

SENSITIVITY ANALYSIS AND CALIBRATION OF THE *EUROSEM* MODEL FOR APPLICATION IN THE NORTHEAST ARID ZONE OF NIGERIA

Audu, I.¹, J.N. Quinton² and A.U. Dzivama¹

Abstract

Sensitivity analysis on the European Soil Erosion Model (*EUROSEM*) was conducted and it was found out that the parameters that affect infiltration of the soil are the most sensitive in the model as far as runoff volume is concerned. These parameters are maximum relative saturation of the soil, effective net capillary drive, saturated hydraulic conductivity and the initial relative saturation of the soil. The model was calibrated and validated using field data from the northeast arid zone of Nigeria. Calibration of the model was based on varying three parameters (maximum relative saturation, porosity and effective net capillary drive) within their range values until best fit between observed and simulated was achieved. Validation was achieved by comparing predicted runoff volumes with observed data not used in calibration. The model was evaluated using coefficients of efficiency and determination. Coefficients of efficiency of 0.82 and 0.74 in calibration and validation respectively were obtained. For the coefficient of determination, the values were 0.82 and 0.83 in calibration and validation. The summary statistics confirmed that the *EUROSEM* model could adequately simulate surface runoff on the degraded lands of northeast Nigeria and, therefore, can be applied to runoff related research in the area.

1. Introduction

A model relates known input with output from a system of interest. Models that relate crop growth to climate, soil and management factors can assist in assessing strategies for enhancing crop production under variable climates (Keating *et al.*, 1992; Carberry *et al.*, 1992). In addition, models can broaden our understanding of the complex phenomena in a system. In situations where time and resources are limited, long-term research can be conducted in relatively short time and at low costs using appropriate models.

EUROSEM is a physically based, distributed erosion model developed by Morgan *et al.* (1998). Modelling soil erosion by water requires adequate and detailed procedures of modelling the generation of runoff and its routing down a hillslope. *EUROSEM* simulates runoff on a surface using the runoff generator of the *KINEROS* model (Woolhiser *et al.*, 1990) to which it is linked.

Mathematical modelling of surface flow and flow in porous media is an increasingly important tool in the management of water resources. Mathematical models transform input parameters into output information. One may ask how sensitive the outputs are to input parameters. Sensitivity analysis supplies the answer. To be a useful tool, a model needs to provide acceptably accurate estimates of the objective function in relation to the major factors that determine the function. Therefore, evaluation of models used for research in hydrology is important. Models used in research often emphasise detailed description of the processes and close matching of model output to field observations. It is against this background that this study was carried out to achieve the following objectives:

¹Department of Agricultural Engineering, Faculty of Engineering, University of Maiduguri, Nigeria. E-mail: idriss@unimaid.edu.ng

²Institute of Water and Environment, Cranfield University at Silsoe, Bedford MK45 4DT, United Kingdom.

1. To conduct sensitivity analysis on the *EUROSEM* model with a view to identifying the sensitive parameters that should be accurately determined.
2. To calibrate and validate the model with field data.
3. To evaluate the model and determine its suitability for application in subsequent studies in semi-arid northeast Nigeria.

2. Brief description of the *EUROSEM* model

EUROSEM model has a modular structure with each module defining a separate process. Computations in *EUROSEM* is based on a numerical solution of the following dynamic mass balance equation (Kirkby, 1980; Woolhiser *et al.*, 1990):

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} - e(x, t) = q_s(x, t) \quad (1)$$

where A = cross sectional area of the flow, m^2
 C = sediment concentration, $m^3 m^{-3}$
 Q = discharge, $m^3 s^{-1}$
 e = net detachment rate of erosion of the bed per unit length of flow, $m^3 s^{-1} m^{-1}$
 q_s = extraction of sediment per unit length of flow, $m^3 s^{-1} m^{-1}$
 t = time, s
 x = horizontal distance, m

The different processes represented in the model include interception of rainfall by plant cover, runoff generation as infiltration excess, surface runoff, soil particle detachment by raindrop impact and by runoff, transport and deposition of sediment. Details of these processes can be found in Morgan *et al.* (1998).

EUROSEM comprises two components: hydrology and erosion. In the present research, only the hydrology component has been used. The model requires two input files to run – these are rainfall and catchment files. The rainfall file describes rainfall of a given storm, while the catchment file describes the catchment characteristics. Both files require information on 62 parameters with 9 and 53 in the rainfall and catchment files respectively (Morgan *et al.*, 1993).

3. Methodology

3.1 Sensitivity analysis

A first step in using a model must be an analysis of its degree of response to changes in the various parameters (Silburn and Loch, 1989). Sensitivity analysis is an evaluation of the relative magnitudes of changes in the model response as a function of relative changes in the values of model input parameters (Nearing *et al.*, 1990). Sensitivity analysis reveals the relative importance of model parameters by ranking the model parameters based on their contribution to overall error in model predictions (McCuen, 1973). It can also provide insight into the factors that influence the response of a physical system once the model accurately represents the physical system that it simulates. The aim of sensitivity analysis is to study the

influence on the output of errors or uncertainties in input data so that such data must be specified with great care. Ranking model parameters according to model sensitivity helps in deciding which parameters can be obtained from the relevant literature and which ones should be measured in the field and to what accuracy. In this exercise, rainfall event of 21st July 1994 (Table 1) for Jawa in Gashua local government area of Yobe state was used for the simulation. This rainfall event was chosen because of its size and the distribution of its intensity. The total rain was 44 mm and its duration was more than 3 hours. Intensity within the storm varied from low to moderate.

Table 1: Summary of rainfall distribution at Jawa on 21/07/1994

Cumulative time, min	Cumulative rainfall, mm	Average intensity, mmh ⁻¹
0	0	0
20	2.4	7.2
30	8.6	17.2
40	24.2	36.3
50	32.8	39.4
60	35.6	35.6
70	38.4	32.9
97	40.4	25.0
201	44.4	13.3

The output (total runoff volume) from the simulations was processed using the average linear sensitivity (*ALS*). The *ALS* is a modification of relative sensitivity and it represents a relative normalised change in output to normalised change in input as shown in Equation 2. According to Nearing *et al.* (1990), the *ALS* is a valid means of comparing sensitivities for different input parameters that have different orders of magnitude.

$$ALS = \frac{\frac{O_2 - O_1}{O_{12}}}{\frac{I_2 - I_1}{I_{12}}} \quad (2)$$

where I_{12} = the average of the inputs I_1 and I_2
 O_{12} = the average of the outputs O_1 and O_2

3.2 Calibration

For a model to be used, and in order to have confidence in its results, predictions from the model have to be validated against field data. It is important that the results from a model are objectively validated to ensure that the model is performing adequately for the task to which it is being applied. The procedure followed in this study involved calibrating the model first and then validating it using field data (Klemes, 1986).

The site selected for this study was a typical degraded land prone to runoff near Gashua in semi-arid northeast Nigeria. As the degraded lands were devoid of vegetation, the parameters

describing cover and vegetation in the catchment input file of the model were assigned zero values. Based on field and laboratory investigations, base values of some parameters in the catchment file were selected, while for the other parameters, values suggested in the *EUROSEM* userguide (Morgan *et al.*, 1993) were used.

Runoff was generated artificially from a rainfall simulator constructed on the field as suggested by USDA (1972). Runoff flow rates were recorded and then plotted against time to obtain hydrographs. The best description of the hydrographs so obtained was given by logarithmic function. The logarithmic function describing each flow was integrated to yield the observed runoff volume (V) as follows:

$$V = \int_{\alpha}^{\beta} [m \ln(x) + c] dx \quad (3)$$

where α and β = the lower and upper time intervals respectively
within which the flow rates were measured
 m and c = slope and intercept of the graph obtained respectively

The runoff volumes obtained were divided into two parts. One part was used for calibration and the other for validation.

Corresponding runoff volumes were obtained from simulations by the *EUROSEM* model. Three parameters were subjected to systematic variation to obtain the corresponding runoff volumes. The parameters were maximum relative saturation of the soil (*THMX*), porosity (*POR*) and net capillary drive (*G*). All other parameters were left at base values. Calibration was achieved by comparing results with alternative parameter values to find those that optimize the fit of predicted runoff volume to observed runoff volume. The method of ordinary least squares was used to estimate parameters with the minimum sum of squares. When the minimum sum of squares is minimised, the fit is optimal and the corresponding value of the parameter could be used with the model to predict output from the input.

Validation of the model was conducted on the second part of the runoff data using the optimum values obtained in calibration. Runoff volumes for the second part of the data were predicted with the model. Predicted and measured runoff volumes were then compared.

3.3 Model evaluation

After validation, the model was evaluated by graphical and analytical methods (ASCE, 1996). Quantitative assessment of the model was carried out using the following statistical goodness-of-fit criteria:

1. Coefficient of efficiency, E (Nash and Sutcliffe, 1970)

$$E = 1 - \frac{\sum (x_i - y_i)^2}{\sum (x_i - x_m)^2} \quad (4)$$

where y_i = simulated value
 x_i = measured value
 x_m = mean measured value

The coefficient of efficiency provides a dimensionless measure of model performance. The value of E can range from 0 to 1, with 1 indicating a perfect fit and a zero value implies that the mean of the observed values provides a better prediction than the model does.

2. *Coefficient of determination (R^2):* This measures the degree of association between observed and predicted measurements. It does not, however, reveal systematic errors.

4. Results and discussion

4.1 Sensitivity Analysis

Table 2 shows the sensitivities ranked in descending order of hydrology parameters to runoff volume from the *EUROSEM* model. The table also shows the range of input for each parameter over which the sensitivity was calculated.

Table 2: Some hydrology parameters of *EUROSEM* model with their base values, range of test and *ALS* sensitivity statistic

Parameter*	Unit	Base value	Range of test	<i>ALS</i>
THMX	cm ³ cm ⁻³	0.38	0.152 - 0.400	-0.658
G	mm	540	216 - 972	-0.410
FMIN	mm h ⁻¹	4	2 - 20	-0.212
THI	cm ³ cm ⁻³	0.131	0.052 - 0.256	0.201
MANN	-	0.03	0.01 - 0.06	-0.01
POR	fraction	0.4	0.4 - 0.7	0.006
RECS	mm	10	4 - 18	0.001

**THMX* - maximum relative saturation; *G* - net capillary drive; *FMIN* - saturated hydraulic conductivity; *THI* - initial relative saturation; *MANN* - Manning's n ; *POR* - porosity and *RECS* - infiltration recession factor.

It can be seen from Table 2 that the model is sensitive to four parameters (*THMX*, *G*, *FMIN* and *THI*) as far as runoff volume is concerned. The negative sign in the table indicates an inverse relationship between runoff volume and the parameter in question. Maximum relative saturation (*THMX*) and effective net capillary drive (*G*) are the most sensitive parameters to which *EUROSEM* responds. The respective *ALS* values for *THMX* and *G* were -0.658 and -0.410. Saturated hydraulic conductivity (*FMIN*) and initial relative saturation (*THI*) follow next with *ALS* of -0.212 and 0.201 respectively. The sensitivities of the model to the other parameters are rather slight with *ALS* ranging from 0.001 for *RECS* to 0.010 for *MANN*.

As the *EUROSEM* model uses the kinematic wave approximation method to route runoff across the soil surface, the first four parameters of Table 2 (*THMX*, *G*, *FMIN* and *THI*) were the hydrology parameters that affect the generation of runoff and, therefore, were most sensitive. They are the principal elements controlling infiltration of water into the soil as described by Equations 5, 6 and 7 (Smith and Parlange, 1978).

$$f_c = \frac{K_s \exp \left(\frac{F}{B} \right)}{\exp \left(\frac{F}{B} \right) - 1} \quad (5)$$

$$\text{with } B = G (\theta_s - \theta_i) \quad (6)$$

$$\text{and } G = \frac{1}{K_s} \int_{-\infty}^0 K(\varphi) d\varphi \quad (7)$$

where f_c = the maximum rate at which water can enter the soil, mm h^{-1}

K_s = the saturated hydraulic conductivity of the soil, mm h^{-1}
(represented by FMIN in the model)

F = the amount of rain already absorbed by the soil, mm

B = water deficit parameter of the soil, mm

G = the effective net capillary drive, mm

θ_s = the maximum value of water content of the soil, $\text{cm}^3 \text{cm}^{-3}$

θ_i = the initial value of soil water content, $\text{cm}^3 \text{cm}^{-3}$

φ = the soil matrix potential, mm

$K(\varphi)$ = a hydraulic conductivity function, mm h^{-1}

The water deficit parameter is a function of the difference between the maximum and initial values of relative saturation of the soil. It can be seen that infiltration capacity changes exponentially with the water deficit parameter. Infiltration capacity increases as saturated hydraulic conductivity is increased and consequently the time to runoff is increased which eventually decreases the total volume of runoff.

Compared to the sensitivity result of Quinton (1994), there is a variation in the ranking of the parameters as well as in the values of the sensitivity statistics. The uniqueness of each rainfall event was responsible for this variation. For the rainfall used in this study, the intensity distribution was such that it was low at the beginning of the storm and only became high enough to cause runoff 30 minutes after the start of the rain. The low intensity rain during the early 30 minutes dampened, to some extent, the effect of varying *THI*. The deficit between *THMX* and *THI* was reduced by increase in *THI* before the start of the runoff-producing intensity. As moisture deficit decreases, f_c tends to the value of K_s . The long early low intensity part of the rain brought the values of *THI* and *THMX* close together and thereby made *ALS* of G close to that of *THMX*.

4.2 Calibration and Validation

The complete runoff data used in the calibration and validation as determined in the field are presented in Tables 3 and 4. The rainfall intensity used ranged from 25 to 169 mmh^{-1} and the average runoff discharges/unit area ranged from 0.7 to 114.4 mmh^{-1} .

Table 3: Observed runoff volumes used in calibration

Site	Rainfall intensity, mmh ⁻¹	Runoff volume, l	α^* , min	β^* , min	Average discharge per unit area, mmh ⁻¹
Jawa	36	1.37	18	32	2.0
	60	13.59	2	15	20.9
	60	14.64	3	15	24.4
	65	19.38	13	26	29.8
	145	44.2	2	13	80.4
	169	61.5	2	18	76.9
Zurkaya	127	58	4	17	89.2
	50	10.9	6	17	19.8
	37.5	11.1	13	29	13.9
	41	6.8	11	21	13.6
	135	46.22	0	11	84
	32	12.6	6	17	22.9
Dumburi	41	17.3	3	16	26.1
	52.5	9.8	21	34	15.1
	72	16.7	2	14	27.8
	145	57.3	2	12	114.4

* α and β are the periods between which measurements were taken after the start of rain

Table 4: Observed runoff volumes used in validation

Site	Rainfall intensity, mmh ⁻¹	Runoff volume, l	α , min	β , min	Average discharge per unit area, mmh ⁻¹
Jawa	25	0.5	8	22	0.7
	32	4.0	11	25	5.7
	45	12.9	16	30	18.4
	54	17.5	4	15	31.9
	156	30.5	4	10	101.6
Zurkaya	142	29.2	2	10	73.0
	156	38.4	3	10	109.7
	162	12.3	3	8	49.2
	50	12.4	0	13	19.1
	58	7.6	3	10	21.7
Dumburi	120	25.4	5	12	72.6
	65	13.2	3	13	26.4
	48	20.8	14	31	24.5
	32	13.1	4	20	16.4

Table 5 shows the calibration parameters and their range values. The range of the maximum relative saturation of the soil was obtained from the water release data (Audu, 1999).

Table 5: Calibration parameters for sandy clay-loam and clay-loam soils

Parameter	Range
porosity	0.33 - 0.52
maximum relative saturation of the soil	0.33 - 0.49
net capillary drive of the soil, mm	220 - 1174

Figure 1 shows a plot of various values of *THMX* versus sum of squared residuals (*SS*) and how the optimum *THMX* value of 0.41 with the least *SS* was selected.

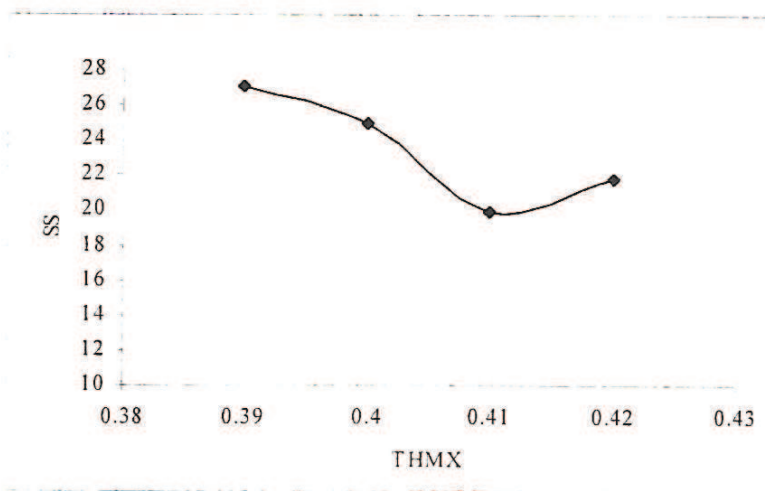


Figure 1: Plot of *THMX* values against sum of squared residuals (*SS*) showing *THMX* value of 0.41 for the minimum *SS*

The complete field geometry and hydrology parameter values of the model after calibration are presented in Table 6. Except for a few parameters that were obtained from the *EUROSEM* userguide (Morgan *et al.*, 1993), most of the parameters were determined in the field (Audu, 1999).

A continuous time series plot shows quite good agreement between measured and predicted runoff rates. A pair of hydrographs for high and low intensities is presented in Figure 2 as an example, where a general overview of the model performance can be seen.

Table 6: Input parameter values used in model simulation

Parameter	Input value	Remarks
Plot length, m	2.0	measured plot
Plot width, m	1.5	measured plot
Slope, %	0.5	measured in the field
Interrill Manning's n	0.02	obtained from User Guide (Morgan <i>et al.</i> , 1993)
Saturated hydraulic conductivity, mmh^{-1}	4.0	measured (average)
Net capillary drive, mm	340	calibrated value
Maximum volumetric soil water content	0.41	calibrated value
Initial volumetric soil water content	variable	measured in the field
Porosity	0.43	calibrated value
Proportion of the soil occupied by stones	0.0	observed in the field
Infiltration recession factor	10.0	obtained from User Guide (Morgan <i>et al.</i> , 1993)
Median particle size of the soil, μm	250	obtained from User Guide (Morgan <i>et al.</i> , 1993)

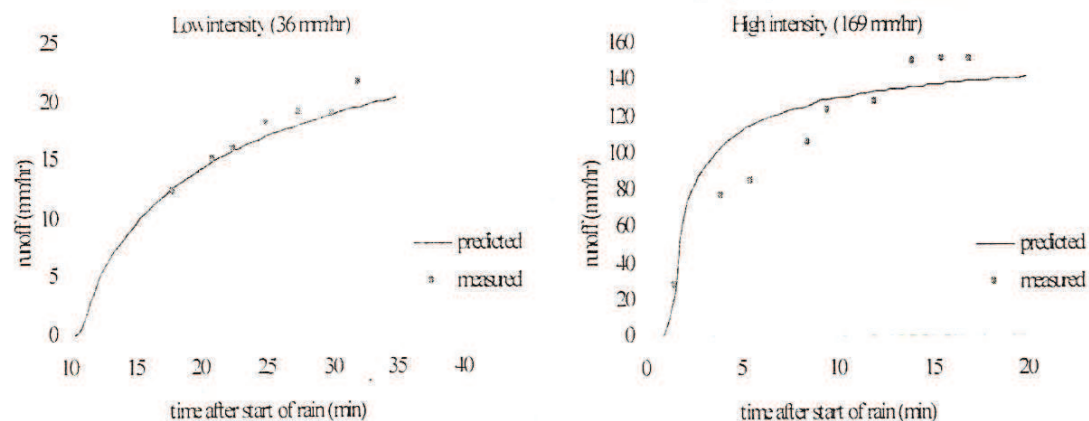


Figure 2: An example of visual assessment of the model with low (36 mmh^{-1}) and high (169 mmh^{-1}) intensity rains

The runoff flow rate from the low intensity storm appears to be better simulated than that from the high intensity storm. This may be due to two reasons. First, different nozzle sizes were used to generate the two intensities. The nozzle used for the high intensity produced bigger drops with higher coefficient of variation across the plot. This is likely to cause error in the actual value of the intensity of the artificial storm. The second reason may be due to variation in soil condition during the storm event. The soil surface condition during the high intensity storm may become sealed due to raindrop impact and assorting action of the flowing

water. The sealing effect is not reflected in the model, and therefore, may have varied slightly with the field situation.

The scatter plot (Figure 3) shows the agreement between observed and predicted pairs of runoff volumes for the calibration and validation.

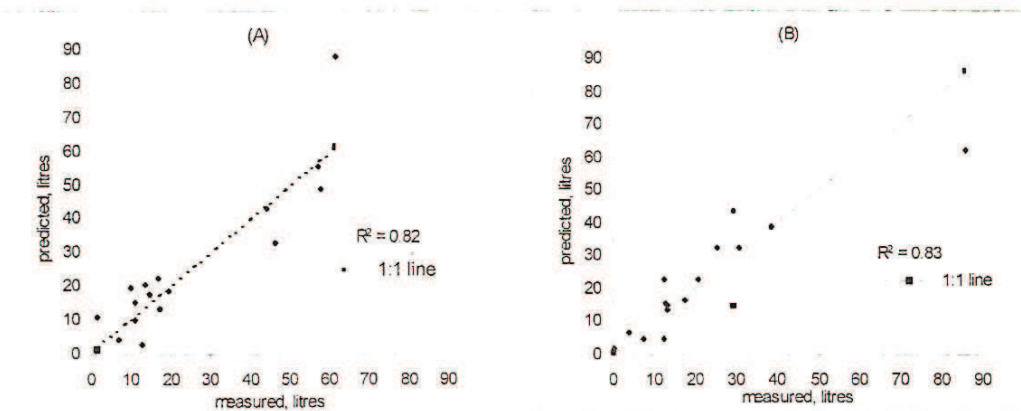


Figure 3: Relationship between measured and predicted values of runoff volume in calibration (A) and validation (B)

Linear regression between predicted and observed runoff volumes gave R^2 value of 0.82 and 0.83 in calibration and validation respectively. The coefficients of efficiency were 0.82 and 0.74 respectively. The result in the calibration is similar to that of the validation, and therefore, the model can be considered stable and is capable of estimating runoff volume quite well in the area.

5. Conclusion

Sensitivity analysis on the *EUROSEM* model revealed that the parameters that affect infiltration of the soil are the most sensitive in the model as far as runoff volume is concerned. The model was calibrated and validated using field data. Calibration of the model was based on varying three parameters (maximum relative saturation, porosity and effective net capillary drive) within their range values until best fit between observed and simulated was achieved. Validation was achieved by comparing predicted runoff volumes with observed data not used in calibration. The model was evaluated, and the summary statistics confirmed that it could adequately simulate surface runoff on degraded lands of northeast Nigeria and, therefore, can be applied to runoff-related research in the area.

Some notable limitations of the *EUROSEM* model in the context of the present study include the following:

1. The model does not include in its structure the process of evapotranspiration and, therefore, cannot simulate periods between events. The model can be used for single events only and this requires that the starting conditions for each storm be specified as data inputs.

2. In order to obtain accurate results, the model requires high-resolution rainfall data and detailed catchment information that are difficult to obtain.

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