R_n	Number of rain days in the year
I	Typical value for intensity of erosive rain, mm/h
P	Percentage rainfall contributing to permanent interception and stemflow
E_t/E_0	Ratio of actual (E_t) to potential (E_0) evapotranspiration
C	Crop cover management factor. Combines C and P factors of the Universal Soil Loss Equation to give ratio of soil loss under a given management to that from bare ground with downslope tillage, other conditions being equal
N	Number of years for which the model is to operate

TABLE 3
Sensitivity analysis

1% change in	*Percentage change in*	
	transport capacity	*detachment rate*
R	$2(1+R_c/R_0)$	1
M; γ; D_r; R_n	$-2(R_c/R_0)$	
E_t/E_0	$-R_c/R_0$	
C; $\sin S$	1	
K		1
I		$(3{\cdot}1+2{\cdot}3\log_{10}I)^{-1}$
P (1% absolute change)		-5

ground surface is assumed to decrease exponentially with increasing interception.[9,10] The transport capacity of overland flow is determined from eqn (4) in Table 1, developed by Kirkby,[5] with experimental support from erosion plot data,[5,11] and depends upon the volume of overland flow, the slope steepness and the effect of the crop cover. Although Kirkby uses the tangent of the slope angle, the sine value is adopted here. This makes very little difference to predictions at low slope angles, but prevents unacceptably high predictions at high slope angles. Tests of this equation[12] show that C takes values in relation to crop cover which are of the same order of magnitude as the C factor values used in the Universal Soil Loss Equation. These are therefore used at present as a convenient method of determining values of C.

The model compares the predicted rate of splash detachment with the transport capacity for overland flow, and equates the rate of soil loss to the lower of the two values, thereby indicating whether detachment or transport is the limiting factor.

The predicted rate of soil loss is compared with an estimated rate of weathering (W) at the soil–bedrock interface to determine the annual loss or gain in total soil depth (D_s). A similar calculation is made for the change in topsoil rooting depth (D_r) by comparing the rate of soil

TABLE 4
Predicted and measured rates of annual runoff and erosion

Site	Runoff, mm		Soil loss, kg/m^2	
	Observed	Predicted	Observed	Predicted
**Lushoto, Tanzania*				
Clay soil, maize and beans intercropping	0·3–1·0	6·85	0·0012–0·0013	0·0018
(2 years)	0·2–1·0	3·74	0·0005–0·0010	0·0005
Sandy clay loam, evergreen forest (2 years)	2·6–5·6	2·59	0·0006–0·0015	0·0000
	4·2–5·7	5·96	0·0012–0·0030	0·0000
Sandy clay loam, steep slope, evergreen	8·5–12·7	3·25	0·0013–0·0057	0·0000
forest (2 years)	10·4–14·8	7·31	0·0105–0·0129	0·0001
Clay, steep slope, maize and beans	0·4–0·8	6·85	0·0007–0·0013	0·0038
intercropping (2 years)	0·4–0·8	3·74	0·0008–0·0010	0·0011
**Adiopodoumé, Ivory Coast*				
Sandy loam, secondary tropical forest	15·0	85·9	0·001–0·02	0·003
Sandy loam, bare ground	707–1415	1268·1	6·9–15·0	15·5†
Sandy loam, oil palm	43–172	57·8	0·001–0·05	0·02
Sandy loam, banana with mulch	11–86	102·4	0·004–0·005	0·002
Sandy loam, maize	643–1608	355·0	3·5–13·1	3·53
Sandy loam, groundnut	579–1565	452·7	5·9–12·0	7·17
Sefa, Senegal				
Loam, secondary tropical forest	1·6–19·2	154·8	0·002–0·02	0·0009
Loam, groundnut	130–699	370·8	0·29–1·63	1·38
Loam, cotton	15–699	429·0	0·05–1·85	1·84
Loam, maize with mechanization	504	420·3	1·03	0·71
Loam, sorghum	390–683	442·5	0·33–1·24	1·57
Pong Khrai, Thailand				
Clay loam, upland rice	22–32	34·4	1·40–2·40	0·07
Clay loam, upland rice, bench terraces	16–53	34·4	1·1–1·3	0·011
Marchiazza Basin, Italy				
Loamy sand, bare soil with tufted grass	201–261	186·7	2·7–3·1	3·25
Loamy sand, Molinia moor grass	51–58	56·9	0·05–0·09	0·0062
Loamy sand, chestnut and oak trees	36–38	48·3	0·009–0·018	0·0014
Hesbaye, Belgium				
Sandy soil, sugar beet	n/a	60·7	0·13–2·95	0·10
Sandy soil, winter wheat	n/a	78·6	0·045–0·10	0·10
Sandy soil, bare ground	n/a	415·6	0·6–8·25	12·01†
Trier, West Germany				
Sandy loam, vines	n/a	5·8	0·0027–0·0044	0·0046
Taiwan				
Clay loam, citrus, clean cultivation	1268	580·2	15·64	10·25†
Clay loam, citrus, bench terracing	344	580·2	0·50	4·71
Clay loam, citrus with mulch	109	517·9	0·094–0·28	0·22
Clay loam, banana, clean cultivation	1113–1449	279·7	3·94–6·37	5·40
Clay loam, banana with mulch	189	245·6	0·009	0·042
Clay loam, banana with contour bunds	483–1029	279·7	0·11–0·39	0·54
Henderson, Zimbabwe				
Clay, maize	8–61	26·7	0·2–0·3	0·013
Clay, cropped grass	8–26	18·6	0·05–0·1	0·0000
Mpwapwa, Tanzania				
Clay loam, bare ground	446	212·7	14·7	2·78
Clay loam, sorghum and millet	80–259	5·72	5·5–9·0	0·0007
Clay loam, tufted grass	8–65	2·9	0·0–0·07	0·0000
Clay loam, savanna grass	3–4	2·04	0·0	0·0000
Lyamungu, Tanzania				
Clay loam, coffee, clean cultivation	15–232	28·18	4·3	0·04
Clay loam, coffee with cover crops	10–98	9·57	0·4	0·002
Clay loam, coffee with contour ridges	36	28·18	0·3	0·004
Clay loam, coffee with cover crops and contour ridges	27	9·57	0·1	0·0001

TABLE 4—*continued*

Site	*Runoff, mm* *Observed*	*Runoff, mm* *Predicted*	*Soil loss, kg/m²* *Observed*	*Soil loss, kg/m²* *Predicted*
Tuanshuangou, China				
Sandy soil, millet/mungbean; potato;	n/a	278·3	0·1	7·89†
millet/mungbean (2 years); alfalfa	n/a	250·3	43·9	7·59†
rotation (5 years)	n/a	278·3	6·3	7·89†
	n/a	278·3	23·4	7·89†
	n/a	238·5	4·4	0·23
Mean values	n/a	264·7	13·1	6·29
**Malaysia*				
Sandy loam, oil palm	263	294	0·77	0·29
(2 years)	657	757	0·89	0·76
Sandy loam, bare soil	532–642	827	2·93–3·39	3·73
Sandy loam, groundnut	273–328	273	0·64–1·01	1·04
Sandy loam, maize	365–378	340	0·56–0·81	1·07
Sandy loam, maize with mulch	73–80	298	0·04–0·06	0·06
Sandy clay loam, bare soil	688–941	829	2·44–3·92	3·93
Sandy clay loam, groundnut	241–388	266	0·51–0·97	0·99
Sandy clay loam, cowpea	260–302	291	0·59–0·61	1·18
Clay loam, primary rain forest	n/a	181	0·004–0·024	0·027
**United Kingdom*				
Sandy soil, bare ground	66	341	3·9	8·0†
Sandy soil, grass	17	28	2·3	0·001
Sandy loam, woodland	9	2	0·001	0·0000
Clay, spring barley	1	9	0·07	0·003
Clay, winter wheat and spring barley	6	5	0·05	0·001
Sandy loam, oats, wheat, beans	11	11	0·06	0·005
Chalk, winter wheat	5	5	0·07	0·002

*Sites where data on soil properties are based on field measurements
†Detachment-limited erosion
Sources of measured data are given in Morgan and Finney [14]

loss with an estimated rate for top soil renewal (V).[13] The new values of D_s and D_r are used as inputs to the following year of simulation. In this way the model is able to simulate positive feedback in the erosion system, where reductions in the topsoil rooting depth lead to reduced soil moisture storage and result in greater runoff and an increased rate of erosion. The process continues until first the topsoil and, finally, the subsoil disappear.

3. Sensitivity analysis

The extent to which predictions of soil loss by the model are affected by small changes in the values of the input parameters was assessed using partial differentiation. The results (Table 3) show that predictions are most sensitive to changes in annual rainfall and the soil properties when erosion is transport-limited and in rainfall interception and annual rainfall when erosion is detachment-limited. The most sensitive parameters need to be assessed with the greatest accuracy.

4. Validation

Validation of the model was carried out using published data for 67 sites in 12 countries where agricultural soil erosion has been measured on hillside erosion plots (Table 4).[14]

The model generally predicted erosion as being limited by the transport capacity of the runoff,

TABLE 5
Input data for simulation of soil erosion with shifting cultivation in a 16-year cycle on an 8° slope

M	γ	D_r	D_s	K	W	V	sin S	N
0·26	1·28	0·15	1·00	0·30	0·02	0·19	0·140	100

Year	R	R_n	T	P	E_t/E_0	C
1	2029	181	25·0	35·0	0·90	0·002
2	2425	195	25·0	20·0	0·60	0·15
3	2413	180	25·0	20·0	0·60	0·20
4	2209	181	25·0	25·0	0·90	0·10
5	2161	183	25·0	30·0	0·90	0·05
6	2479	193	25·0	35·0	0·95	0·002
7	2305	181	25·0	35·0	0·95	0·002
8	2163	181	25·0	35·0	1·00	0·001
9	2152	171	25·0	35·0	1·00	0·001

Data shown for the first nine years only. Rainfall data are a synthetic sequence generated by Monte Carlo method from a log-normal distribution with the same mean and standard deviation as sample data from the study area. Selection of the parameter values is discussed in Morgan *et al.*[14]

but where runoff rates were very high erosion was detachment-limited. The soil loss predictions were worst at very low annual rates of soil erosion ($<0·1$ kg/m^2), when they were often an order of magnitude or more out, and at very high rates of erosion (>20 kg/m^2). Runoff predictions were often poor where mechanical soil conservation measures, such as ridging and terracing, were used or where mulching was adopted. This can be explained by the inability of the model to allow for surface depression storage of rainfall in the water phase. The soil conservation practices are accounted for in the sediment phase, however, through the values selected for the crop management factor so that soil loss predictions are often satisfactory when the runoff prediction is not.

In comparing predicted values (Y) with measured data (X), reduced major-axis lines[15,16] were fitted in preference to regression lines because of the likelihood of errors in both the predicted and measured values. The following relationships were obtained:

$$Y = 19·776 + 0·775X \text{ for runoff}, \quad r = 0·735, n = 56, \qquad \ldots(5)$$
$$Y = 0·472 + 0·503X \text{ for soil loss}, \quad r = 0·583, n = 67. \qquad \ldots(6)$$

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 erosion rates in China. If these two cases are omitted, the relationship becomes

$$Y = -0·090 + 0·896X \text{ for soil loss}, r = 0·671, n = 65, \qquad \ldots(7)$$

where the slope of the regression line is not significantly different from unity ($P > 0·05$).

Since correlation analysis gives equal weight to the differences between predicted and observed values regardless of their magnitude, an alternative validating procedure was sought which allowed much greater differences to be acceptable at very high and, in particular, at very low values of soil loss. Predictions were viewed as successful if (1) the annual predicted and observed values were both less than 0·1 kg/m^2, the model therefore correctly predicting that soil erosion was unlikely to be a problem, or otherwise (2) the ratio of the predicted value to either a single observed value or to the mid-point of a range of observed values was between 0·5 and 2·0. No threshold value was applied to the runoff predictions and their success was judged solely in terms of whether the ratio of predicted to observed values was in the range 0·5–2·0.

TABLE 6
Changes in topsoil rooting depth (in mm) for 100-year simulations of soil erosion

Shifting cultivation cycle	*Slope steepness, degrees*				
	2	*4*	*8*	*16*	*34*
16 years	+18·3	+17·6	+16·2	+13·1	+5·4
11 years	+17·1	+16·1	+14·1	+9·4	−3·4
4 years	+12·4	+9·4	+2·2	−26·0	−150·0

Initial topsoil rooting depth was 150 mm. For the four-year cycle on the 34° slope, the topsoil disappears in Year 73

TABLE 7
Selected output for the simulation of a four-year shifting cultivation cycle on a 34° slope

Year	*Rain, mm*	*Soil loss, kg/m²*	*Rooting depth, mm*	*Soil depth, mm*
5	2161	0·0475	148·2	997·6
9	2152	0·0839	146·4	995·3
13	2282	0·0808	142·0	990·3
17	2214	0·0791	140·7	988·5
37	2669	1·0112	122·1	967·3
41	2389	0·3579	115·9	960·5
45	2483	0·9312	106·4	950·5
49	2406	1·9267	93·5	937·2
65	2473	3·9908*	32·0	873·6
69	2106	3·3986*	15·5	856·6
73	2305	3·7197*	0·0	840·3
89	2499	4·0328*	0·0	775·5
93	2021	3·2614*	0·0	759·2
97	2128	3·4341*	0·0	743·0

Data are given for fourth year of each cycle. Values for rooting depth (D_r) and soil depth (D_s) are for the end of the year of simulation allowing for the rate of erosion, the bulk density of the soil, a topsoil renewal rate of 0·19 mm/a and a weathering rate of 0·02 mm/a. Initial values were $D_r = 150$ mm and $D_s = 1000$ mm

*Detachment-limited erosion rate

From Morgan *et al.*[16]

Applying these criteria, the model successfully predicted runoff for 33 out of 56 test sites and soil loss for 47 out of 67 test sites, giving respective success rates of 59% and 70%. If only those sites are considered, 31 in all, where data on soil properties were obtained in the field instead of being estimated, the success rates are 57% and 90%, respectively.

5. Applications

The availability of data restricted the validation of the model to single years. Whilst it can be used to predict annual runoff and erosion, the design of strategies for soil conservation also demands information on trends in rates of erosion in the longer term. An attempt was therefore made to see how well the model could simulate erosion problems over time with a view to providing an understanding and indication of trends rather than details of absolute quantities.

It was decided to examine the effects of shifting cultivation on soil erosion in a tropical rainfall forest environment using data from Malaysia. Simulations were carried out for a typical area of undulating hill country to the south and west of Kuala Lumpur with shifting cultivation following traditional practice. One crop per year is obtained, usually of upland rice, with the land being cleared in April and burned in May and the crop being planted in June and harvested in December. The land is farmed for two years and then allowed to revert to fallow for 14 years, giving a 16-year cycle. The cycle is simulated by making appropriate changes to the parameter values of I, P, E_t/E_0 and C according to the guidelines set out in Reference (3) (Table 5).

To assess the effect of population pressure on the land reducing the length of the cycle, simulations were also carried out for 11- and four-year cycles.

The results of the simulations[17] (Table 6) show that erosion is not a problem on slopes of 2° and 4°, as evidenced by the net increases in topsoil rooting depth over the 100-year period ranging from 9·4 mm to 18·3 mm. This is also the case for the 11- and 16-year cycles on an 8° slope where the topsoil rooting depth increases by 14·1 mm and 16·2 mm, respectively. The four-year cycle on the 8° slope reveals an approximate balance between the rates of erosion and soil renewal.

The four-year cycle on a 34° slope (Table 7) illustrates the worst effects of erosion. In the early years of simulation, topsoil rooting depth is reduced by between 1·3 mm and 4·4 mm over a four-year cycle, but between years 38 and 45 the rate increases to between 6·2 mm and 12·9 mm. This change in rate is associated with an increase in the number of years when soil loss is detachment-limited until it becomes detachment-limited every year. The high rate of decrease in rooting depth is maintained until all the topsoil is removed after 73 years.

6. Conclusion

The model predicts annual soil loss from hillslopes. The results of a validation exercise show that, except for very low and very high rates of erosion, the model gives realistic predictions over a wide range of conditions. In addition, it is reasonably efficient in terms of data input requirements, ease of computation and time. The case study of shifting cultivation in Malaysia indicates that the model provides a reasonable simulation of runoff and sediment production on a hillside over a long sequence of years in such a way that the effects of the various factors influencing the soil erosion system, including the adoption of soil conservation practices, can be readily understood and that, in general trend, accords with reality. Only the 16-year cultivation cycle is acceptable on all the slopes tested, which compares well with the minimum 10-year fallow period recommended by Hurni[18] in Thailand. All the cycles tested are acceptable up to 8° slope, implying that continuous cropping with agronomic soil conservation measures would also be possible; this fits well with the 7° slope recommended by Sheng[19] as the maximum slope steepness for the tillage without bench terracing in humid tropical areas.

Acknowledgements

Research on the model was carried out with the aid of grants from the United Kingdom Natural Environment Research Council and the International Institute for Applied Systems Analysis, Laxenburg, Austria. The encouragement of Mr V. Svetlosanov (IIASA) is appreciated.

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