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

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PREFACE

The interaction between man and his environment is increasing from year to year and one of the important problems that environmentalists face is the evaluation of the negative consequences of man's activities. Very often, anthropogenic activities are small perturbations in real systems, but over a long period of time this accumulates and the end effect may be unexpected. What is the result of the interaction between man and the environment over long periods of time? Which ecosystems are stable with what possible perturbations? What quantitative values of perturbations can destroy natural ecosystems and for what periods of time? In working on these problems, the terms stability, resilience, adaptivity, homeostasis, reliability, etc., appeared in ecological investigations. Beginning in 1982, one of the aims of IIASA's "Land and Landcover Resources" task within the Resources and Environment Area (REN) has been to investigate the agroecosystems of stability. The main factors and process which influence agroecosystems are erosion, salinization, and waterlogging. The estimation of the stability of agroecosystems which are subject to these processes is the central concern of REN's Land and Landcover Resources task. The research institutes of Bulgaria, Canada, Czechoslovakia, England, Hungary, USA and USSR collaborated to investigate this issue.

This paper sets out the work performed by English researchers within the framework of this cooperation. It considers the stability of the agro-ecosystems with regard to just the erosion process.

V. Svetlosanov
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Land and Landcover Resources

ABSTRACT

Documentation is presented of a model for assessing the stability of the soil erosion component of an agricultural ecosystem. The model uses a simplified version of the Meyer-Wischmeier approach to predict the annual rate of soil erosion by water on hillslopes and this is compared with the rates of weathering and top soil renewal to determine changes in the depth of the soil profile and the top soil or rooting layer. Erosion is taken to be the result of splash detachment and runoff transport. Splash detachment is related to rainfall energy and rainfall interception by the crop. Runoff volume and sediment transport capacity are estimated from equations first presented by Kirkby. The results of trials with the model in the Silsoe area of Bedfordshire, England, show that realistic values of runoff and erosion are obtained for a range of soil and crop conditions. The model can be used to assess the stability of the erosion system under existing landuse conditions and to determine what changes need to be made in the erosion system to produce stability when unstable conditions are predicted.

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

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INTRODUCTION

Under natural conditions the plant cover on any part of the earth's surface is the result of a series of cause and effect relationships involving the plant assemblage and the physical environment. This interacting complex or ecosystem may be stable if it is capable of regenerating itself or unstable if successive or cyclic changes are taking place in the plant species making up the assemblage. Man has influenced the plant cover over much of the earth's surface and in most flat or gently sloping areas has cleared the climax vegetation in favour of agriculture. The agricultural plant assemblages are vitally important for producing the food necessary to sustain the increasing world population.

Many agricultural ecosystems are inherently unstable. The plant community only survives because of man's inputs in cultivation, irrigation, fertilizers, herbicides and pesticides. Through changes in the density, morphology and root structure of the plant cover, generally resulting in decreases in rainfall interception, infiltration and soil moisture storage, agricultural ecosystems have higher rates of runoff and erosion than natural ecosystems. In many instances, rates of erosion are greater than rates of soil renewal. Soils become shallower over time and their productivity declines. To attain sustained food production, agricultural ecosystems must be made stable and it is in this context that soil conservation becomes important. The objective of soil conservation is to manipulate the erosion system component of the agricultural ecosystem so as to maintain the maximum sustained level of production whilst keeping the rate of soil loss below a threshold level which theoretically permits the rates of soil erosion and soil formation to balance. Soil depth thus remains stable through time.

Prerequisites for assessments of the stability of agricultural ecosystems include information on rates of soil erosion and soil renewal. Obtaining data on soil erosion by field measurement is expensive and time consuming and so, for rapid assessments, recourse is made to prediction. Predictions can be made using techniques such as the Universal Soil Loss Equation (Wischmeier and Smith, 1978) and the CREAMS model (Knisel, 1980). These techniques require considerable quantities of data. Compared with the scanty knowledge on soil renewal rates and the difficulties of determining what the maximum acceptable rate of erosion or soil loss tolerance should be, these predictive models are too complicated for use when all that is needed is a reconnaissance survey or an initial assessment of stability.

A simple model is required from which rapid assessments of erosion stability can be made. This paper documents the model first presented by Morgan (1981), later tested for Malaysia by Morgan, Hatch and Sulaiman (in press) and to which subsequent developments have been made within the framework of the research programme on the stability of ecosystems being carried out by the Resources and Environment Section of the International Institute for Applied Systems Analysis.

APPROACH

The model assesses the stability of the erosion system in terms of the change in soil depth over time. Soil depth is increased at rate W through weathering of the bedrock at the base of the soil profile. Soil depth is decreased by erosion of the soil at the surface at rate SL. Comparison of the two rates gives the change in depth over time. The model also makes a separate assessment for the top soil or rooting layer. The depth of this layer is decreased at rate SL and increased at a soil renewal rate, RN, a rate which takes account of the natural rate of weathering and the addition of fertilizers and organic material through agricultural management.

The procedure used to predict the rate of soil erosion is a simplification of the soil loss model described by Meyer and Wischmeier (1969). It considers soil erosion to result from the detachment of soil particles by raindrop impact and the transport of those particles by overland flow. The processes of splash transport and detachment by runoff are ignored (Morgan, Hatch and Sulaiman, in press). The model is designed to predict mean annual soil loss from field-sized areas on hillslopes, although it may be expected to give reasonable results for any given year if data describing the conditions for that year are used as input parameter values. The model should not be used to estimate sediment yield from drainage basins nor to predict soil loss over shorter time periods such as the duration of individual storms or days. Because, in the model, surface runoff is generated through exceedance of the soil moisture storage capacity, it cannot be expected to predict erosion successfully where runoff is due to infiltration capacity excess.

The model separates the erosion process into a water phase and a sediment phase. Two predictive equations, one for the rate of splash detachment and one for the transport capacity of the overland flow, constitute the sediment phase. The rate of soil loss is determined by whichever of these processes is the limiting one. The respective inputs to these equations of rainfall energy and runoff volume are determined from the water phase.

The effects of soil conservation practices can be accounted for within the separate phases. For example, the introduction of agronomic measures of erosion control is allowed for by changes in evapotranspiration, interception and crop management which respectively affects the volume of runoff, the rate of splash detachment and the transport capacity of overland flow.

Although still empirical, the model has a stronger physical base than the Universal Soil Loss Equation (Wischmeier and Smith, 1978) but retains the elements of simplicity and flexibility which are lost in the more recently developed and more sophisticated CREAMS model (Knisel, 1980). It also has the potential to determine whether erosion is detachment or transport limited which it is helpful to know when designing soil conservation strategies.

The model requires sixteen input parameters describing rainfall, soil, slope and landuse conditions (Table 1) and seven governing equations (Table 2).

Table 1. Input parameters

MS Soil moisture content at field capacity or 1/3 bar tension (% w/w).
Determine experimentally using the gravimetric method or select a typical value for the soil type in question (Table 4).
The model is sensitive to a 1% change in the value of this parameter if erosion is transport-limited.

BD Bulk density of the top soil layer (g/cm^3).
Determine experimentally or select a typical value for the soil type in question (Table 4).
The range of bulk density values is low over most agricultural soils but the model is sensitive to a 1% change in the value of this parameter if erosion is transport-limited.

RD Rooting depth (m) defined as the depth of the soil from the surface to an impermeable or stony layer; to the base of the A horizon; to the dominant root base; or to 1.0m which ever is the shallowest.
Determine from field observations on site. If profile descriptions from soil survey reports are used and local slope differs from that at the profile site, it may be necessary to adjust the value of RD to allow for shallower soils on steeper slopes.
The model is sensitive to a 1% change in the value of this parameter if erosion is transport-limited

SD Total soil depth (m) defined as the depth of the soil from the surface to the bedrock.
Determine from field observations on site or from profile descriptions in soil survey reports.
The model is not sensitive to changes in the values of this parameter which is not used in the procedure for predicting erosion.

K Soil detachability index ($g/J/m^2$) defined as the amount of soil detached from the soil mass per unit of rainfall energy per unit area.
Determine experimentally using rainfall simulation or select a typical value for the soil type in question. (Table 4).
The model is moderately sensitive to a 1% change in this parameter if erosion is detachment-limited.

W The rate of increase in soil depth by weathering at the soil-rock interface (mm/y).
Obtain information from published researches on weathering rates in the study area. Alternatively, use data on measured rates of erosion in the area under reasonably natural conditions, based on the assumption that under such conditions the rates of erosion and weathering are in balance.
This parameter is not used in the procedure for predicting erosion but it needs to be determined as accurately as possible because changes in the soil depth (SD) are computed by comparing the predicted rate of erosion with the rate of weathering.

RN The rate of renewal of the top soil layer (mm/y) as a result of crop management practices, e.g. tillage, addition of fertilizers and organic material, as well as the natural breakdown of vegetative matter into humus. Where possible, use data from researches on soil renewal rates in the study area or apply data from similar areas. Otherwise, select a value from Table 5.
This parameter is not used in the procedure for predicting erosion but it needs to be determined as accurately as possible because changes in the top soil depth (RD) are computed by comparing the predicted rate of erosion with the rate of renewal. Also, the value of RD predicted after one year of simulation is used as the input value for the following year of simulation and the model is sensitive to a 1% change in the value of RD if erosion is transport-limited.

SLP Steepness of ground slope expressed as the sine of the slope angle.
Determine from field measurement.
The model is only moderately sensitive to a 1% change in the value of this parameter.

NY Number of years for which the model is to operate.

YEAR Year of simulation for which values of RAIN, RDAY, INTENS, INCEP, ETEO and CFAC apply.
A separate card must be used for these input parameters for each year of simulation. The total number of cards must equal NY.

RAIN Annual rainfall total (mm).
Obtain information from measurements on site or from meteorological records.
The model is very sensitive to a 1% change in the value of this parameter if erosion is transport-limited and moderately sensitive if erosion is detachment-limited.

RDAY Number of rain days in the year.
Obtain information from measurements on site or from meteorological records.
The model is sensitive to a 1% change in the value of this parameter is erosion is transport-limited.

INTENS Typical value for intensity of erosive rain (mm/h). Obtain information from rainfall measurements on site with intensity or autographic gauges or from meteorological records.
The model is only slightly sensitive to a 1% change in the value of this parameter if erosion is detachment-limited and not sensitive if erosion is transport-limited.

INCEP Percentage rainfall contributing to permanent interception and stemflow.
Determine experimentally in the field or laboratory.
Alternatively, use information from published researches (Table 6).
The model is very slightly sensitive to a 1% absolute change in the value of this parameter if erosion is detachment-limited.

ETEO The ratio of actual to potential evapotranspiration.
Determine experimentally or use data from published researches (Table 6).
The model is moderately sensitive to a 1% change in the value of this parameter if erosion is transport-limited.

CFAC Crop cover management factor defined as the ratio of soil loss under a given land use to that from bare ground with downslope tillage.
Previous trials with the model have shown that the C-factor values in the Universal Soil Loss Equation can be used for this parameter. They should be calculated from the information contained in Wischmeier and Smith (1978) but first approximation values may be selected from Table 6. Where contouring, contour strip cropping or terracing are practised the values should adjusted by the P-factor values listed in Table 6.

Table 2. Operating functions used in the model.

Equation 1	$KE = R\,(11.89 + 8.74 \log INTENS)$	Wischmeier & Smith (1978)
Equation 2	$OF = R \,.\, e^{-Rc/Ro}$	Kirkby (1976)
Equation 3	$H = 1{,}000\ MS.BD.RD$	Withers & Vipond (1974)
Equation 4	$Rc = H\,(Et/Eo)^{0.5}$	Kirkby (1976)
Equation 5	$DET = K\,(KE \,.\, e^{-a.INCEP})^{b} \,.\, 10^{-3}$	Morgan, Hatch & Sulaiman (in press)
Equation 6	$G = C\ OF^{2} \sin SLP \,.\, 10^{-3}$	Kirkby (1976)
Equation 7	$Ro = R/Rn$	

Notes:

OF = volume of overland flow (mm)

DET = rate of splash detachment (kg/m^2)

G = transport capacity of overland flow (kg/m^2)

KE = Kinetic energy of the rainfall (J/m^2)

H = soil moisture storage capacity (mm) under a dense vegetation cover

Rc = soil moisture storage capacity (mm) under actual vegetation cover

Ro = mean rain per rain day (mm)

a = interception exponent, assumed to equal -0.05

b = splash detachment exponent, assumed to equal 1.0

Other parameter notation and units as in Table 1.

INPUT DATA

Definitions of and data sources for the input parameters are presented in Table 1. This information must be compiled as an input file in the following format:

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. A sample input file is given in Table 3.

Table 3. Sample input file

Silsoe
Cottenham series: sandy variant
Market gardening: good husbandry

0.15	1.50	0.05	1.00	0.70	0.20	0.15	0.191	20
1973	590	162	11.3	14.0	0.39	0.41		
1974	630	154	11.3	16.0	0.44	0.42		
1975	650	168	11.3	14.0	0.39	0.41		
1976	590	168	11.3	16.0	0.44	0.42		
1977	440	118	11.3	14.0	0.39	0.41		
1978	430	131	11.3	16.0	0.44	0.42		
1979	510	151	11.3	14.0	0.39	0.41		
1980	590	155	11.3	16.0	0.44	0.42		
1981	450	123	11.3	14.0	0.39	0.41		
1982	590	162	11.3	16.0	0.44	0.42		
1983	440	132	11.3	14.0	0.39	0.41		
1984	490	134	11.3	16.0	0.44	0.42		
1985	690	163	11.3	14.0	0.39	0.41		
1986	540	150	11.3	16.0	0.44	0.42		
1987	540	151	11.3	14.0	0.39	0.41		
1988	630	171	11.3	16.0	0.44	0.42		
1989	450	135	11.3	14.0	0.39	0.41		
1990	680	164	11.3	16.0	0.44	0.42		
1991	520	148	11.3	14.0	0.39	0.41		
1992	550	156	11.3	16.0	0.44	0.42		

MODEL OPERATION

This section describes the stages involved in operating the model, taking the water phase and sediment phase in turn.

Water phase

Annual precipitation is the basic input parameter and is used to determine the energy of the rainfall available for splash detachment and the volume of runoff.

The rainfall energy component is modelled empirically from the annual precipitation total (RAIN) and an estimate of a typical hourly rainfall intensity for erosive rain (INTENS), using equation 1 (Table 2). The rainfall energy calculation is based on the relationship between energy and intensity presented by Wischmeier and Smith (1978).

The annual volume of overland flow (OF) is predicted from equation 2 using the model presented by Kirkby (1976) where runoff is assumed to occur whenever the daily rainfall total exceeds a critical value (Rc) which represents the storage capacity of the surface soil layer. The equation assumes that the daily rainfalls approximate an exponential frequency distribution.

The parameter Rc is related to the soil moisture storage capacity (H) which would exist under a dense vegetation cover. Values of H may be determined for given soils, using equation 3 (Table 2), from either field measurements or reasoned estimates (Table 4) of bulk density (BD) and the moisture content of the soil at field capacity (MS). In determining Rc, the value of H is adjusted to allow for the effects of different vegetative covers on evapotranspiration, expressed in terms of the ratio between actual evapotranspiration (Et) and potential evapotranspiration (Eo) (Table 6). Thus, using equation 4 (Table 2), reductions in runoff volume resulting from an increase in vegetation cover are accounted for by an increase in soil moisture storage.

Table 4. Typical input values for selected soil types

Soil	Moisture content at field capacity (% w/w) (MS)	Bulk density (g/cm^3) BD	Detachability index (K)
Clay	0.45	1.1	0.02
Clay loam	0.40	1.3	0.4
Sandy loam	0.28	1.2	0.3
Fine sand	0.15	1.4	0.2
Sand	0.08	1.5	0.7

Sources: MS - Withers and Vipond (1974); BD - Hall (1945); K - Quansah (1981)

Table 5. Soil renewal rates

Rooting depth (RD)	Soils with favourable subsoils that can be renewed by agricultural management	Soils with unfavourable subsoils of rock or soft weathered material that cannot be economically renewed
0-25 cm	0.22 mm/y	0.22 mm/y
25-50 cm	0.45 mm/y	0.22 mm/y
50-100 cm	0.67 mm/y	0.45 mm/y
100-150 cm	0.90 mm/y	0.67 mm/y
over 150 cm	1.12 mm/y	1.12 mm/y

Source: Data are from McCormack and Young (1981) and represent conversions from t/ha/y assuming a bulk density of 1.0 g/cm^3 for soil.

Sediment phase

The sediment phase is divided into two components: splash detachment and runoff transport.

Splash detachment is modelled as a function of rainfall energy (KE), an index of soil detachability (K), a rainfall interception parameter (INCEP) and exponents a and b (equation 5; Table 2). Values of K are obtained from rainfall simulation experiments (Table 4). Values of INCEP are either determined experimentally in the field or in the laboratory or estimated from percentage canopy cover (Table 6). Working values of -0.05 and 1.0 are adopted for exponents a and b respectively (Morgan, Hatch and Sulaiman, in press).

Equation 6 (Table 2) is used to estimate the transport capacity of the overland flow (Kirkby, 1976). The relationships between transport capacity and the first power of the sine of the slope angle (SLP) and the square of the volume of overland flow conform, as mathematically convenient and working approximations, to those derived both theoretically and experimentally by other workers (reviewed in Morgan, Hatch and Sulaiman, in press). Parameter C in the equation takes account of plant cover effects. The basis for modelling these effects is poor at present but previous trials with the model (Morgan, 1981; Morgan, Hatch and Sulaiman, in press) have shown that the C-factor values from the Universal Soil Loss Equation (Wischmeier and Smith, 1978) can be used for this parameter. Because macro changes in surface roughness brought about by contour cultivation, terracing and contour strip cropping also affect transport capacity, it was decided to allow for these under this parameter which thus combines the C and P factors of the Universal Soil Loss Equation.

Table 6. Typical input values for plant parameters

	INCEP	ETEO	CFAC
wet rice		1.35	0.1 - 0.2
wheat	43%	0.59-0.61	0.1 - 0.2 (winter sown)
			0.2 - 0.4 (spring sown)
maize	25%	0.67-0.70	0.2
barley	30%	0.56-0.60	0.1 - 0.2
millet/sorghum		0.62	0.4 - 0.9
cassava/yam			0.2 - 0.8
potato	12%	0.70-0.80	0.2 - 0.3
beans	20-25%	0.62-0.69	0.2 - 0.4
groundnut	25%	0.50-0.87	0.2 - 0.8
cabbage/Brussels sprouts	17%	0.45-0.70	
banana		0.70-0.77	
tea		0.85-1.00	0.1 - 0.3
coffee		0.50-1.00	0.1 - 0.3
cocoa		1.00	0.1 - 0.3
sugar cane		0.68-0.80	
sugar beet	12-22%	0.73-0.75	0.2 - 0.3
rubber	20-30%	0.90	0.2
oil palm	30%	1.20	0.1 - 0.3
cotton		0.63-0.69	0.3 - 0.7
cultivated grass		0.85-0.87	0.004 - 0.01
prairie/savanna grass	25-40%	0.80-0.95	0.01 - 0.10
forest/woodland	25-35% (coniferous & tropical)	0.90-1.00	0.001 - 0.002 (with under-growth)
	15-25% (temperate broad-leaved)		0.001 = 0.004 (no under-growth)
bare soil	0%	0.05	1.00

Note

CFAC values should be adjusted by the following PFAC values if mechanical soil conservation measures are practised:

contouring: multiply by 0.6

contour strip cropping: multiply by 0.35

terracing: multiply by 0.15

Sources: INCEP - Wollny (1890), sources cited in Morgan, Hatch and Sulaiman (in press) and studies at NCAE, Silsoe, ETEO - Withers and Vipond (1974), Doorenbos and Pruitt (1977).

CFAC - Wischmeier and Smith (1978), Roose (1977 and sources cited in Morgan, Hatch and Sulaiman (in press). PFAC values may be adjusted for variations in slope steepness (Wischmeier and Smith, 1978).

Soil loss prediction

The model compares the predictions of the rate of splash detachment and the transport capacity of overland flow and determines the rate of soil loss according to which ever is the limiting factor. Thus the rate of soil loss is equated with the lower of the two values.

Erosion stability analysis

The predicted rate of soil loss is compared with the rate of weathering (W) and the rate of top soil renewal (RN). Information on rates of weathering is rarely available and needs to be obtained from geomorphological researches. Where no direct measurements of weathering rates have been made, data on rates of erosion under relatively natural or undisturbed conditions may provide reasonable approximations, based on the argument that, under such conditions, the rates of soil erosion and soil formation are generally in balance. Estimates of soil renewal rates can be based on the guidelines outlined by McCormack and Young (1981) and summarised in Table 5.

The difference between the predicted rate of soil loss and the rate of weathering is used to calculate the loss or gain in soil depth (SD). The difference between the rate of soil loss and the rate of top soil renewal allows a similar calculation to be made for top soil depth (RD). The new values of SD and RD provide the input to the following year of simulation. In this way, the effects of a continued reduction in top soil depth can be simulated, acting through reductions in soil moisture storage capacity and hence increases in the volume of overland flow and in erosion. The model therefore shows how erosion can create an ever worsening condition of yet more erosion. The model contains a stop procedure when soil depth reaches zero to prevent the depth from becoming negative. At present no such stop procedure is included to control either the maximum soil depth (SD) or the maximum top soil depth (RD). This is because it is envisaged that simulations would not be carried out for periods longer than 50 years during which time the effects of increasing soil depth on, for example, the rate of weathering, are likely to be small. Clearly, a stable erosion system is indicated when the soil depth (SD) and top soil depth (RD) remain relatively constant through time.

MODEL OUTPUT

For each year simulated the output file lists:

rainfall (RAIN)
kinetic energy of the rain (KE)
moisture retention/storage capacity of the surface soil (RC)
overland flow (O/FLOW)
soil detachment rate (DET)
overland flow transport capacity (TR/CAP)
soil loss (SL)
change in rooting depth (CH/RD)
rooting depth at end of year (RD)
change in total soil depth (CH/SD)
total soil depth at end of year (SD)

Table 7. Sample output file

NCAE erosion stability model

Silsoe
Cottenham series: sandy variant
Market gardening: good husbandry

year	rain (mm)	ke (j/m^2)	rc (mm)	o/flow (mm)	det (kg/m^2)	tr/cap (kg/m^2)	s/loss (kg/m^2)	ch/rd (mm)	rd (mm)	ch/sd (mm)	sd (mm)
1973	590	12445	7.0	85.7	4.33	0.77	0.77	-0.36	49.6	-0.31	999.7
1974	630	13289	7.4	103.0	4.18	1.11	1.11	-0.59	49.0	-0.54	999.2
1975	650	13711	6.9	109.5	4.77	1.26	1.26	-0.69	48.4	-0.64	998.5
1976	590	12445	7.2	75.6	3.91	0.60	0.60	-0.25	48.1	-0.02	998.3
1977	440	9281	6.8	71.8	3.23	0.54	0.54	-0.21	47.9	-0.16	998.2
1978	430	9070	7.1	48.7	2.85	0.25	0.25	-0.02	47.9	0.03	998.2
1979	510	10758	6.7	69.6	3.74	0.51	0.51	-0.19	47.7	-0.14	998.0
1980	590	12445	7.1	91.0	3.91	0.87	0.87	-0.43	47.3	-0.38	997.7
1981	450	9492	6.6	69.1	3.30	0.50	0.50	-0.18	47.1	-0.13	997.5
1982	590	12445	7.0	85.7	3.91	0.77	0.77	-0.36	46.7	-0.31	997.2
1983	440	9281	6.6	61.4	3.23	0.40	0.40	-0.11	46.6	-0.06	997.2
1984	490	10336	7.0	73.2	3.25	0.56	0.56	-0.22	46.4	-0.17	997.0
1985	690	14555	6.5	148.1	5.06	2.30	2.30	-1.39	45.0	1.34	995.7
1986	540	11391	6.7	83.7	3.58	0.74	0.74	-0.34	44.6	-0.29	995.4
1987	540	11391	6.3	93.5	3.96	0.92	0.92	-0.46	44.2	-0.41	995.0
1988	630	13289	6.6	105.2	4.18	1.16	1.16	-0.63	43.6	-0.58	994.4
1989	450	9492	6.1	71.7	3.30	0.54	0.54	-0.21	43.3	-0.16	994.2
1990	680	14344	6.5	142.9	4.51	2.14	2.14	-1.28	42.1	-1.23	993.0
1991	520	10969	5.9	96.7	3.81	0.98	0.98	-0.50	41.6	-0.45	992.5

Table 7. Sample output file (contd)

year	rain (mm)	ke (j/m^2)	re (mm)	o/flow (mm)	det (kg/m^2)	tr/cap (kg/m^2)	s/loss (kg/m^2)	ch/rd (mm)	rd (mm)	ch/sd (mm)	sd (mm)
1992	550	11602	6.2	94.7	3.65	0.94	0.94	-0.48	41.1	-0.43	992.1
mean	550	11602		89.0	3.83	0.89	0.89	-0.45		-0.40	

Mean annual values are displayed for RAIN, KE, O/FLOW, DET, TR/CAP, S/LOSS, CH/RD, CH/SD.

A sample output file, showing the results of the model when run using the sample input file (Table 3) is shown in Table 7.

SENSITIVITY ANALYSIS

In any modelling work it is important to know to what extent the model's output is affected by small changes in the values of the input data. One advantage of a simple model is that such a sensitivity analysis can be carried out by the relatively straightforward process of partial differentiation. With more complex models cumbersome numerical work is required, yielding results which are difficult to interpret and generalize (Lane and Ferreira, 1980).

Sensitivity analysis by differentiation is most simply illustrated by assessing the effect on transport capacity (G) of changes in input parameters. Equations 2 and 6 from Table 2 can be manipulated to give:

$$G = CFAC * SLP * (RAIN)^2 * EXP(-2Q) * .001 \qquad \text{(where } Q = Rc/Ro\text{)}$$

Taking natural logarithms and differentiating yields

$$\frac{dG}{G} = \frac{d(CFAC)}{CFAC} + \frac{d(SLP)}{SLP} + 2\,\frac{d(RAIN)}{RAIN} - 2dQ.$$

Hence for small changes, the proportional change in G will be given by the sum of the proportional changes in C and SLP plus twice the proportional change in RAIN minus twice the absolute change in Q. The value of Q is determined by the values of MS, BD, RD, ETEO, RAIN and RDAY, and its derivative can easily be calculated in terms of these parameters. Table 8 shows the effect on transport capacity of a 1% change in various input parameters.

Table 8: Sensitivity of Transport Capacity

1% change in	% change in transport capacity
RAIN	2(1+Q)
MS; BD; RD; RDAY	-2Q
ETEO	-Q
CFAC; SLP	1

For the data set presented earlier, the value of Q is around 2, though it will be greater for soils with a larger moisture storage capacity and topsoil depth. Table 8 presents the parameters in decreasing order of sensitivity: the most sensitive input parameters need to be assessed with the greatest accuracy.

The sensitivity of the detachment rate can be determined in a similar manner, though more involved algebraic manipulation is necessary. Table 9 summarizes the results.

Table 9: Sensitivity of Detachment Rate

1% change in	% change in detachment
K;RAIN	1
INTENS	$(3.1 + \ln \text{INTENS})^{-1}$ (=0.2 here)
INCEP (1% absolute change)	-0.05

Clearly the detachment rate is overall much less sensitive to changes in values of input parameters than is transport capacity: although careful thought will need to be given to values of K and INCEP, good quality data exists for RAIN, and INTENS has little effect. However if erosion is generally transport limited the validity of the results produced by the model will depend crucially on the accuracy of the input data for the soil parameters, especially moisture storage capacity (MS), bulk density (BD) and topsoil depth (RD), which can be difficult to estimate. No matter how good the predictions of soil loss are, the assessment of the stability of the soil depends equally importantly on the estimate for RN, the renewal rate of the topsoil, and good quality data on this parameter are extremely hard to obtain.

One further topic deserves mention, namely the possible use of average annual rainfall data. The use of average figures for RAIN and RDAY causes a slight underestimation of the average annual soil erosion rate, as the decreased erosion in relatively dry years does not balance out the increase in relatively wet years, due to the non-linearity of the relationships involved. One strategy that should not be adopted is the use of actual values of RAIN with average values of RDAY, as their ratio will then not be realistic, and this ratio is an important determinant of the transport capacity: use of this strategy is likely to cause substantial over-estimation of transport capacity.

EXAMPLES OF USE

The following examples taken from the Silsoe area of Bedfordshire, England, show how the model might be applied. This region was selected for trials with the model because measurements of soil loss and runoff were available and a comparison is therefore possible between observed and predicted values.

Table 10 shows the results of using the model to assess the stability of the erosion system under existing landuse at seven sites. All except the sandy soil with no plant cover are stable over the seven-year period considered, with slight increases being predicted in both total and top soil depth. Comparison of the results with observed data reveals that the model consistently underpredicts the rate of splash detachment but gives reasonable predictions of runoff and soil loss except for the sandy

Table 10. Observed and predicted mean annual values of runoff and soil loss and their effects on soil depth for sites in Bedfordshire, England.

Site	Runoff (mm)		Detachment (kg/m^2)		Soil loss (kg/m^2)		Predicted change (mm/y) in	
	Obs	Pred	Obs	Pred	Obs	Pred	Soil depth	Rooting or top soil depth
Silsoe - sand soil, no plant cover, 11^o slope	66	341	28.29	8.03	3.9	8.0	-5.1	-5.3
Silsoe - sand soil, grass, 11^o slope	17	28	n/a	1.79	2.3	0.001	+0.2	+0.2
Maulden - sandy loam soil, woodland, 16^o slope	9	2	n/a	1.20	0.001	0.00	+0.2	+0.2
Pulloxhill - clay soil, spring barley, 10^o slope	1	9	5.30	0.15	0.07	0.003	+0.19	+0.14
Ashwell - chalk soil, winter wheat, 10^o slope	5	5	15.87	2.11	0.07	0.002	+0.19	+0.14
Meppershall - clay soil, wheat/barley rotation, 10^o slope	6	5	4.47	0.12	0.05	0.001	+0.19	+0.14
Woburn - sandy loam soil, oats/wheat/beans rotation 7^o slope	11	11	19.75	3.43	0.06	0.005	+0.19	+0.14

Notes

Initial rooting depth = 50 mm for all sites. Weathering rate = 0.2 mm/y for all sites. Soil renewal rate = 0.01 for bare soil; 0.2 for grass and woodland; and 0.15 mm/y for other sites. Simulation for 1973-1979 inclusive

Table 11. Predicted mean annual values of runoff, soil loss and changes in soil depth and rooting depth for a sandy soil site at 11^{o} slope at Silsoe, Bedfordshire, England

Management system	Runoff (mm)	Detachment (kg/m^2)	Soil loss (kg/m^2)	Change (mm/y) in	
				Soil depth	Top soil or rooting depth
Continuous winter wheat	53	2.99	0.21	+0.06	+0.01
Market gardening good husbandry	84	3.83	0.60	-0.20	-0.25
Market gardening bad husbandry	88	3.83	0.65	-0.34	-.039

Notes

Initial rooting depth = 50 mm

Weathering rate = 0.2 mm/y

Soil renewal rate = 0.15 for winter wheat and market gardening with good husbandry; 0.05 for market gardening with bad husbandry

Simulation for a 20-year period.

soil plots with grass and with no plant cover. The predicted soil loss is lower than the observed for the plot with grass but higher than the observed for the plot with no cover. In both cases the predicted runoff is higher than the observed. It should be noted, however, that if the observed runoff were used as input to the sediment phase of the model, the observed soil loss on the bare soil plot could never be predicted from it. Generally, the results of these trials are not as good as those obtained when applying the model to conditions in Malaysia (Morgan, Hatch and Sulaiman, in press) but, given the levels of accuracy of determining soil renewal rates and weathering rates, the model still provides a realistic and very rapid indication of the effects of existing landuse on soil depths over a period of years.

To show how the model could be used to compare the effects of different landuse strategies, a synthetic 20-year sequence of rainfall records was generated for the Silsoe area, based on the statistical distribution of the observed data. Erosion rates were predicted for a sandy soil site on an 11^{o} slope under continuous winter wheat, market gardening with good husbandry and market gardening with bad husbandry. Because of the steep slope, a top soil depth of only 50 mm was assumed for the initial condition. Field observations support the selection of such a shallow depth. The weathering rate is taken as 0.2 mm/y. The recommendations of McCormack and Young (1981; Table 5) indicate a value of 0.2 mm/y as appropriate for the top soil renewal rate but, given the dependence of the local farming system on chemical rather than organic fertilizers and on continuous cropping without grass leys or rotation, the renewal rate has been reduced to 0.15 mm/y for winter wheat and market gardening with good husbandry. It is assumed that for market gardening with bad husbandry the farmer adds very little nutrient to the soil and that a renewal rate of 0.05 mm/y is realistic. The market gardening regime comprises a two-year rotation of broad beans and cabbage in the first year followed by early potatoes and cabbage.

The results (Table 11) of the twenty-year simulation show that continuous winter wheat produces relatively stable conditions but that market gardening even with good husbandry, produces a decreasing soil depth. Further simulations were carried out for the market gardening with good husbandry to determine the maximum permissible slope steepness at which stable conditions would occur; this was found to be 5^{o}. Similar simulations could be undertaken to determine the values of rainfall interception, Et/Eo and C-factor which would be required to produce stable soil depths. Using the model in this way illustrates perhaps its greatest advantage. The model simulates the production of runoff and sediment from a hillside in a manner which, qualitatively at least, represents what happens in practice. The major factors which influence the runoff and erosion processes are included in the model in a structure which is sufficiently simple for the user to understand their effects. Thus, when the model predicts that a particular landuse system is unstable in terms of its erosion effects, it is generally clear which factors should be changed in order to bring about stability. With this background, the soil conservationist can then work out a strategy to produce the required change.

APPENDIX 1 - PROGRAM LISTING

```
      Program Ncmod
c***** NCAE Erosion stability model;
c***** Program written by D. Morgan: June 1982
      integer year,rday
      real ms,k,intens,incep,ke
      dimension blurbl(15),blurb2(15),blurb3(15),t(8)
      ir=2
      iw=3
      read (ir,100) (blurbl(i),i=1,15)
      read (ir,100) (blurb2(i),i=1,15)
      read (ir,100) (blurb3(i),i=1,15)
      read (ir,200) ms,bd,rd,sd,k,weart,rnwrt,slp,ny
      rda=rd*1000
      sda=sd*1000
      do 20 i=1,8
   20 t(i)=0.
      write (iw,700)
      write (iw,800) (blurbl(i),i=1,15)
      write (iw,800) (blurb2(i),i=1,15)
      write (iw,800) (blurb3(i),i=1,15)
      write (iw,900)
      write (iw,950)
      do 10 n=1,ny
      read (ir,500) year,irain,rday,intens,incep,eteo,cfac
      rain=irain
      ke=(11.89+8.74*alog10(intens))*rain
      wsat=ms*bd
      h=wsat*rda
      rc=h*sqrt(eteo)
      ro=rain/rday
      of=rain*exp((-1)*rc/ro)
      det=k*ke*exp(-.05*incep)*.001
      g=cfac*of**2*slp*.001
      sl=g
      if (det.lt.g) sl=det
      delrd=rnwrt-sl/bd
      if (rda+delrd.ge.0.) goto 30
      delrd=(-1)*rda
      rda=0.
      goto 40
   30 rda=rda+delrd
   40 delsd=weart-sl/bd
      if (sda+delsd.ge.0.) goto 50
      delsd=(-1)*sda
      sda=0
      goto 60
   50 sda=sda+delsd
   60 ike=int(ke+0.5)
      t(1)=t(1)+rain/ny
      t(2)=t(2)+ke/ny
      t(3)=t(3)+of/ny
      t(4)=t(4)+det/ny
```

```
      t(5)=t(5)+g/ny
      t(6)=t(6)+sl.ny
      t(7)=t(7)+delrd/ny
      t(8)=t(8)+delsd/ny
   10 write (iw,600) year,irain,ike,rc,of,det,g,sl,delrd,rda,delsd,sda
      it1=int(t(1)+0.5)
      it2=int(t(2)+0.5)
      write (iw,300)
      write (iw,400) it1,it2,(t(i),i=3,8)
      stop
  100 format (15a4)
  200 format (8f6.2,i6)
  300 format (/,94('-')/)
  400 format (' mean',2i8,8x,f8.1,4f8.2,8x,f8.2)
  500 format (3i6,4f6.2)
  600 format (1h ,i4,2i8,2f8.1,4f8.2,f8.1,f8.2,f8.1)
  700 format (29h ncae erosion stability model,/)
  800 format (1h ,15a4)
  900 format (//' year    rain     ke       rc     o/flow   det     tr/cap
     1 s/loss   ch/rd    rd     ch/sd    sd')
  950 format ('          (mm)    (j/m2)   (mm)     (mm)   (kg/m2) (kg/m2) (k
     1g/m2)   (mm)     (mm)     (mm)     (mm)',/)
      end
      finish
***F
***F
```

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