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Catena 44 (2001) 305–322

CATENA

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A simple approach to soil loss prediction: a revised Morgan–Morgan–Finney model

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Received 18 April 2000; received in revised form 20 August 2000; accepted 10 November 2000

Abstract

A revised version of the Morgan–Morgan–Finney model for prediction of annual soil loss by water is presented. Changes have been made to the way soil particle detachment by raindrop impact is simulated, which now takes account of plant canopy height and leaf drainage, and a component has been added for soil particle detachment by flow. When tested against the same data set used to validate the original version at the erosion plot scale, predictions made with the revised model gave slopes of a reduced major-axis regression line closer to 1.0 when compared with measured values. The coefficient of efficiency, for sites with measured runoff and soil loss, increased from 0.54 to 0.65. When applied to a new data set for erosion plots in Denmark, Spain, Greece and Nepal, very high coefficients of efficiency of 0.94 for runoff and 0.84 for soil loss were obtained. The revised version was applied to two small catchments by dividing them into land elements and routing annual runoff and sediment production over the land surface from one element to another. The results indicate that, when used in this way, the model provides useful information on the source areas of sediment, sediment delivery to streams and annual sediment yield. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Soil erosion; Sediment yield; Erosion modelling

1. Introduction

Morgan et al. (1984) presented a simple empirical model for predicting annual soil loss from field-sized areas on hillslopes. The MMF model used the concepts proposed by Meyer and Wischmeier (1969) and Kirkby (1976) to provide a stronger physical base than the Universal Soil Loss Equation (Wischmeier and Smith, 1978), yet retain the

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PII: S0341-8162(00)00171-5

advantages of an empirical approach regarding ease of understanding and availability of data. The model was validated by the authors (1984) using erosion plot data for 67 sites in 12 countries and then applied to simulate erosion over a 100-year period in Malaysia under shifting cultivation. Since then, several researchers have used the model successfully in a wide range of environments ranging from Indonesia (Besler, 1987) to Nepal (Shrestha, 1997) and the Rocky Mountains (Morgan, 1985a). De Jong and Riezebos (1992) incorporated the model into a Geographical Information System from which De Jong (1994) developed SEMMED (Soil Erosion Model for Mediterranean areas) and applied it to the Bas-Vivarais area of Ardèche Province, southern France, using remote sensing as a data source. Paracchini et al. (1997) applied SEMMED to the 100-km^2 Timeto watershed in Sicily. A more recent summary of results with SEMMED is given by De Jong et al. (1999). The MMF model was also adapted to provide a method of assessing erosion and evaluating different control methods on road banks and construction sites (Coppin and Richards, 1990).

Although the MMF model has proved simple to use and is able to give reasonable estimates of annual runoff and erosion, some input parameters have been difficult to determine. In particular, the top soil rooting depth (RD) gives problems of definition since it describes the effective hydrological depth within which the storage of water affects the generation of runoff. Although water storage in the soil is clearly affected by the depth and density of the roots, it is also dependent upon the horizonation of the soil profile, especially the depth of the A-horizon. Therefore, RD is invariably much shallower than that normally recognised by an agriculturalist or agronomist. Morgan et al. (1984) recommended values of 0.05 m for grass and 0.1 m for trees and tree crops. Where measured runoff data are available, RD can be used as a calibrating term when operating the model.

At the time the MMF model was developed, the soil detachability index (K) was not determined experimentally for all soil types. Since then, detachability values have been obtained for a wider range of soils for use in the European Soil Erosion Model (EUROSEM; Morgan et al., 1998). The values included in the EUROSEM User Guide (Morgan et al., 1993; http://www.silsoe.cranfield.ac.uk/eurosem/eurosem.htm) are an order of magnitude higher than those proposed by Morgan et al. (1982) which were based on rainfall simulation experiments carried out by Quansah (1982). If the values for EUROSEM are used, the MMF model will overpredict erosion. A consistent set of values suitable for the MMF model is therefore required.

Research on rainfall interception has indicated that the exponential decay function used in the MMF model to calculate soil particle detachment as a function of rainfall energy is a simplification. It assumes that the intercepted rainfall does not contribute to detachment whereas, in reality, the proportion which reaches the ground surface as leaf drainage is capable of detaching soil particles from the soil mass, depending on the height of fall (Finney, 1984; Morgan, 1985b; Styczen and Høgh-Schmidt, 1988). An improved description is required for the soil detachment by raindrop impact, allowing for the effect of leaf drainage.

The MMF model simplified the erosion processes into two: detachment of soil particles from the soil mass by raindrop impact and the transport of those particles by runoff. The ability of rainfall to transport soil particles downslope and of runoff to detach soil particles were ignored. Since the model was designed to evaluate erosion where rates are likely to be accelerated by human impact, it may be reasonable to neglect the transport of particles by raindrop impact because the rates will not be high enough to present a problem. However, the case for neglecting the detaching power of runoff is harder to sustain, particularly on steep slopes and where runoff becomes channelled into rills. The model should therefore be improved by including soil particle detachment by runoff.

The last decade has seen a change in the use of erosion models from prediction of soil loss at a field scale to the simulation of the movement of sediment over the land surface from its point of detachment to either sites of deposition or delivery to water courses. The change in focus arises from increasing concern about pollution and sedimentation problems downstream of eroded areas with less emphasis, particularly in North America and the European Union, on the implications of erosion for long-term soil productivity.

This paper presents a revised version of the MMF model which takes account of the need to improve the description of the processes of erosion and the requirement of users for better guidance on the choice of input parameter values. The revised version is tested against the data set used to validate the original version of the model and the differences in performance are noted. The revised version is further tested against a smaller more recent data set. The model is then applied to two small catchments to show how it might be used to evaluate the transport of sediment over the landscape and its delivery to water courses.

2. The revised MMF model

The MMF model separates the soil erosion process into two phases: the water phase and the sediment phase. The water phase determines the energy of the rainfall available to detach soil particles from the soil mass and the volume of runoff. In the erosion phase, rates of soil particle detachment by rainfall and runoff are determined along with the transporting capacity of runoff. Using the procedure proposed by Meyer and Wischmeier (1969), predictions of total particle detachment and transport capacity are compared and erosion rate is equated to the lower of the two rates. Table 1 gives a list of the input parameters needed to operate the revised version.

2.1. Estimation of rainfall energy

The procedure for calculating the energy of rainfall is revised from that in the original version of the model to take account of the way rainfall is partitioned during interception and the energy of the leaf drainage. The model takes the annual rainfall total (R; mm) and computes the proportion (between 0 and 1) which reaches the ground surface after allowing for rainfall interception (A) to give the effective rainfall (ER):

$$\mathrm{ER} = RA \tag{1}$$

Table 1
Input parameters for the revised MMF model

Factor	Parameter	Definition and remarks
Rainfall	R	Annual or mean annual rainfall (mm)
	R_n	Number of rain days per year
	I	Typical value for intensity of erosive rain (mm/h); use 10 for temperate climates, 25 for tropical climates and 30 for strongly seasonal climates (e.g. Mediterranean type and monsoon)
Soil	MS	Soil moisture content at field capacity or 1/3 bar tension (% w/w)
	BD	Bulk density of the top soil layer (Mg/m^3)
	EHD	Effective hydrological depth of soil (m); will depend on vegetation/crop cover, presence or absence of surface crust, presence of impermeable layer within 0.15 m of the surface
	K	Soil detachability index (g/J) defined as the weight of soil detached from the soil mass per unit of rainfall energy
	COH	Cohesion of the surface soil (kPa) as measured with a torvane under saturated conditions
Landform	S	Slope steepness (°)
Land cover	A	Proportion (between 0 and 1) of the rainfall intercepted by the vegetation or crop cover
	E_t/E_o	Ratio of actual (E_t) to potential (E_o) evapotranspiration
	C	Crop cover management factor; combines the C and P factors of the Universal Soil Loss Equation
	CC	Percentage canopy cover, expressed as a proportion between 0 and 1
	GC	Percentage ground cover, expressed as a proportion between 0 and 1
	PH	Plant height (m), representing the height from which raindrops fall from the crop or vegetation cover to the ground surface

Typical values for A for different vegetation and crop types are given in Morgan (1995).

The effective rainfall (ER) is then split into that which reaches the ground surface as direct throughfall (DT) and that which is intercepted by the plant canopy and reaches the ground as leaf drainage (LD). The split is a direct function of the percentage canopy cover (CC):

$$\mathrm{LD} = \mathrm{ER} \times \mathrm{CC} \tag{2}$$

$$\mathrm{DT} = \mathrm{ER} - \mathrm{LD} \tag{3}$$

The kinetic energy of the direct throughfall (KE(DT); J/m^2) is determined as a function of the rainfall intensity (I; mm/h), using a typical value for the erosive rain of the climatic region (Table 1). The original version of the MMF model used the relationship (Wischmeier and Smith, 1978):

$$\mathrm{KE(DT)} = \mathrm{DT}(11.9 + 8.7 \log I) \tag{4}$$

which would be applicable to much of the USA east of the Rocky Mountains. Alternative equations based on local rainfall energy–intensity relationships are now available (Table 2) and may be used for the bracketed term in Eq. (4).

Table 2
Relationships between kinetic energy (KE; J m^{-2} mm^{-1}) and rainfall intensity (I; mm/h)

Equation	Remarks
$KE = 11.87 + 8.73 \log_{10} I$	Assumes raindrop size distribution similar to that measured by Laws and Parsons; used as the basis for rating erosivity in the Universal Soil Loss Equation (Wischmeier and Smith, 1978); suitable for North America east of the Rocky Mountains
$KE = 8.95 + 8.44 \log_{10} I$	Assumes raindrop size distribution similar to that measured by Marshall and Palmer; suitable for north-western Europe and similar climates
$KE = 9.81 + 11.25 \log_{10} I$	Developed by Zanchi and Torri (1980) for central Italy; suitable for Mediterreanean-type climates
$KE = 35.9(1 - 0.56e^{-0.034I})$	Developed by Coutinho and Tomás (1995) in Portugal; suitable for western Mediterranean
$KE = 29.8 - (127.5/I)$	Developed by Hudson (1965) in Zimbabwe; use for tropical climates
$KE = 9.81 + 10.60 \log_{10} I$	Developed by Onaga et al. (1998) for Okinawa, Japan; use for eastern Asia
$KE = 29.0(1 - 0.6e^{-0.04I})$	Developed by Rosewell (1986) for New South Wales, Australia; use for temperate southern hemisphere climates

Where available, other locally derived equations may be used in preference to the above.

The kinetic energy of the leaf drainage (KE(LD); J/m^2) is dependent upon the height of the plant canopy (PH; m) as proposed by Brandt (1990):

$$KE(LD) = (15.8 \times PH^{0.5}) - 5.87 \tag{5}$$

Where Eq. (5) yields a negative value, the energy of the leaf drainage is assumed to be zero.

The total energy of the effective rainfall (KE; J/m^2) is obtained from:

$$KE = KE(DT) + KE(LD) \tag{6}$$

2.2. Estimation of runoff

The procedure for estimating the annual runoff (Q; mm) remains unchanged. It is based on the method proposed by Kirkby (1976) which assumes that runoff occurs when the daily rainfall exceeds the soil moisture storage capacity (R_c; mm) and that daily rainfall amounts approximate an exponential frequency distribution. The annual runoff is obtained from:

$$Q = R\exp(-R_c/R_o) \tag{7}$$

where R_o = the mean rain per rain day (mm) (i.e. R/R_n, where n = the number of rain days in the year).

The soil moisture storage capacity is estimated from:

$$R_c = 1000MS \times BD \times EHD(E_t/E_o) \tag{8}$$

where MS = the soil moisture content at field capacity (% w/w), BD = the bulk density of the soil (Mg/m^3), EHD = the effective hydrological depth of the soil (m) and E_t/E_o = the ratio of actual to potential evapotranspiration. The term, EHD, replaces the rooting depth (RD) used in the original model and indicates the depth of soil within which the moisture storage capacity controls the generation of runoff. It is a function of the plant cover, which influences the depth and density of roots, and, in some instances, the effective soil depth, for example on soils shallower than 0.1 m or where a surface seal or crust has formed. Table 3 gives some guide values for EHD for use with the revised MMF model. At present, the effect of different types of tillage practice on EHD has not been evaluated. It is recommended that tillage be accounted for by adjusting the C factor value (Eq. (12) below).

2.3. Soil particle detachment by raindrop impact

In the revised MMF model, rainfall interception is allowed for in the estimation of rainfall energy. It is therefore removed from the equation used to describe soil particle detachment by raindrop impact (F; kg/m^2) which then simplifies to:

$$F = K \times \mathrm{KE} \times 10^{-3} \tag{9}$$

where K is the erodibility of the soil (g/J). Guide values for K have been revised and now cover a wider range of soil textures (Table 4).

2.4. Soil particle detachment by runoff

The revised model includes a new component to estimate the detachment of soil particles by runoff. Based on experimental work by Quansah (1982), this is considered

Table 3
Recommended values for Effective Hydrological Depth (EHD)

Condition	EHD (m)
Bare soil without surface crust; no impermeable barrier in top 0.2 m	0.09
Bare shallow soils on steep slopes; crusted soils	0.05
Row crops (e.g. wheat, barley, maize, beans, rice)	0.12
Row crops intercropped with legumes/grasses	0.15
Mature forest, dense secondary forest	0.20
Rubber, oil palm	0.15
Cocoa, coffee	0.12
Banana	0.18
Savanna/prairie grass	0.14
Cultivated grass	0.12
Cotton	0.10
Groundnut	0.12

Where terracing is used, add 0.01 to EHD to take account of the resulting increase in water storage.

Table 4
Guide values for soil parameters

Soil type	MS	BD	K	COH
Sand	0.08	1.5	1.2	2
Loamy sand	–	–	0.3	2
Sandy loam	0.28	1.2	0.7	2
Loam	0.20	1.3	0.8	3
Silt	–	–	1.0	–
Silt loam	0.25	1.3	0.9	3
Sandy clay loam	–	–	0.1	3
Clay loam	0.40	1.3	0.7	10
Silty clay loam	–	–	0.8	9
Sandy clay	–	–	0.3	–
Silty clay	0.30	–	0.5	10
Clay	0.45	1.1	0.05	12

The parameters MS, BD, K and COH are defined in Table 1; where available, measured values should always be used in preference to the guide values given above.

as a function of runoff (Q), slope steepness (S) and the resistance of the soil (Z). The detachment by runoff (H; kg/m^2) is estimated from:

$$H = ZQ^{1.5}\sin S(1 - \mathrm{GC}) \times 10^{-3} \tag{10}$$

where GC = percentage ground cover. The equation assumes that soil particle detachment by runoff occurs only where the soil is not protected by ground cover. As a first approximation, this seems reasonable since, where a vegetation cover is present, the shear velocity of the flow is imparted to the plants and not to the soil.

For loose, non-cohesive soils, $Z = 1.0$. Based on a simplification of the work of Rauws and Govers (1988) which emphasized the cohesion of the soil (COH; kPa) as an important component of its resistance to erosion:

$$Z = \frac{1}{(0.5\mathrm{COH})} \tag{11}$$

Values of cohesion should be obtained for saturated soil using a torvane. Table 4 gives some guide values based on those used in EUROSEM (Morgan et al., 1993).

2.5. Transport capacity of runoff

The method for estimating transport capacity of the runoff (TC; kg/m^2) remains unchanged from that used in the original version of the model, so that:

$$\mathrm{TC} = CQ^2\sin S \times 10^{-3} \tag{12}$$

where C = the crop or plant cover factor, taken as equal to the product of the C and P factors of the Universal Soil Loss Equation, and S is the slope angle (°). The C factor can be adjusted to take account of different tillage practices and levels of crop residue retention.

Table 5
Comparison of predicted annual runoff and soil loss from old and new versions of the MMF model

Site	Runoff (mm)			Soil loss (kg/m^2)		
	Observed	Prediction old version	Prediction new version	Observed	Prediction old version	Prediction new version
Lushoto, Tanzania						
Clay soil, maize/beans intercropping	0.2–1.0	3.74–6.85	11.93–18.98	0.001	0.001–0.002	0.005–0.014
Sandy clay loam, evergreen forest	2.6–5.7	2.59–5.96	45.57–79.39	0.001–0.003	0.000	0.002–0.005
Sandy clay loam, steep slope, evergreen forest	8.5–14.8	3.25–7.31	51.25–88.29	0.001–0.013	0.000	0.004–0.013
Clay, steep slope, maize/beans intercropping	0.4–0.8	3.74–6.85	1.06–11.93	0.001	0.001–0.004	0.000–0.012
Adiopodoumé, Ivory Coast						
Sandy loam, secondary tropical forest	15.0	85.9	315.5	0.001–0.02	0.003	0.0464
Sandy loam, bare ground	707–1415	1268.1	1141.8	6.9–15.0	15.5	17.5
Sandy loam, oil palm	43–172	57.8	332.5	0.001–0.05	0.02	0.77
Sandy loam, banana with mulch	11–86	102.4	384.5	0.004–0.005	0.002	0.021
Sandy loam, maize	643–1608	355.0	616.9	3.5–13.1	3.53	8.85
Sandy loam, groundnut	579–1565	452.7	730.9	5.9–12.0	7.17	3.09
Sefa, Senegal						
Loam, secondary tropical forest	1.6–19.2	154.8	399.9	0.002–0.02	0.009	0.006
Loam, groundnut	130–699	370.8	723.4	0.29–1.63	1.38	2.43
Loam, cotton	15–699	429.0	645.8	0.05–1.85	1.84	4.17
Loam, mechanized maize	504	420.3	636.8	1.03	0.71	1.62
Loam, sorghum	390–683	442.5	659.9	0.33–1.24	1.57	3.48
Pong Khrai, Thailand						
Clay loam, upland rice	22–32	34.4	102.3	1.4–2.4	0.07	2.20
Clay loam, upland rice, bench terraces	16–53	34.4	83.9	1.1–1.3	0.011	0.63
Marchiazza Basin, Italy						
Loamy sand, bare soil with tufted grass	201–261	186.7	341.2	2.7–3.1	3.25	4.14
Loamy sand, Molinia moor grass	51–58	56.9	112.1	0.05–0.09	0.006	0.02
Loamy sand, chestnut and oak trees	36–38	48.3	92.0	0.009–0.018	0.002	0.005

Hesbaye, Belgium						
Sandy loam, sugar beet	n/a	60.7	5.24	0.13–2.95	0.10	0.001
Sandy loam, winter wheat	n/a	78.6	8.66	0.045–0.10	0.10	0.003
Sandy loam, bare ground	n/a	415.6	84.13	0.6–8.25	12.01	0.78
Trier, Germany						
Sandy loam, vines	n/a	5.8	25.54	0.003–0.004	0.005	0.134
Taiwan						
Clay loam, citrus, clean cultivation	1268	580.2	654.4	15.64	10.25	16.34
Clay loam, citrus, bench terracing	344	580.2	543.0	0.50	4.71	8.25
Clay loam, citrus with mulch	109	517.9	360.0	0.094–0.28	0.22	0.07
Clay loam, banana, clean cultivation	1113–1449	279.7	346.1	3.94–6.37	5.40	8.27
Clay loam, banana with mulch	189	245.6	256.5	0.009	0.042	0.015
Clay loam, banana with contour bunds	483–1029	279.7	346.1	0.11–0.39	0.54	0.22
Henderson, Zimbabwe						
Clay, maize	8–61	26.7	77.7	0.2–0.3	0.013	0.106
Clay, cropped grass	8–26	18.6	60.8	0.05–0.1	0.000	0.016
Mpwapwa, Tanzania						
Sandy loam, bare ground	446	212.7	389.5	14.7	2.78	6.64
Sandy loam, sorghum and millet	80–259	5.72	140.9	5.5–9.0	0.001	0.61
Sandy loam, tufted grass	8–65	2.9	109.6	0.0–0.07	0.000	0.07
Sandy loam, savanna grass	3–4	20.4	58.6	0.0	0.000	0.002
Lyamungu, Tanzania						
Clay loam, coffee, clean cultivation	15–232	28.18	165.5	4.3	0.04	1.36
Clay loam, coffee, cover crops	10–98	9.57	54.3	0.4	0.002	0.015
Clay loam, coffee, contour ridges	36	28.18	165.5	0.3	0.004	0.09
Clay loam, coffee, cover crops, contour ridges	27	9.57	54.3	0.1	0.000	0.005

(continued on next page)

Table 5 (*continued*)

Site	Runoff (mm)			Soil loss (kg/m^2)		
	Observed	Prediction old version	Prediction new version	Observed	Prediction old version	Prediction new version
Tuanshuangou, China						
Silt loam, millet/mungbean	n/a	278.3	117.6–307.5	0.1–23.4	7.89	0.84–3.15
Silt loam, potato	n/a	250.3	219.6	43.9	7.59	2.00
Silt loam, alfalfa	n/a	238.5	257.8	4.4	0.23	0.27
Malaysia						
Sandy loam, oil palm	263–657	294–757	307–792	0.77–0.89	0.29–0.76	0.32–0.73
Sandy loam, bare soil	532–642	827	1346	2.93–3.39	3.73	6.56
Sandy loam, groundnut	273–328	273	636	0.64–1.01	1.04	0.74
Sandy loam, maize	365–378	340	726	0.56–0.81	1.07	1.36
Sandy loam, maize with mulch	73–80	298	638	0.04–0.06	0.06	0.15
Sandy clay loam, bare soil	688–941	829	1667	2.44–3.92	3.93	7.10
Sandy clay loam, groundnut	241–388	266	439	0.51–0.97	0.99	0.61
Sandy clay loam, cowpea	260–302	291	471	0.59–0.61	1.18	1.37
Clay loam, primary rain forest	n/a	181	111	0.004–0.024	0.027	0.01
Silsoe, United Kingdom						
Sandy soil, bare ground	66	341	355	3.9	8.0	3.95
Sandy soil, grass	17	28	68	2.3	0.001	0.18
Sandy loam, woodland	9	2	0.65	0.001	0.000	0.000
Clay, spring barley	1	9	0.39	0.07	0.003	0.000
Clay, winter wheat/spring barley	6	5	4.73	0.05	0.001	0.001
Sandy loam, oats/wheat/beans	11	11	0.39	0.06	0.005	0.000
Chalk, winter wheat	5	5	6.34	0.07	0.002	0.002

For sources of measured data, see Morgan and Finney (1982).

2.6. Estimation of erosion

The estimates of soil particle detachment by raindrop impact and by runoff are added together to give a total annual detachment rate. This is then compared with the annual transport capacity and the lesser of the two values is the annual erosion rate (Meyer and Wischmeier, 1969).

3. Validation of the revised MMF model with the original data set

New data input files were prepared for the 67 sites used for validating the original version of the MMF model on erosion plots of varying sizes. Table 5 lists the sites, the observed annual runoff and erosion rates, and the predicted values obtained with the old and new versions of the model. Information on the sites and sources of the measured data are contained in Morgan and Finney (1982).

For comparing the predicted (Y) with the observed (X) values, Morgan et al. (1984) used reduced major-axis regression lines (Kermack and Haldane, 1950; Till, 1973) to allow for likely errors in observed values. The original version of the model produced the following results for which coefficient of efficiency (CE) values (Nash and Sutcliffe, 1970; Risse et al., 1993) have been calculated to indicate the variance from a one-to-one prediction line:

$$Y = 19.776 + 0.775X \text{ for runoff}, n = 56, \mathrm{CE} = 0.69 \tag{13}$$

$$Y = 0.472 + 0.503X \text{ for soil loss}, n = 67, \mathrm{CE} = 0.43 \tag{14}$$

$$Y = -0.090 + 0.896X \text{ for soil loss}, n = 65, \mathrm{CE} = 0.54 \tag{15}$$

Eq. (15) is obtained after the removal of 2 years of data from the site in China where the model failed to predict extremely high rates of erosion; the slope of the regression line is not significantly different from unity ($t = 1.112 < t_{0.05} = 2.00$) and the CE value compares with the value of 0.58 obtained by Risse et al. (1993) for predicting annual soil loss with the Universal Soil Loss Equation. Although these results indicated that the model performed reasonably well, runoff predictions were poor where ridging and terracing were used for erosion control or where mulching was adopted. In addition, although the model correctly indicated very low rates of erosion (< 0.1 kg/m^2) where this was the case, the predictions were often an order of magnitude out (see values for the sites in Tanzania and UK in Table 5).

The results for the new version of the model are:

$$Y = 80.71 + 1.000X \text{ for runoff}, n = 56, \mathrm{CE} = 0.58 \tag{16}$$

$$Y = 0.386 + 0.527X \text{ for soil loss}, n = 67, \mathrm{CE} = 0.27 \tag{17}$$

$$Y = 0.092 + 1.064X \text{ for soil loss}, n = 56, \mathrm{CE} = 0.65 \tag{18}$$

Eq. (18) is based on omitting data for those sites in Belgium, Malaysia and China for which observed runoff values are not available. The results for runoff (Eq. (16)) give a

Table 6
Comparison of observed and predicted annual runoff and soil loss for revised MMF model

Site	Runoff (mm)		Soil loss (kg/m^2)	
	Observed	Predicted	Observed	Predicted
Foulam, Denmark (loamy sand, 10% slope)				
Rye grass cut four times per year	11.0	4.5	0.003	0.000
Spring barley sown with rye grass, over winter, spring-ploughed	18.4	1.5	0.042	0.000
Spring barley, autumn ploughing	17.4	3.3	0.269	0.000
Winter wheat, autumn ploughing up-and-down slope	98.4	3.3	1.279	0.000
Winter wheat, autumn ploughing across slope	89.1	3.3	1.108	0.000
Bare soil fallow	111.6	59.2	1.087	0.365
Ødum, Denmark (sandy loam, 10% slope)				
Rye grass cut four times per year	4.7	3.5	0.003	0.000
Spring barley sown with rye grass, over winter, spring-ploughed	5.3	4.3	0.013	0.000
Spring barley, autumn ploughing	8.9	8.0	0.045	0.001
Winter wheat, autumn ploughing up-and-down slope	20.9	8.0	0.012	0.001
Winter wheat, autumn ploughing across slope	16.9	8.0	0.049	0.001
Bare soil fallow	46.2	83.7	0.593	0.672
El Ardal, Spain				
Sandy loam, bare soil fallow, 7% slope	5.9	116.7	0.009	0.948
Loam, matorral (mainly Rosemary, Juniper) 28% slope	5.0	20.8	0.007	0.018
Loam, cut matorral, 28% slope	9.4	20.8	0.046	0.049
Clay loam, barley, 7% slope	10.4	51.1	0.061	0.037
Clay loam, wheat, 7% slope	10.4	42.6	0.061	0.026
Spata, Greece				
Clay loam, olives, 19% slope	0.7	1.2	0.005	0.000
Clay loam, vineyard, 11% slope	3.4	1.3	0.041	0.000
Pakhribas, Nepal (sandy loam, 5% slope)				
Bare soil fallow	488	675	2.575	3.347
Maize/millet intercrop, tillage up-and-down slope	513	453	3.667	4.106
Maize/millet intercrop, tillage across slope	444	447	2.206	3.370
Traditional maize cultivation	487	453	3.286	3.286
Maize, minimum till, mulch	390	431	1.692	0.929

Observed data taken from Schjønning et al. (1995), López-Bermúdez (1993), Romero-Díaz et al. (1999) and Wouters and Shrestha (1986).

very good 1:1 relationship between observed and predicted values but the intercept value is much higher than was the case with the original model, indicating an overprediction of runoff at low values. This overprediction is the cause of the decrease in the coefficient of efficiency. The predicted erosion, expressed by Eq. (18), also yields a 1:1 relationship with an intercept value close to zero and a much improved value of the coefficient of efficiency. Overall, the revised MMF model appears to give better annual predictions of both runoff and soil loss than the original version.

4. Validation of the revised MMF model with a new data set

A further test of the new model was carried out using data from research stations at Foulum and Ødum, Denmark (Schjønning et al., 1995), El Ardal, Spain (López Bermúdez, 1993), Spata, Greece (Romero-Díaz et al., 1999) and Pakhribas, Nepal (Wouters and Shrestha, 1986) covering 24 sites in all. The list of sites with observed annual runoff and erosion rates and the rates predicted by the model is given in Table 6. The reduced major-axis regression lines for runoff and erosion show 1:1 relationships between observed and predicted values and, for erosion, an intercept value close to zero:

$$Y = -6.204 + 1.086\,X \text{ for runoff}, n = 24, \text{CE} = 0.94 \tag{19}$$

$$Y = -0.172 + 1.172\,X \text{ for soil loss}, n = 24, \text{CE} = 0.84 \tag{20}$$

These tests, with very high values for the coefficient of efficiency, indicate that the revised version of the model can give reasonable results in conditions ranging from the temperate climate of northern Europe to the Mediterranean climate of southern Europe and the tropical monsoon climate of the Himalayas.

5. Applications to small catchments

The application of the model to a catchment requires dividing the catchment into hillslope elements which can be considered reasonably homogeneous in their soil, slope and land cover. The elements are then arranged in a cascading sequence to represent how runoff passes over the land surface from one element to the next. The application depends on the assumption that it is feasible to average the water and sediment budgets for these elements over the period of 1 year or, in some cases, an average of years where mean annual data are used as inputs.

The routing procedure is relatively simple and operates as follows. The total runoff (Q) on element (i) is the summation of the runoff generated on element (i) and that received from the element immediately upslope. This summated runoff is used to determine the transport capacity on element (i). The annual rate of the supply of detached material on element (i) is the sum of the detachment rate by rainfall and runoff on element (i) and the influx of material from the element above. These estimates of detachment and transport capacity are used to determine the annual rate of sediment output from element (i) to either the next element downslope or the river system.

5.1. Application to the Kulekhani Watershed, Nepal

The revised MMF model is applied to a 0.0268-km^2 catchment within the Kulekhani Watershed which lies between 1620 and 1720 m in altitude in the middle mountains of the Himalayan Range in Nepal. Some 0.0252 km^2 of the catchment is treated with outward-sloping bench terraces on which maize, millet and beans are grown, and the remainder of the catchment is under a poor growth of secondary broad-leaved forest which is pruned annually for fodder and compost. The model is applied to the water year November 1991 to October 1992 when the rainfall total was 1106 mm. The soils are silt loams and 84% of the land area has slopes steeper than 15% (Perino, 1993). The catchment is divided into 17 land elements (Fig. 1; Table 7).

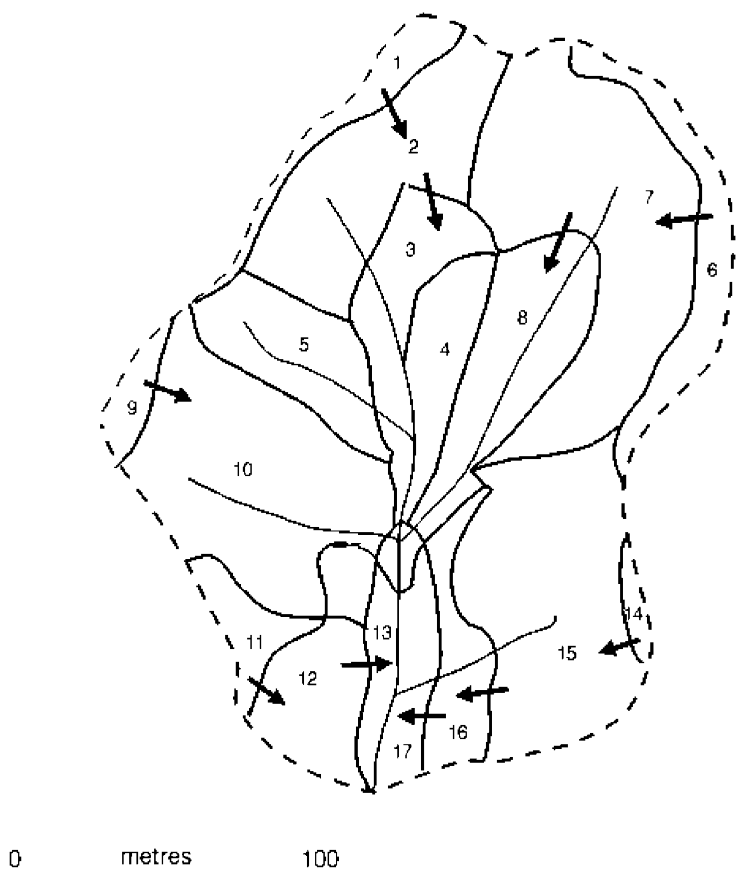

Fig. 1. Kulekhani Watershed showing land elements (numbered) and direction of flow from one element to another. Where no arrow is indicated, the element discharges directly into the river system.

Table 7
Predicted annual runoff and soil loss in the Kulekhani Watershed, Nepal, for the water year November 1991–October 1992

Land element	Soil loss (kg/m^2)		
	As single element	Allowing for routing	Net erosion
1—1% slope, bench terraces	0.01	0.01	0.01
2—40% slope, bench terraces	0.39	0.71	0.70
3—63% slope, bench terraces	0.61	3.19	2.48
4—23% slope, bench terraces	0.22	0.22	0.22
5—40% slope, bench terraces	0.39	0.39	0.39
6—1% slope, bench terraces	0.01	0.01	0.01
7—40% slope, bench terraces	0.39	0.51	0.50
8—23% slope, bench terraces	0.22	2.20	1.69
9—1% slope, bench terraces	0.01	0.01	0.01
10—63% slope, bench terraces	0.10	0.11	0.10
11—63% slope, bench terraces	0.61	0.61	0.61
12—40% slope, forest	0.17	0.64	0.04
13—23% slope, forest	0.10	1.76	2.40
14—1% slope, bench terraces	0.01	0.01	0.01
15—63% slope, bench terraces	0.61	0.76	0.75
16—63% slope, forest	0.27	1.80	1.05
17—23% slope, forest	0.10	6.28	4.48
Observed soil loss from catchment	0.53 kg/m^2		
Predicted soil loss from catchment	0.64 kg/m^2		
Observed runoff from catchment	7.24 mm		
Predicted runoff from catchment	9.22 mm		

Soil loss predictions are for each element with no input of soil from the slope above (column 2) and allowing for inputs of runoff and sediment from upslope (column 3). Net erosion (column 4) is the result of comparing annual output of sediment from the element with annual input from the slope above.

The results (Table 7) indicate that the model gives reasonable predictions of both runoff and erosion for the catchment as a whole. A detailed analysis of the individual elements shows that the contributors of sediment to the river system are elements 3, 13 and 17. By comparing the input and output of sediment, it is possible to determine the net erosion or deposition on each element. Table 7 also gives the field-scale erosion rate which would be predicted if each element was considered in isolation, i.e. with no routing of runoff and sediment over the land surface. These data show that erosion is highest on elements 3, 11 and 15 which are terraced slopes of 63%; in all cases, the annual amount is less than 1.0 kg/m^2. The routing procedure implies that with the downslope accumulation of runoff, giving increased erosion potential, the poor secondary growth of forest on elements 13 and 17 provide insufficient protection. For example, the predicted erosion for the year on element 17 is 0.10 kg/m^2 when considered in isolation but 0.28 kg/m^2 when it is placed in its catenary sequence. Summing the erosion on the individual elements yields a gross erosion rate of 1.02 kg/m^2 and a predicted sediment delivery ratio (0.64:1.02) of 63% which, for this size of catchment, seems reasonable (Renfro, 1975).

Table 8
Comparison of observed and predicted annual runoff and soil loss for the Catsop watershed in 1989

	Runoff (mm)	Soil loss (kg/m^2)
Observed value	7.35	not measured
Predicted value (data on land cover based on crops grown)	1.08	0.000006
Predicted value (data on land cover seasonally weighted to allow for periods of bare ground)	12.48	0.035

5.2. Application to the Catsop Watershed, The Netherlands

The Catsop is a 0.4585-km^2 catchment in South Limburg at altitudes of 80–110 m above sea-level, with silt loam soils and slopes of less than 10% over 84% of the land area. Mean annual precipitation is 675 mm. The revised MMF model was applied to the year 1989 when the land was under winter wheat, sugar beet and potatoes. The catchment was divided into 32 land elements which effectively represent different fields (see Folly et al., 1999 for the details). The predicted runoff for the year was 1.08 mm compared with a measured 7.35 mm. No data are available on measured erosion rates but the predicted rate is very low at 0.6 mg/m^2. These values were obtained using input data on land cover which is representative of the crops being grown in each field. However, data published by De Roo (1993) show that four of the eight major storms in 1989 occurred in December when the land in much of the catchment was bare. Values of the land cover parameters (CC, GC, E_t/E_o, C, PH) were therefore recalculated to give seasonally weighted data, taking account of the likely conditions at the time of the storms. With these recalculated values, the predicted runoff increases to a more reasonable 12.48 mm and the erosion rate to 0.35 g/m^2 (Table 8).

6. Conclusions

The revised MMF model provides an improved description of the water erosion processes operative on hillslopes in small catchments. The predictions of annual runoff and soil loss at an erosion plot scale are better than those obtained with the original version of the model, using results from the original data set as a basis for comparison. However, neither version predicts the very high rates of erosion measured on plots in the loess region of China. Taking results from a new data set covering north European, Mediterranean and tropical monsoon conditions, the generally improved performance of the model is confirmed, using the values of the slope and intercept of reduced major-axis regression lines between predicted and observed data as criteria. In addition, the model yields high values of the Nash and Sutcliffe coefficient of efficiency. Applications of the model to two small catchments show that meaningful results can be obtained from routing runoff and sediment over the landscape on an annual basis. Output from the model can be used to identify source areas of sediment within the catchment and to estimate sediment delivery ratios. Overall, the model is considered suitable for rapid first-approximaton determinations of erosion rates.

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