HYDROLOGICAL PROCESSES
Hydrol. Process. **14**, 927–939 (2000)

Sensitivity analysis of EUROSEM using Monte Carlo simulation II: the effect of rills and rock fragments

A. Veihe,*[1] J. Quinton[2] and J. Poesen[3]
[1] *Department of Geography and International Development Studies, Roskilde University, PO Box 260, 4000 Roskilde, Denmark*
[2] *Institute of Water and Environment, Cranfield University, Silsoe, Bedford MK45 4DT, UK*
[3] *Fund for Scientific Research Flanders, Redingenstraat 16, 3000 Leuven, Belgium*

Abstract:

A sensitivity analysis of the surface and catchment characteristics in the European soil erosion model (EUROSEM) was carried out with special emphasis on rills and rock fragment cover. The analysis focused on the use of Monte Carlo simulation but was supplemented by a simple sensitivity analysis where input variables were increased and decreased by 10%. The study showed that rock fragments have a significant effect upon the static output parameters of total runoff, peak flow rate, total soil loss and peak sediment discharge, but with a high coefficient of variation. The same applied to the average hydrographs and sedigraphs although the peak of the graphs was associated with a low coefficient of variation. On average, however, the model was able to simulate the effect of rock fragment cover quite well. The sensitivity analysis through the Monte Carlo simulation showed that the model is particularly sensitive to changes in parameters describing rills and the length of the plane when no rock fragments are simulated but that the model also is sensitive to changes in the fraction of non-erodible material and interrill slope when rock fragments were embedded in the topsoil. For rock fragments resting on the surface, changes in parameter values did not affect model output significantly. The simple sensitivity analysis supported the findings from the Monte Carlo simulation and illustrates the importance when choosing input parameters to describe both rills and rock fragment cover when modelling with EUROSEM. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS soil erosion modelling; sensitivity analysis; Monte Carlo simulation; rock fragment cover; model uncertainty

INTRODUCTION

Parameterizing soil erosion models constitutes one of the major sources of model uncertainty and sensitivity analysis is an important tool for addressing this issue. It provides information about the response of selected output variables to variations in input parameters driving the model. In physically based models such as EUROSEM (Morgan *et al.*, 1998a), single values are used to represent soil, vegetation and topography parameters over an entire grid cell, assuming that these areas are homogeneous. The single output values obtained from using these models consequently do not reflect the variability within each of the grid cells (Quinton, 1997).

* Correspondence to: A. Veihe, Department of Geography and International Development Studies, Roskilde University, PO Box 260, 4000 Roskilde, Denmark. E-mail: veihe@ruc.dk

Contract/grant sponsor: European Union-Soil Productivity Indices and their Erosion Union.
Contract/grant number: IC18CT960096.

Received 14 December 1998
Accepted 3 August 1999

A number of different sensitivity analysis methods exist ranging from simple analysis, where individual input variables and parameters are increased and decreased and the model output examined (Nearing *et al*., 1990; De Roo *et al*., 1995), to methods based on the Monte Carlo simulation, which is suitable for complex non-linear models such as EUROSEM where the input parameters' probability distributions can be described, and for models that involve the use of time-dependent driving variables (Tiscareno-Lopez *et al*., 1993). The basic theory of Monte Carlo simulation is described in detail in Veihe and Quinton (2000).

When parameterizing input parameters describing the surface and catchment characteristics in EUROSEM, two conditions are particularly important. One is the description of concentrated flow paths including rills, tractor wheelings and plough furrows (referred to as rills in this paper), and the other is the cover of rock fragments. Studies of rill and interrill erosion by Govers and Poesen (1988) and Vandaele and Poesen (1995) have shown that provided both rill and interrill erosion takes place, soil loss within a catchment mainly stems from rills, the development of which depends on the slope steepness, the activation of sidewall processes and gullying in the channel network. It also has been shown that soil loss associated with rills varies with time and is highly dependent on the rainfall pattern (Fullen and Reed, 1987; Hasholt and Hansen, 1995; Vandaele and Poesen, 1995).

Over the last decade, the effect of rock fragment cover on soil erosion has attracted considerable attention and the need for incorporating this parameter in physically based soil erosion models has been widely accepted (Casenave and Valentin, 1989; Poesen *et al*., 1994). It is particularly important to include the effect of rock fragments if models are to be used in, for instance, the Mediterranean and in many parts of Africa, where rock fragments often occupy more than 60% of the land (Casenave and Valentin, 1989; Poesen and Lavee, 1994; Folly, 1997).

In this study, rock fragments are defined as mineral particles 2 mm or larger in diameter, including all sizes that have horizontal dimensions less than the size of a pedon (Poesen and Lavee, 1994). The observed effect of rock fragments on soil loss in previous studies has varied from acting as a mulch to reduce soil erosion (Wishmeier and Smith, 1978; Collinet and Valentin, 1984; Casenave and Valentin, 1989) to increase runoff and thereby soil erosion (Poesen and Ingelmo-Sanchez, 1992; Moustakas *et al*., 1995). The effect is clearly ambivalent and depends upon the spatial scale, porosity of the soil, the embedding and the size of the rock fragments as well as the steepness of the slope (Poesen *et al*., 1990; Roy and Jarrett, 1991; Poesen, 1992; Bunte and Poesen, 1993; Bunte and Poesen, 1994; Poesen *et al*., 1994). An important aspect of rock fragment cover is also its water conserving ability (Danalatos *et al*., 1995; van Wesemael *et al*., 1995) which should be taken into consideration when modelling.

Parameterizing models with respect to rock fragment cover can, however, be rather difficult because cover characteristics in terms of percentage of rock fragments, rock fragment size and the embedding of these can vary considerably within short distances (Folly, 1997). This variation is in some cases related to catenas, as shown by Simanton *et al*. (1994) and Poesen *et al*. (1998). For elements that are smaller than 1 m^2 or larger than 100 m^2, the effect of rock fragments is to reduce erosion, whereas for elements between 1 m^2 and 100 m^2 in size, rock fragments may act to either decrease or increase erosion, depending on their position on the surface and the porosity of the soil, as illustrated in Figure 1 (Poesen and Ingelmo-Sanchez, 1992; Poesen *et al*., 1994).

Toebat *et al*. (1994) carried out a simple sensitivity analysis of an earlier version of EUROSEM with special emphasis on rock fragment cover and it is one of the few studies that have been carried out on this issue so far. By using a single data set, the effect of each of the input parameters expressing rock fragment cover on runoff and erosion was determined for a range of input values and compared with experimental findings.

The aim of this paper is to investigate the sensitivity of EUROSEM (version 3·6, July 1998) to changes in surface and catchment characteristics, with particular emphasis on the effect of rills and rock fragment cover. The sensitivity analysis will be carried out primarily using Monte Carlo simulation but will be supplemented by a simple sensitivity analysis, where input parameters are increased and decreased by 10% and the effect on the output parameters studied.

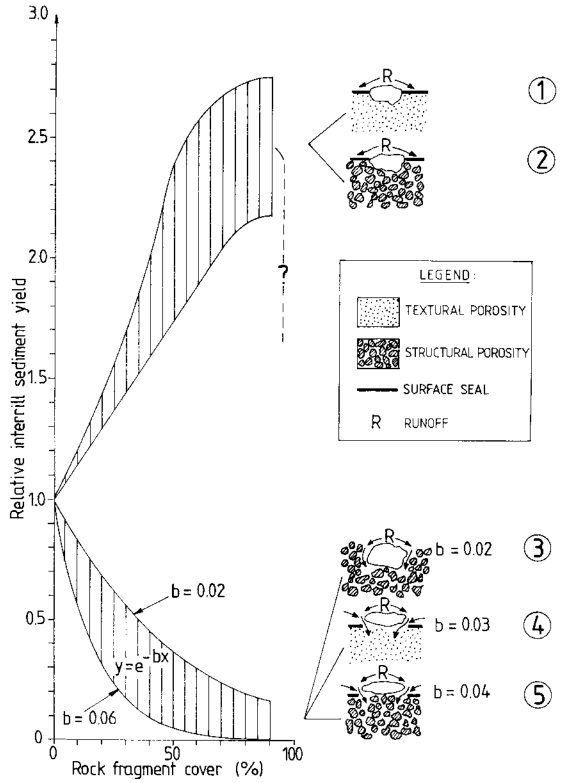

Figure 1. Effect of fine earth structure and position of rock fragments in the soil top layer on the relationship between rock fragment cover and relative interrill sediment yield. A positive relationship is observed for rock fragments partly incorporated into a surface seal which developed on a top layer with essentially textural pore spaces (1) or on a top layer with structural pore spaces (2); a negative relationship is observed for rock fragments embedded in a top layer with structural porosity (3) or for rock fragments resting on the surface of a soil top layer characterized by either essentially textural pore spaces (4) or by structural pore spaces (5) (Poesen *et al.*, 1994)

THE EUROSEM MODEL

The European soil erosion model (EUROSEM) is a single event process-based model for predicting soil erosion by water from fields and small catchments. The model is based on a physical description of the erosion processes and operates for short time steps, in the region of one minute (Morgan *et al.*, 1998a). A more detailed description of the model structure is described in Veihe and Quinton (2000).

In the EUROSEM model all types of concentrated flow paths are treated as rills and are described in terms of their width, depth and side slope as well as their number per element width. It is also possible to specify whether the rills are of uniform depth over the whole length of the plane or whether the depth increases downslope. In the last mentioned case, the rill geometry is specified at the bottom of the element and scaled automatically within the model (Morgan *et al.*, 1998b).

The effects of rock fragment cover are simulated using the three parameters of ROC, PAVE and ISTONE (Morgan *et al.*, 1998a). The ROC parameter is used to reduce the overall storage of water in the soil using the equation:

$$B_{\mathrm{ROC}} = B(1 - ROC) \tag{1}$$

where B_{ROC} is the parameter B modified for rock fragments (mm min^{-1}), B is an integral capillary and water deficit parameter of the soil (mm min^{-1}) and ROC is the fraction of the topsoil composed of rock fragments, expressed as a volume.

The PAVE parameter reduces the area of fine earth exposed to raindrop impact using the equation:

$$DET_{pav} = DET(1 - PAVE) \tag{2}$$

where DET_{pav} is the detachment rate allowing for the non-erodible surface ($m^3\,s^{-1}\,m^{-1}$) and $PAVE$ is the proportion (between 0 and 1) of the soil surface covered by non-erodible surface.

Finally, the effective saturated hydraulic conductivity of the soil is affected using the equation:

$$K_{sroc} = K_s(1 - PAVE) \tag{3}$$

or

$$K_{sroc} = K_s(1 + PAVE) \tag{4}$$

where K_{sroc} is a modified value of saturated hydraulic conductivity ($mm\,min^{-1}$) and $PAVE$ is the rock fragment cover, expressed as a fraction.

It is the sign of ISTONE that determines whether the effect of PAVE is to increase or decrease the saturated hydraulic conductivity of the soil (Equations 3 and 4). Rocks that are embedded in a surface seal will reduce infiltration (Equation 3), whereas rocks that rest on the surface or are surrounded by macropores will be modelled as protecting the soil structure and promote infiltration (Equation 4) (Poesen and Ingelmo-Sanchez, 1992; Morgan *et al.*, 1998a). It is the user who predetermines how the rock fragment effect works depending on personal judgment.

METHODOLOGY

The methodology used for the sensitivity analysis based on Monte Carlo simulation is outlined in detail in Veihe and Quinton (2000). The sample statistics for the theoretical slope plane showing the expected parameter variability of the input parameters describing the surface and catchment characteristics are shown in Table I. Random variates of these input parameters were generated based on the sample statistics and their associated probability distributions. All input distributions were assumed to be normally distributed except for values of Manning's n, which is assumed to exhibit a log-normal distribution. Four thousand simulations were made using a 50 mm storm event with a delayed pattern, as described in Veihe and Quinton (2000).

Table I. Soil surface and catchment characteristics used for the random number generation. The figures are based mainly on Quinton (1994), although the information on rill width and depth was derived from Madsen (1992) and the information on rock fragments from Folly (1997)

	Parameter	Mean	Range	St. Dev.	C.V. (%)	Units
Catchment geometry	Interrill slope (%)	0·20	0·1–0·5	0·04	0·20	m/m
	Length of plane or channel element	25	5–100	2·00	0·08	m
Soil surface	Downslope roughness	5	1–10	2·00	0·40	
	Width of concentrated flow path	0·2	0·01–1·0	0·06	0·60	m
	Depth of concentrated flow path	0·5	0·02–1·0	0·25	0·50	m
	Side slope of rills	1·0	0·1–4·0	0·40	0·40	1 : x
	Number of rills	4	1–16	2·00	0·50	
	Slope of rills (%)	0·20	0·1–0·5	0·08	0·40	m/m
	Manning's n for interrill area	0·10	0·01–0·5	0·20	2·00	$m^{1/3}$ s
	Manning's n for rills	0·10	0·01–0·5	0·20	2·00	$m^{1/3}$ s
	Fraction of rock fragments	0·50	0–1·0	0·25	1·00	
	Fraction covered by non-erodible material	0·50	0–1·0	0·25	0·50	

Three sets of Monte Carlo simulations were carried out using EUROSEM modified for sensitivity analysis purposes, i.e. the introduction of a routine that allows the model to run a specified number of times using an input parameter file with randomly selected sets of input parameter values. This enabled a simulation of a situation without any rock fragments and two with rock fragments either embedded in the soil surface or resting on the surface. The static model predictors that were examined with respect to their sensitivity consisted of total runoff, total soil loss, peak flow rate and peak sediment discharge, and time to runoff, time to peak flow rate, time to peak sediment discharge and duration of runoff were assessed based on their relative frequency distributions only. Sensitivity was assessed using beta (β), which is the normalized slope for the independent variables derived through stepwise multiple linear regression, as described in Veihe and Quinton (2000). Finally, an average hydrograph and an average sedigraph were produced, with a graph showing the coefficient of variation through the rainfall event.

The sensitivity analysis using Monte Carlo simulation was supplemented by a simple sensitivity analysis covering both embedded rock fragments and rock fragments lying on the soil surface. The input parameters listed in Table I were increased and decreased by 10% and the changes in the output parameters observed.

RESULTS AND DISCUSSION

Relative frequency distributions of static output parameters

For the static output parameters of time to peak flow rate, time to peak sediment discharge, time to runoff and duration of runoff, little variation was observed in output values, whereas the relative frequency distributions for the remaining static output parameters (Figures 2 and 3) was high. The ability of the model to predict time to peak flow rate and time to peak sediment discharge accurately corresponded with the observations for the hydrological, soil and vegetation parameters (Veihe and Quinton, 2000). On the other hand, parameters describing surface and catchment characteristics influence time to runoff and duration of runoff a lot less as compared with the hydrological, soil and vegetation parameters, which are influenced by changes in the hydrological parameters. Figure 2 shows that both runoff and peak flow rate are well defined when no rock fragments are present, whereas the presence of rock fragments introduces a high variability for the frequency distributions owing to the rock fragment's effect on the hydrology. For the soil loss variable (Figure 3) the situation with embedded rock fragments shows a high variability, whereas the variability is much less when rock fragments rest on the surface or no rock fragments are present, although the latter on average is giving higher soil loss values. A high variability is observed for peak sediment discharge (Figure 3) regardless of the conditions, with the variability slightly higher when rock fragments are present as compared with no rock fragments. This indicates that peak sediment discharge is very sensitive to changes in input parameter values describing surface and catchment characteristics.

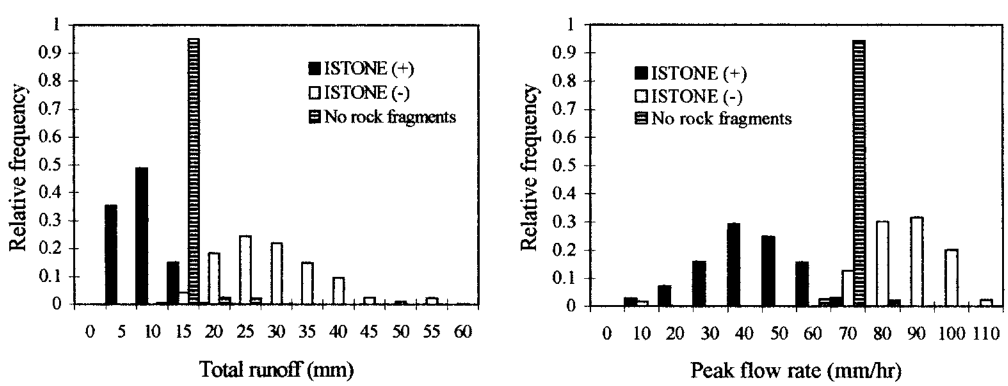

Figure 2. Relative frequency distributions for the hydrological output variables of total runoff and peak flow rate. ISTONE (+): rock fragments resting on the surface, ISTONE (−): embedded rock fragments

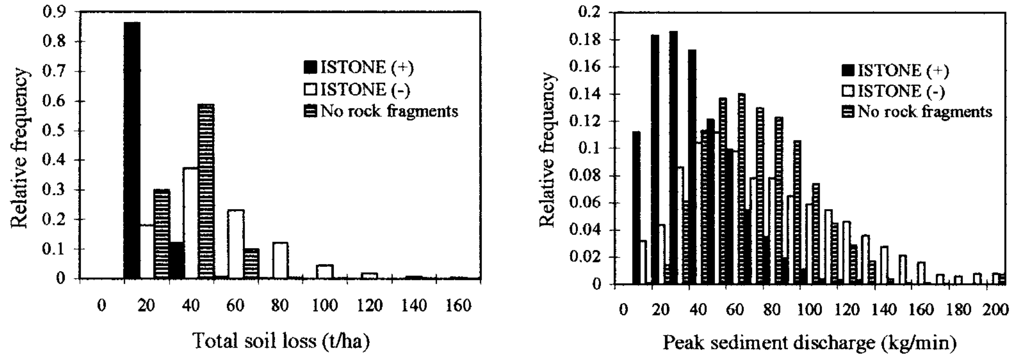

Figure 3. Relative frequency distributions for the erosion output variables of total soil loss and peak sediment discharge. ISTONE (+): rock fragments resting on the surface, ISTONE (−): embedded rock fragments

The variability of the static output parameters is further illustrated in Table II, except for time to runoff and peak flow rate, which hardly varied. For the parameters total runoff, peak flow rate, total soil loss and peak sediment discharge, embedded rock fragments reduce total runoff and peak flow rate as compared with no rock fragments, whereas the opposite was the case when rock fragments were resting on the surface. Rock fragments embedded in the soil reduce the duration of runoff, whereas the opposite is the case when rock fragments are resting on the surface. The presence of rock fragments generally reduces time to peak sediment discharge regardless of their position. It is noticeable that whereas total runoff is in the same range (Table II) as observed for the Monte Carlo simulation with the hydrological, soil and vegetation parameters (Veihe and Quinton, 2000), soil loss figures are much higher for the surface and catchment parameters, especially when rock fragments are embedded. In field conditions this happens too, but only temporarily because the increased erosion rate will expose more rock fragments and these in turn will reduce soil loss when rock fragment cover is high.

Table II. Descriptive statistics of the static output variables for simulations excluding and *including* (*resting on the soil surface*)/including (embedded) rock fragment cover

Output variables	$\bar{\chi}$	σ	CV	Median	Kurtosis	Skewness
Total runoff (mm)	14·37	8·57	0·60	13·70	266·43	15·59
	6·26	*4·61*	*0·74*	*6·08*	*405·75*	*12·46*
	28·02	16·71	0·60	25·51	120·82	8·82
Peak flow rate (mm/h)	61·30	3·84	0·06	61·12	88·09	−4·97
	37·88	*20·08*	*0·53*	*38·28*	*380·09*	*13·94*
	84·70	53·76	0·63	81·58	281·83	13·82
Total soil loss (kg)	859·62	519·33	0·60	799·09	85·84	7·01
	338·47	*337·57*	*1·00*	*272·32*	*136·31*	*7·17*
	1420·23	1296·32	0·91	1153·18	39·21	4·95
Peak sediment discharge (kg/min)	70·53	79·01	1·12	62·44	155·11	11·55
	35·37	*39·35*	*1·11*	*30·82*	*633·77*	*20·61*
	83·60	132·54	1·59	63·09	277·00	12·78
Duration of runoff (min)	15·23	5·49	0·36	16·50	1·50	−1·41
	19·61	*6·73*	*0·34*	*21·50*	*2·78*	*−1·92*
	11·75	22·56	1·92	8·00	27·00	5·28
Time to peak sediment discharge (min)	59·82	0·81	0·01	60·00	37·37	−5·72
	58·70	*8·44*	*0·14*	*60·00*	*42·64*	*−6·64*
	58·04	7·64	0·13	60·00	42·10	−6·31

The coefficient of variation is high, ranging from 0·34 to 1·92 for all static output parameters, except for time to peak sediment discharge and peak flow rate when rock fragments are present, which are somewhat lower. The high variability of output parameter values is further supported when looking at the kurtosis values and shows a much higher variability as compared with the effect from the hydrological, soil and vegetation parameters (Veihe and Quinton, 2000). All frequency distributions are leptokurtic, which means that the tails of the distributions are fatter than those of a corresponding normal distribution and the skewness is generally positive for the parameters runoff, peak flow rate, soil loss and peak sediment discharge, indicating a log-normal distribution, which is supported when looking at the frequency distributions in Figures 2 and 3.

The changes in average runoff and soil loss figures (Table II) when introducing rock fragments correspond with experimental findings by Poesen *et al.* (1990 and 1994) for mesoscale plots (see also Figure 1). For embedded rock fragments, the increased runoff results from the reduced infiltration rate and is linked with an increased soil detachment by interrill flow and transport capacity though raindrop detachment is reduced. Rock fragments resting on the surface protect the soil surface against physical degradation and favour high infiltration rates, leading to a reduction in both runoff and soil loss. The trends in the degree of variability associated with a particular rock fragment cover illustrated by the envelope curves in Figure 1 were to some extent reflected in the Monte Carlo simulations. For simulations with embedded rock fragments, an increase in cover from 15 to 65% increased the coefficient of variation associated with soil loss from 0·44 to 0·64, whereas the increase was from 0·38 to 0·78 for rock fragments resting on the surface. The model response therefore is likely to be better for embedded rock fragments than for rock fragments resting on the surface.

Although the model generated runoff after 0·5 min, the time at which the hydrograph started to rise varied according to findings by Poesen *et al.* (1990), with embedded rock fragments providing a quicker response time as compared with situations with rock fragments resting on the surface or no rock fragments.

Sensitivity of static output parameters

Tables III to VI show the sensitivity of the static output parameters with and without rock fragments (embedded). For rock fragments resting on the soil surface (not shown), only total soil loss appeared to be sensitive to changes — mainly in rill slope, number of rills, length of plane and depth of rills. The model is generally sensitive to changes in input parameter values when rock fragments are embedded in the topsoil, particularly when it comes to peak flow rate, whereas little effect is observed in the situation without rock fragments (see Tables III to VI). The increased sensitivity of the model when rock fragments are embedded is attributed to rock fragment's effect on the saturated hydraulic conductivity, which is relatively more pronounced for embedded rock fragments as compared with rock fragments resting on the surface. The increased sensitivity of the model with embedded rock fragments also affects the sensitivity of the model to other input parameters. The importance of choosing the right parameter values to describe surface and catchment characteristics is therefore increased when rock fragments are embedded.

Table III. Sensitivity of total runoff to surface and catchment characteristics excluding and *including* (*embedded*) rock fragments. Twelve variables were included in the stepwise linear regression

Parameters	Sensitivity of total runoff (β)	F statistics	*Parameters*	*Sensitivity of total runoff* (β)	*F statistics*
Depth of rills	−0·145	83	*Fraction covered by non-erodible material*	*−0·537*	*1570*
Slope of rills	0·110	48	*Depth of rills*	*−0·086*	*40*
Interrill slope	−0·050	10	*Slope of rills*	*0·074*	*29*
Length of plane	0·031	4	*Number of rills*	*0·048*	*13*
			Interrill slope	*−0·036*	*7*
r-square = 0·0359			*r-square = 0·303*		

Table IV. Sensitivity of peak flow rate to surface and catchment characteristics excluding and *including* (*embedded*) rock fragments. Twelve variables were included in the stepwise linear regression

Parameters	Sensitivity of peak flow rate (β)	*F* statistics	*Parameters*	*Sensitivity of peak flow rate (β)*	F statistics
Width of rills	0·098	37	*Fraction covered by non-erodible material*	*−0·927*	*23443*
Depth of rills	0·084	28	*Width of rills*	*0·038*	*39*
Number of rills	−0·050	10	*Number of rills*	*−0·012*	*4*
Slope of rills	−0·045	8	*Manning's n for interrill area*	*−0·011*	*3*
Interrill slope	0·044	7	*Side slope of rills*	*0·009*	*2*
Sideslope of rills	0·029	3			
Length of plane	−0·026	3			
r-square = 0·024			*r-square = 0·861*		

Table V. Sensitivity of total soil loss to surface and catchment parameters excluding and *including* (*embedded*) rock fragments. Twelve variables were included in the stepwise linear regression

Parameters	Sensitivity of total soil loss (β)	*F* statistics	*Parameters*	*Sensitivity of total soil loss (β)*	*F statistics*
Slope of rills	0·465	1121	*Fraction covered by non-erodible material*	*−0·530*	*2441*
Length of plane	0·140	102	*Slope of rills*	*0·493*	*2109*
Depth of rills	−0·132	90	*Interrill slope*	*0·130*	*148*
Interrill slope	−0·113	66	*Length of plane*	*0·117*	*119*
Number of rills	−0·029	4	*Number of rills*	*0·083*	*59*
Manning's *n* for interrill area	−0·024	3	*Depth of rills*	*−0·063*	*35*
			Manning's n for rill	*−0·030*	*8*
r-square = 0·268			*r-square = 0·564*		

Table VI. Sensitivity of peak sediment discharge to surface and catchment parameters *including* (*embedded*) rock fragments. Twelve variables were included in the stepwise linear regression

Parameters	Sensitivity of peak sediment discharge (β)	*F* statistics	*Parameters*	*Sensitivity of peak sediment discharge (β)*	*F statistics*
Slope of rills	0·321	460	*Slope of rills*	*0·342*	*550*
Depth of rills	−0·182	148	*Fraction covered by non-erodibile material*	*−0·217*	*223*
Length of plane	0·088	35	*Depth of rills*	*−0·116*	*63*
Number of rills	0·070	22	*Number of rills*	*0·102*	*49*
Width of rills	−0·034	5	*Length of plane*	*0·067*	*21*
Sideslope of rills	−0·027	3	*Interrill slope*	*0·049*	*11*
			Width of rill	*−0·026*	*3*
r-square = 0·149			*r-square = 0·195*		

Looking at the simulations without rock fragments, the slope and depth of rills, the interrill slope, the length of plane and the number of rills influence the static output parameters the most. When embedded rock fragments are included, the static output parameters are most sensitive to changes in the fraction covered by non-erodible material, followed by parameters describing the rills for the hydrological variables and both length of plane and interrill slope for the erosion variables. None of the simulations including rock fragments, however, indicate any sensitivity of the static output parameters to changes in the fraction of rock fragments. This can be explained by the fact that the fraction of rock fragments affect the overall storage of water in the soil, whereas the fraction of non-erodible material changes the saturated hydraulic conductivity of the soil shown to affect output variables considerably (Veihe and Quinton, 2000). Generally speaking, the static output parameters are a lot less sensitive to changes in parameters describing surface and catchment characteristics as compared with the hydrological, soil and vegetation parameters.

The great sensitivity of the model to changes in parameters describing rills calls for careful parameterization of these parameters. Whereas the characteristics of a single rill can be estimated quite easily, it is much more difficult to parameterize elements containing both wheel tracks and rills with different characteristics in terms of width, depth, slope, etc. The parameterization of rill characteristics is further made difficult because of rill dynamics, with their location and dimensions changing temporally. This study shows the importance of developing models that can predict the location of rills and their development through time.

Dynamic output parameters

The average hydrographs and sedigraphs with and without rock fragments and their associated coefficient of variation are illustrated in Figure 4. The differences in time to peak flow rate are negligible as noticed for the static output parameters. When rock fragments are embedded, the hydrograph starts to rise after about 26 min, whereas the equivalent time is 40 min when no rock fragments are present and 42 min when rock fragments are resting on the surface. If the time to runoff is ignored, the time at which the hydrographs start rising corresponds with experimental findings by Poesen *et al.* (1990) and shows that on average the model is able to reflect the effect of rock fragment cover quite well.

The coefficient of variation for the hydrographs (Figure 4) varies depending on the presence of rock fragments, but is generally low, whereas the hydrographs are at their peak and with the highest coefficient of variation at the tail of the hydrographs. For the sedigraphs (Figure 4), the coefficient of variation is low at the peak of the hydrographs and increases towards the tail, whereas the highest coefficient of variation is observed during the first 30 min of the rainstorm. This reflects the fact that runoff alternately picks up and deposits sediment at this stage, although the amount transported is small. The coefficient of variation is generally much higher (up to three times higher) as compared with the coefficient of variation found for the hydrological, soil and vegetation parameters (Veihe and Quinton, 2000). This shows that the dynamic output parameters overall are more sensitive to changes in the surface characteristics immediately when runoff and soil loss starts and at the tail of the hydrographs and sedigraphs. However, overall the hydrographs and sedigraphs are predicted quite accurately by the model.

Simple sensitivity analysis

The simple sensitivity analysis showed that the model is not sensitive to changes in rill slope, side slope of the rills and the downslope roughness. The sensitivity of the model to the remaining surface and catchment parameters is shown in Figure 5 where the effect of rock fragments' position on soil loss has been examined. Changes in runoff values were almost not noticeable . The model is most sensitive to changes in interrill slope and length of slope followed by the fraction covered by non-erodible material under conditions where the element size is smaller than 1 m^2 or larger than 100 m^2 or where stones are resting on the surface (see Figure 1). Apart from the rill width and the fraction of rock fragments resting on the surface, the model is fairly sensitive to changes in the remaining parameters.

Whereas a decrease in PAVE by 10% increases soil loss by as much as 8·8% when rock fragments are resting on the surface, a decrease of 3·6% is observed when stones are embedded. The response of the model to changes in PAVE correspond with findings from experiments carried out by Poesen *et al.* (1994) (see Figure 1) with an increase in total soil loss for increasing rock fragment cover when rock fragments are embedded and vice versa. For the fraction of rock fragments (ROC) the situation is different, with an increase in soil loss of 2·8% when ROC is increased and a 3·6% decrease when ROC is decreased, and with a

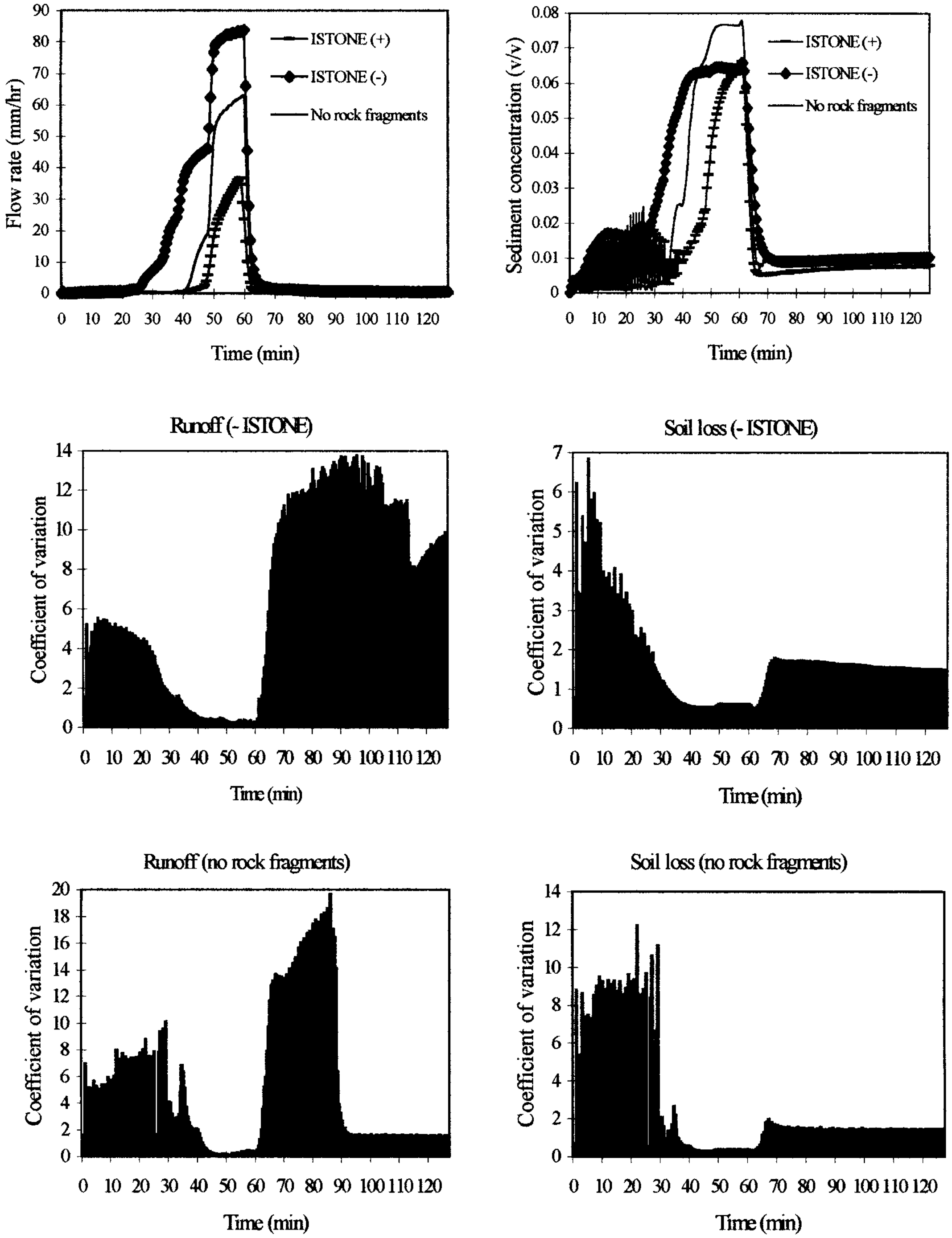

Figure 4. Average hydrographs and sedigraphs for rock fragments resting on the surface (+ ISTONE), embedded rock fragments (− ISTONE) and no rock fragments and their associated coefficient of variation

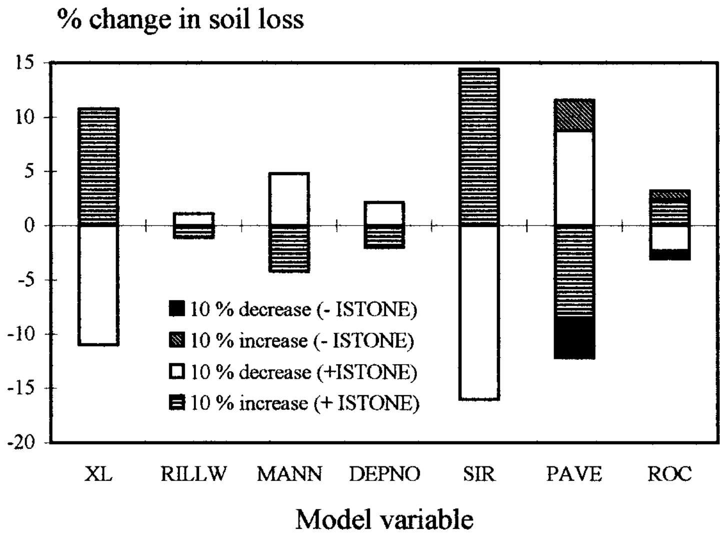

Figure 5. Sensitivity of the model output of total soil loss to changes in the slope length (XL), rill width (RILLW), Manning's n (MANN), the number of rills (DEPNO), interrill slope (SIR), the fraction covered by non-erodible material (PAVE) and the fraction of rock fragments (ROC)

similar trend for embedded rock fragments when ROC is increased, although the change in soil loss is less than 1%. This reflects a similar trend as observed for PAVE, with the model being relatively more sensitive when rock fragments are resting on the surface provided PAVE is kept constant. The higher response to changes in rock-related parameters when the rock fragments are resting on the surface should be seen in light of the generally much lower average soil loss of 0·3 tons as opposed to about 1·4 tons when rock fragments are embedded, and reflects the non-linear relationship between saturated hydraulic conductivity and soil loss.

A series of simulations were carried out for a range of rock fragment cover percentages to investigate the extent to which the model describes the relationship shown in Figure 1. When rock fragments are resting on the surface, an exponentially decreasing function was found ($y = 1{\cdot}0736e^{-0.0122x}$), which indicates that the model response to changes in the percentage of embedded rock fragments is less than what has been observed in the laboratory, where b is larger than 0·02 (see Figure 1). A linear relationship was found ($y = 0{\cdot}017x + 1{\cdot}06$) when simulating the effect of embedded rock fragment percentages up to a cover of 60%, after which sediment yield decreased drastically as rock fragment cover was increased. The effect of the percentage of embedded rock fragments on interrill yields corresponded very well with observations made by Poesen *et al.* (1994) (see also Figure 1).

As expected, the simple sensitivity analysis gives a different picture of which parameters the model is most sensitive to as compared with the sensitivity analysis using Monte Carlo simulation. This reflects the fact that the Monte Carlo simulation takes into account the real variation in parameter values, the uncertainty associated with parameterizing the individual parameters and the interaction between these, whereas the simple sensitivity analysis considers uniform percentage wise changes in parameter values. Although the model is most sensitive to changes in slope length and slope, these parameters are easy to assess as opposed to, for instance, rock fragment cover and their embedding.

In the field rock fragments are often both embedded and resting on the surface (Folly, 1997; Mati, personal communication). This situation is expected to decrease runoff and thereby soil erosion, although a lot less as compared with when rock fragments are resting on the surface (Poesen and Lavee, 1997). This situation currently cannot be modelled explicitly by EUROSEM but may be approximated by simulating a situation with a reduced number of rock fragments resting on the surface. Another aspect that the model does not take into account is the size of the rock fragments, which influences overland flow hydraulics (Bunte and Poesen, 1994). It also must be emphasized that when parameterizing the model, the user should take into account the size of the plot, which determines the effect of rock fragments (Poesen *et al.*, 1994). More research is required for the above-mentioned conditions to be incorporated in EUROSEM.

Finally, the number and dimension of rills and wheel tracks, if both of them are present within the same element, have to be parameterized carefully and the effect of these parameters can be assessed running a range of simulations for different rill conditions.

CONCLUSION

This study showed that rock fragment cover has a significant effect upon the frequency distributions of the static output parameters of total soil loss, peak sediment discharge and in particular runoff and peak flow rate. The coefficient of variation for the static output parameters was high, but on average the runoff and soil loss calculations from the simulations with and without rock fragments corresponded with experimental studies.

The average hydrographs and sedigraphs were associated with a high coefficient of variation, except for the peak of the graphs, which was simulated accurately. When comparing the time at which the hydrograph starts to rise with experimental studies, it appeared that EUROSEM was able to model the effect of rock fragment cover well.

Based on the Monte Carlo simulation, the model proved most sensitive to changes in parameters describing rills and the length of the plane when no rock fragments were present, and the fraction covered by non-erodible material was important when rock fragments were embedded, as well as interrill slope. For simulations where rock fragments rest on the surface, changes in parameter values did not significantly affect model output. Overall, the results from the Monte Carlo simulation were supported by the results from the simple sensitivity analysis and show that the model is not very sensitive to changes in the volume fraction of rock fragments (ROC) in the top layer, but very sensitive to changes in the soil surface fraction occupied by non-erodible material (PAVE) because of the effect of PAVE on saturated hydraulic conductivity. It was also shown that EUROSEM simulated interrill sediment yield associated with the percentage of rock fragment cover well, particularly when rock fragments are embedded. This study shows the importance of choosing the right parameter values for both rills and rock fragment cover if a successful model simulation with EUROSEM should be achieved and that more studies are required in the future to improve the modelling of these conditions.

ACKNOWLEDGEMENTS

This research work was carried out as part of the SPIES project (Soil Productivity Indices and their Erosion Sensitivity), project no. IC18CT960096, whose funding by the European Union is gratefully acknowledged.

REFERENCES

Bunte K, Poesen J. 1993.Effects of rock fragment covers on erosion and transport of non-cohesive sediment by shallow overland flow, *Water Resources Research* **29**(5): 1415–1424.

Bunte K, Poesen J. 1994. Effects of rock fragment size and cover on overland flow hydraulics, local turbulence and sediment yield on an erodible soil surface, *Earth Surface Processes and Landforms* **19**: 115–135.

Casenave A, Valentin C. 1989. *Les états de surface de la zone sahélienne. Influence sur l'infiltration*. l'ORSTOM, Paris, 229 pp.

Collinet J, Valentin C. 1984. Evaluation of factors influencing water erosion in West Africa using rainfall simulation, *International Association of Hydrological Sciences* **144**, 451–461.

Danalatos NG, Kosmas CS, Moustakas NC, Yassoglou N. 1995. Rock fragments II. Their impact on soil physical properties and biomass production under Mediterranean conditions, *Soil Use and Management* **11**: 121–126.

De Roo APJ, Offermans RJE, Cremers NHDT. 1995. LISEM: a single-event, physically based hydrological and soil erosion model for drainage basins. II: sensitivity analysis, validation and application, *Hydrological Processes* **10**: 1119–1126.

Folly A. 1997. *Land use planning to minimize soil erosion — a case study from the upper East Region in Ghana*. Geographica Hafniensia A6. PhD thesis. Publications, Institute of Geography, University of Copenhagen, Denmark.

Fullen MA, Reed AH. 1987. Rill erosion on arable loamy sands in the West Midlands of England. In *Rill Erosion, Processes and Significance*. Bryan RB (Ed.). *Catena supplement* **8**, 85–96.
Govers G, Poesen J. 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field flot, *Geomorphology* **1**: 343–354.
Hasholt B, Hansen BS. 1995. Monitoring of rill formation. In *Effects of Scale on Interpretation and Management of Sediment and Water Quality. Proceedings of a Boulder Symposium* (Publication 226), July. International Association of Hydrological Sciences, Wallingford, 285–291.
Madsen S. 1992. *Rilleerosion ved Søsum*. Unpublished MSc project, Institute of Geography, University of Copenhagen.
Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME. 1998a. The European soil erosion model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments, *Earth Surface Processes and Landforms* **23**: 527–544.
Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME, Folly AJV. 1998b. *The European Soil Erosion Model (EUROSEM): Documentation and User Guide*, version 3·6. Silsoe College, Cranfield University, Bedford.
Moustakas NC, Kosmas CS, Danalatos NG, Yassouglou N. 1995. Rock fragments I. Their effect on runoff, erosion and soil properties under field conditions, *Soil Use and Management* **11**: 115–120.
Nearing MA, Deer-Ascough L, Laflen JM. 1990. Sensitivity analysis of the WEPP hillslope profile erosion model, *Transactions of the ASAE* **33**(3), 839–849.
Poesen JWA. 1992. Mechanisms of overland-flow generation and sediment production on loamy and sandy soils with and without rock fragments. In Parsons AJ, Abrahams AD (Eds), *Overland Flow. Hydraulics and Erosion Mechanics*. UCL Press, London, pp. 275–306.
Poesen J, Ingelmo-Sanchez F. 1992. Runoff and sediment yield from topsoils with different porosity as affected by rock fragment cover and position, *Catena* **19**: 451–474.
Poesen J, Lavee H. 1994. Rock fragments in top soils: significance and processes *Catena* **23**: 1–28.
Poesen J, Lavee H. 1997. How efficient were ancient rainwater harvesting systems in the Negev Desert, Israel?, *Bulletin Academie Royale des Sciences d'Outre-Mer (Belgium)* **43**: 405–419.
Poesen J, Ingelmo-Sanchez F, Mücher H. 1990. The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer, *Earth Surface Processes and Landforms* **15**: 653–671.
Poesen JW, Torri D, Bunte K. 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review, *Catena* **23**: 141–166.
Poesen J, van Wesemael B, Bunte K, Solé Benet A. 1998. Variation of rock fragment cover and size along semiarid hillslopes: a case-study from southeast Spain, *Geomorphology* **23**: 29–42.
Quinton J. 1994. The validation of physically-based erosion models — with particular reference to EUROSEM. Unpublished PhD thesis. Silsoe College, Cranfield University, Bedford.
Quinton J. 1997. Reducing predictive uncertainty in model simulations: a comparison of two methods using the European soil erosion model (EUROSEM), *Catena* **30**: 101–117.
Roy BL, Jarrett AR. 1991. The role of coarse fragments and surface compaction in reducing interrill erosion, *Transactions of the ASAE* **34**(1): 149–154.
Simanton JR, Renard KG, Christiansen CM, Lane LJ. 1994. Spatial distribution of surface rock fragments along catenas in semiarid Arizona and Nevada, USA, *Catena* **23**: 29–42.
Tiscareno-Lopez M, Lopes VL, Stone JJ, Lane LJ. 1993. Sensitivity analysis of the WEPP watershed model for rangeland applications, I: hillslope processes, *Transactions of the ASAE* **36**(6): 1659–1672.
Toebat K, Poesen J, Govers G. 1994. *Testing EUROSEM for bare soils with and without rock fragments*. Internal Report. Laboratory For Experimental Geomorphology: Leuven.
Vandaele K, Poesen J. 1995. Spatial and temporal patterns of soil erosion rates in an agricultural catchment, central Belgium, *Catena* **25**: 213–226.
Van Wesemael B, Poesen J, de Figueiredo T. 1995. Effects of rock fragments on physical degradation of cultivated soils by rainfall, *Soil and Tillage Research* **33**: 229–250.
Veihe A, Quinton J. 2000. Sensitivity analysis of EUROSEM using Monte Carlo simulation. I: hydrological, soil and vegetation parameters, *Hydrological Processes* **14**: 915–926.
Wischmeier WH, Smith DD. 1978. *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning* (537), USDA Agricultural Handbook, 537 pp.

