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Soil Erosion and Sediment Yield Estimation by Empirical and Process-Based Approaches

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ABSTRACT: The paper presents the outcomes of a comparative analysis of erosion and sediment yield estimation using two different modeling approaches. The main objective of the study was to simulate soil erosion and sediment yield using two different approaches: empirical and process-oriented. The Revised form of Universal Soil Loss Equation (USLE) along with the Sediment Delivery Distributed Model (SEDD) was the empirical approach and 1-D model based on kinematic routing was the process-based approach selected for modeling. The grid-based models developed using these two approaches were applied in a sub-basin of Mun river basin, Thailand to simulate soil erosion, sediment transport and delivery. The simulated outcomes from the process-oriented model are found to be closer to observations as compared to the outcomes of the empirical approach.

INTRODUCTION

Soil erosion is recognized as a major problem arising from agricultural intensification and land degradation; and is likely to be exacerbated as a result of global climatic change. Information on the sources of sediment yield within a catchment can be used as a perspective on the rate of soil erosion occurring within that catchment. Since it is not possible to monitor the influence of every land-use practice in all ecosystems under all weather conditions, erosion predictions are used to rank alternative practices with regard to their likely impact on erosion and sediment dynamics in river basins. Modeling tools can provide a quantitative and consistent approach to estimate soil erosion and sediment transport and yield in river basins under various scenarios (including changed and/or proposed changes in climate and/or land use). Models currently available for sediment yield estimation can be grouped into two categories: (i) empirical models; and (ii) physically-oriented models. Simple empirical methods such as the Universal Soil Loss Equation (USLE), the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), or the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1991) have been frequently used for the estimation of surface erosion and sediment yield from catchment areas (Ferro and Minacapilli 1995; Ferro 1997; Kothyari and Jain, 1997) because of their simple structure and ease of application.

Physically based models are intended to represent the essential mechanisms controlling the erosion process by solving the corresponding equations. These models synthesize individual components that affect the erosion process and they are designed for assessing both the spatial and temporal variability of the natural erosion processes. Examples for physically-based models include ANSWERS (Beasley *et al.*, 1980), AGNPS (Young, 1987; Nugroho, 2003), WEPP (Nearing *et al.*, 1989, Cochrane and Flanagan, 1999), KINEROS (Woolhiser *et al.*, 1990) and EUROSEM (Morgan *et al.*, 1998, Folly *et al.*, 1999).

The aim of this study was to evaluate soil erosion and sediment yield estimation by two different approaches: empirical and processed-based modeling approaches and compare their performances. For the empirical approach, the revised form of USLE model, RUSLE was used in conjunction with SEDD model, to predict erosion potential on a cell by cell basis and to determine the catchment sediment yield by using the concept of sediment delivery ratio (Ferro and Porto, 2000). The selected process-oriented soil erosion and sediment transport model was developed at the

University of Tokyo, Japan and it contains an overland flow simulation model coupled with a sediment transport model (Mughal, 2001). It was applied for the same study areas and finally the performances of the empirical and process-oriented model were evaluated.

METHODOLOGY

Sediment Delivery Distributed (SEDD) Model

SEDD model couples USLE with a spatial disaggretion criterion of sediment delivery processes. Empirical methods such as the USLE have been found to produce realistic estimates of surface erosion over areas of small size (Wischmeier and Smith, 1978).

The USLE is expressed as,

$$A = R*K*L*S*C*P \qquad \ldots (1)$$

Where, A = average annual soil loss predicted (ton ha^{-1}), R = rainfall runoff erosivity factor (MJ mm ha^{-1} hr $^{-1}$), K = soil erodibility factor (ton ha hr MJ^{-1} ha^{-1} mm^{-1}), L = slope length factor, S = slope steepness factor, C = cover management factor and P = support practice factor.

The value of USLE factors are computed using the methods described in the Agricultural Handbook 703 (Renard *et al.*, 1996).

In a catchment, part of the soil eroded in an overland region deposits within the catchment before reaching its outlet. The values of ratio of sediment yield to total surface erosion, which is termed as sediment delivery ratio (D_R), for an area are found to be affected by catchment physiography, sediment sources, transport system, texture of eroded material, land cover etc. (Walling, 1983, 1988). However, variables such as catchment area, land slope and land cover have been mainly used as parameters in empirical equations for D_R (Hadley *et al.*, 1985; Williams and Berndt, 1972; Kothyari and Jain, 1997). Ferro and Minacapilli (1995) and Ferro (1997) hypothesized that D_R in grid cells is a strong function of the travel time of overland flow within the cell. Based on their studies on probability distribution of travel time, the following relationship was assumed herein for a grid cell lying in an overland region of a catchment,

$$D_R = \exp(-\gamma t_i) \qquad \ldots (2)$$

Where, t_i = travel time (hr) of overland flow from the i^{th} overland grid to the nearest channel grid down the drainage path and γ = coefficient considered as constant for a given catchment.

The travel time for grids located in a flow path to the nearest channel can be estimated if the lengths and velocities for the flow paths are known. In grid-based GIS analysis, the direction of flow from one cell to a neighboring cell is often ascertained by using an eight direction pour point algorithm (Tarboton, 1991). Once the pour point algorithm identifies the flow direction in each cell, a cell-to-cell flow path is determined to the nearest stream channel and thus to the catchment outlet.

Process-oriented Distributed Model

The process-oriented distributed model was developed using the physically based governing equations of overland flows and soil erosion and sediment transport mechanisms (Mughal, 2001). The overland flow simulation model is coupled with a soil erosion and sediment transport model for grid-based simulation. The one-dimensional form of the Saint-Venant's continuity and momentum equations is used for overflow routing. The momentum equation is used with a kinematic wave approximation.

The continuity equation is represented as,

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad \ldots (3)$$

The continuity equation is applied between the center points of the two consecutive grids. Similarly, the kinematic wave approximation of the momentum equation can be represented as (Chow *et al.*, 1988),

$$S_f = S_o \qquad \ldots (4)$$

Where, t = time, x = distance along the longitudinal axis of the water course, A = cross sectional area, Q = discharge through A, S_f = friction slope and S_o = bed slope.

The soil erosion and sediment transport is modeled as the detachment of soil by raindrop impact, leaf drip impact, detachment by overland flow over the entire grid and one-dimensional transport or routing of the eroded material by overland flow on the regular square grid discretized system.

Detachment due to raindrop impact process is modeled based on relationships between detachment and kinetic energy of the rainfall due to both direct through fall and leaf drip impact as a function of their kinetic energies. This enables the effects of different heights of vegetation and canopy and residue to be simulated explicitly. The rainfall energy reaching the ground surface as direct throughfall (*KE* (*DT*)) is assumed the same as that of the natural rainfall. It is estimated as a function of rainfall intensity from an equation derived by Brandt (1989). Detachment due to rainfall impact is estimated for each time step using the following equation (Torri *et al.*, 1987), which relates the detachment due to raindrop impact with the total kinetic energy of the rainfall,

$$D_R = (1-C_g)\, k.\, (KE)\, e^{-ZH} \quad \text{... (5)}$$

Where, D_R = soil detachment by raindrop impact (g m^{-2}), k = an index of the detachability of the soil (g J^{-1}) and depends on the soil texture (Morgan, 1995), KE = total kinetic energy of the rain (J m^{-2}), z = an exponent and working value of 2.0 is therefore as representative of a range of values between 0.9 and 3.1, H = depth of surface water layer (mm) and C_g = proportion of ground cover in each processing cell or flow element to consider the non-erodable surfaces, such as rock outcrops, surface rock fragments, thick grass and surface vegetation less than 0.5 m height, concrete and tarmac, occurring within the flow element.

For modeling soil detachment due to overland flow, the following equation (Ariathurai and Arulanandan, 1978) is used,

$$D_F = K_f(T/T_c - 1) \text{ for } T > T_c \quad \text{... (6)}$$

$$D_F = 0 \text{ for } T \leq T_c \quad \text{... (7)}$$

Where, D_F = overland flow detachment (kg m^{-2} s^{-2}), K_f = overland flow detachability coefficient (kg m^{-2} s^{-1}) and can be determined experimentally, T_c = critical shear stress for initiation of motion from the Shield's curve and T = hydraulic shear stress (N m^{-2}) as given by,

$$T = \gamma.h.\, S \quad \text{... (8)}$$

Where, γ = specific weight of water (N m^{-3}), h = depth of overland flow (m) and S = slope of the ground surface. K_f is best regarded as a calibration coefficient, to be determined by fitting the simulated variation of sediment discharge to be measured.

Transportability of the detached material depends on the amount of the detached material and the remaining transport capacity of the flow (transport capacity—existing sediment discharge from upstream). When transport capacity of the flow is greater than the sediment load, the actually detached load (erosion) is estimated. If the transport capacity of the flow will be lesser than the sediment load, then excess material will drop as "deposition" and the actually detached load will be zero and the load carried by the flow will be equivalent to the transport capacity.

After considering the transport capacity of flow, the total actually detached load is determined which is assumed that flow can carry, and this load is considered as the lateral sediment flow and is added at the inlet of the control volume,

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} = 0 \quad \text{... (9)}$$

Where, C = sediment concentration, A = cross-sectional area of flow and Q = discharge or volume flow rate.

Since there is only one unknown in sediment mass balance equation, that is sediment concentration at any time and space. The above equation can be rewritten in terms of sediment discharge as,

$$\frac{\partial(Q_s/V)}{\partial t} + \frac{\partial(Q_s)}{\partial x} = 0 \quad \text{... (10)}$$

Where, V = mean velocity of flow and Q_s = Sediment discharge

Using a finite difference approach, sediment discharge Q_s can be obtained since other parameters in the equation are known.

STUDY AREA

Mun River Basin lies between latitude 14°N and 16°N, and longitude 101°E and 105°E. The Mun River is the largest right bank tributary of the Mekong River, situated in the northeastern part of Thailand. The Chi River joins the Mun River at about 100 km upstream of the confluence with the Mekong River. Chi-Mun basin covers 15% area of Mekong basin and the discharge contribution of the basin is 6.1% in dry season and 4.7% in rainy season. The total draining area of Mun basin is approximately 69,000 km^2. In an average year, the contribution of Chi-Mun to the Mekong is approximately 25,000 hm^3 (Million Cubic Meter), which is equivalent to an annual runoff of 210 mm or 800 m^3 s^{-1}. Roughly two third of this comes from the Mun River. The average annual rainfall in the basin is 1200 mm which varies from 1600 mm in the east and 1000 mm in the west part of the basin. Based on the locations of the flow and sediment gauging stations, several upstream sub-watersheds of the Mun-River basin were identified for modeling. Due to the similarity of sizes, landcover and hydrogeological characteristics of these watersheds and modeling outcomes, only the modeling outcomes in the M91 sub-watershed are presented in this paper. The size of the M91 sub-watershed is 128 km^2 with an average annual sediment yield of 12,648 tons for the duration of 1987–2000 (Figure 1). Its outlet is the sediment gauging station M91, which is not affected by the reservoir located in the downstream. Monthly average sediment yield for the gauging station was obtained from weekly depth integrated suspended sedimen

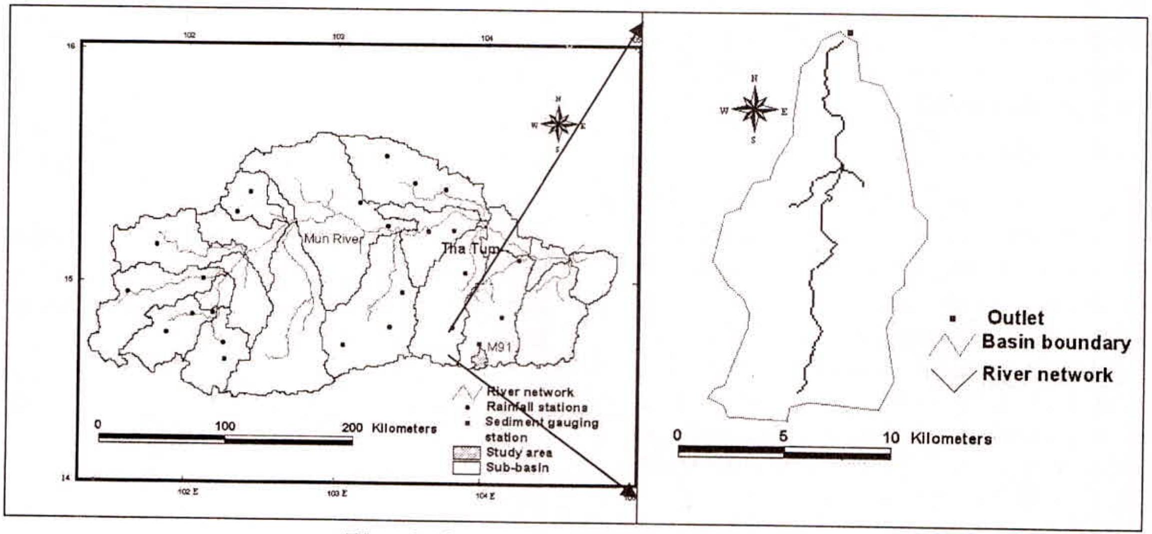

Fig. 1: Study area (M91 sub-basin)

sampling. The elevation in the sub-watershed varies from 183 m to 483 m from msl with an average slope of 3.9%. Agricultural land is the major land use which covers 62% of the sub-watershed while forest covers remaining 38% area. Sandy loam soil covers 93% of the sub-watershed area while remaining 7% area is covered by silty clay loam soil.

DATA PREPARATION AND SIMULATION

For modeling, 3 hourly rainfall data from year 1985–2000 was obtained from the Thailand Meteorological Department. *R* value for RUSLE model was computed by evenly distributing each 3 hourly rainfall event into 30 minutes interval. The long term annual averaged *R* value for the station Tha Thum was computed to be 968. Topographical parameters (*L, S*) were extracted from 90 m resolution Digital Elevation Model (DEM) obtained from NASA (http://srtm.usgs.gov). While computing *L* factor, the contributing slope length, λ was set to a fixed value of 90 m when the flow is in cardinal direction (flow direction values 1, 4, 16 and 64), and 127.28 m when the flow is in diagonal direction (for flow direction values 2, 8, 32 and 128), for the entire basin. The values for the factors *K*, *C* and *P* were estimated for different grids using the soil and land cover data. The spatial data of landuse and soil characteristics were obtained from the digital database (CDROM "Thailand on a disc") provided by the Department of Land Development in the scale of 1:250,000. K values were assigned on the basis of soil texture (Schwab *et al.* 1981) and are presented in Table 1. *C* value, which depends on landuse, was derived from several existing literature (Schwab *et al.* 1981; Morgan, 1995) is shown in Table 2. In case of *P* factor, the value is taken as 0.5 for agricultural land where soil conservation practices like contour farming were applied and '1' for rest of the landuse where farmers did not apply any soil conservation practices (Schwab *et al.,* 1981). The "*a*" values used to compute SDR for different land-use are presented in Table 2.

In case of process-oriented model, it is necessary to calibrate and verify the model for water discharge before applying it to the sediment yield comparison. The model was calibrated for monthly mean discharge at M91. Daily discharge data from year 1987 to 2000 for M91 sub-watershed was obtained from Royal Irrigation Department, Thailand. The land-use parameter used during the calibration and verification is presented in Table 3. Soil water properties in the study area were obtained from the study of Department of Soil Science, Kasetsart University, Thailand (Suntaree, 1993). The model calibration was performed for the period of June–November 1990 and verification was done for the same period in 1991. Since the model computes only surface component of the total river flow, the base flow was separated from total river discharge before model calibration and validation for water discharge. The results obtained from the model calibration and verification are compared with the mean observed discharge and the comparisons are shown in Figures 2(a) and 2(b). Discharge is generally overestimated by the model during the model calibration and verification for water discharge except for June 1990. The overestimation of discharge may result because of higher value of runoff coefficient (0.8) considered during model simulation as the model lacks sub-surface flow components.

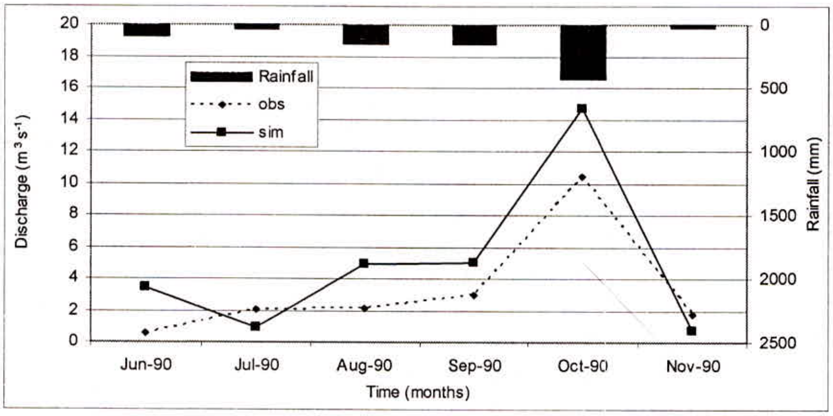

Fig. 2(a): Process-oriented model calibration for water discharge (June–November 1990)

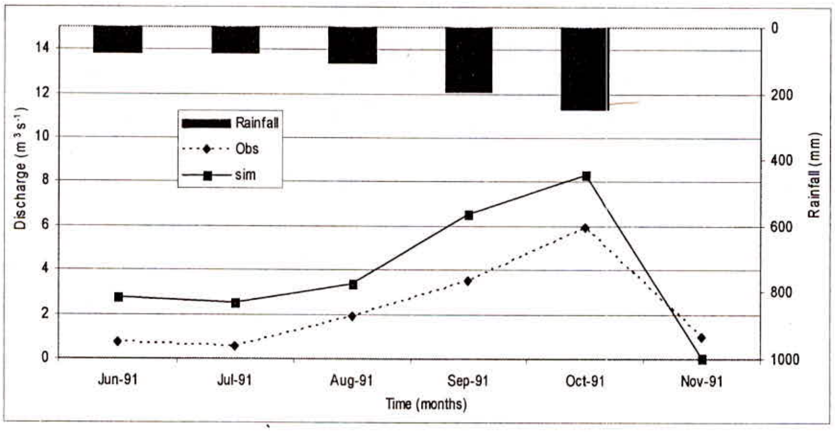

Fig. 2(b): Process-oriented model verification for water discharge (June–November 1991)

Table 1: Soil Erodibility Factor by Soil Texture in SI Unit (ton ha hr MJ^{-1} ha^{-1} mm^{-1})

Textural Class	*Organic Matter Content (%)*		
	0.5	*2.0*	*4.0*
Sandy loam (Group A)	0.0356	0.0316	0.0250
Silty clay loam(Group D)	0.0487	0.0422	0.0343

Table 2: Cover Management Factor (C), CN and "a" Value on the Basis of Landuse Type

Sl. No.	*Land Use*	*C Value Basis*	*C Value*	*CN*	*"a" Value*
1.	Cultivated land	Crops, disturbed land	0.4000	62 (Group A) 81 (Group D)	1.55
2.	Forest land	Forest	0.0020	30 (Group A) 77 (Group D)	0.76

Table 3: Different Land Use Parameters

Land Use Type	*Manning's Roughness Coefficient (n)*	*Canopy Cover (frac.)*	*Canopy Height (m)*	*Ground Cover (frac.)*	*Leaf Area Index*
Cultivated land	0.040	0.60	1.00	0.020	3.52
Forest	0.060	0.70	30.0	0.030	2.84

(*Source:* Mugal, 2001)

RESULTS AND DISCUSSION

The sediment contribution of each grid to the outlet was computed with the help of an erosion potential map and a *SDR* map. The simulated sediment yield at the outlet was compared with the measured field data obtained from Royal Irrigation Department, Thailand.

The simulation was carried out for two DEM resolutions: 90 m and 30 m (re-sampled from 90 m). In Arc/Info, the slope for a cell is calculated from the 3 × 3 neighborhood using the average maximum technique. The technique is effective in preserving topographical variation while resampling a DEM into finer resolution to some extent. The computed values of average annual sediment yield at the catchment outlet by RUSLE method is presented in Table 4 together with the observed data. In case of 30 m resolution, the simulated yield is closer to the observation than the value obtained using 90 m DEM resolution. Table 5 shows the effect of DEM resolution on different RUSLE parameters and *SDR* values and it can be seen from this table that the *L* and *S* factors vary significantly for the two DEMs of different resolutions. Changes in grid sizes affect the slope values and ultimately affect the values of L and S factors. L factor is dependent on grid size and slope, whereas S factor depends on slope only. The time series of computed and observed sediment yields in monthly scale are shown in Figure 3. Improved results were obtained for DEM resolution of 30 m compared to the results obtained from 90 m resolution. From the results and analysis, it is found that the RUSLE based SEDD model has grossly over-estimated sediment yield and the simulated results are greatly influenced by the resolution of DEM. The model prediction may have been improved if γ coefficient was calibrated using the measured sediment yield values at mean annual scale for SDR computation. During *SDR* calculation, the sensitivity analysis of the parameter γ showed that the computed S_y was not very sensitive to γ. The variation of γ value by 15 times (from 0.1 to 1.5) changed the S_y value only 10%. Since large variation in γ affected S_y insignificantly during sensitivity analysis, γ value was taken as 1 in the computation for simplicity. The sensitivity analysis has supported the findings of Jain and Kothyari (2000), where they had reported that S_y was not very sensitive to γ in their study.

Process-oriented model outputs for the period of June to November 1990 are shown in the Figure 4 together with the observed monthly sediment yields. As seen from the figure, the simulated results show better agreement with the observed monthly sediment yield at the catchment outlet. Different soil parameters used in the model simulation are shown in Table 6. The error statistics of the model is shown in the Table 7. The Nash-Sutcliffe Coefficient or Efficiency Index (*EI*) value of 0.78 and R^2 value of 0.92 shows that model results possess high correlation with the observed value. Similarly, sediment yield was simulated for a period of 6 months from June to November 1991. The simulated sediment yield is shown in Figure 5 together with the observed data in monthly time scale. As seen from the Figure 5, the simulated results agree well with the observed monthly sediment yield at the catchment outlet. In this simulation, Efficiency Index (*EI*) value was obtained to be 0.93 and R^2 value of 0.93 shows that model results possess high correlation with the observed value.

Table 4: Computed and Observed Value of Annual Average Sediment Yield Using RUSLE

Station	*Observed (tons km^{-2})*	*Computed for 90 m DEM Resolution (tons km^{-2})*	*Computed for 30 m DEM Resolution (tons km^{-2})*	*% Error for 90 m DEM*	*% Error for 30 m DEM*
M91	98.81	505.41	322.46	411	226

Table 5: DEM effect on USLE Parameters and SDR in RUSLE

DEM Resolution	*Range of L Factor*	*Range of S Factor*	*Range of SDR*
90 m	1.30–3.38	0.03–6.73	0.78–1
30 m	1.05–1.61	0.03–11.98	0.83–1

Table 6: Soil Parameters Used in Process-Based Model Simulation

Soil Texture	*Soil Detachability Index, K_r (g J^{-1})*	*Overland Flow Detachability Index, K_f (mg m^{-2})*	*Density of Particle (kg m^{-3})*	*Median Particle Dia (µm)*
Sandy clay loam	3.50	0.60	2680	45.0
Loamy sand	2.00	0.40	2650	47.0

Table 7: Error Statistics of Process-Based Model Simulation

Year	*Efficiency Index (EI)*	*Room Mean Square Error (RMSE)*	*Mean Absolute Error (MAE)*	*Mean Percent Error (MPE)*	*R^2*
1990	0.78	437	284	–40	0.92
1991	0.93	127	92	–216	0.93

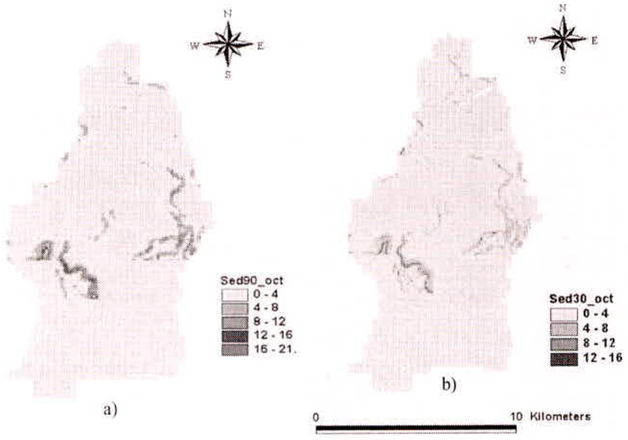

Fig. 3: Time series of observed and simulated yield by RUSLE based model

A comparison of the simulated results obtained from RUSLE/SEDD and process-oriented model are presented in Table 8 together with the observed values. The results reflect that the RUSLE/SEDD computed values were higher than the observations from the period of August to October 1990. Unlike RUSLE approach, the process-oriented model results showed good agreement with the observations for the same period.

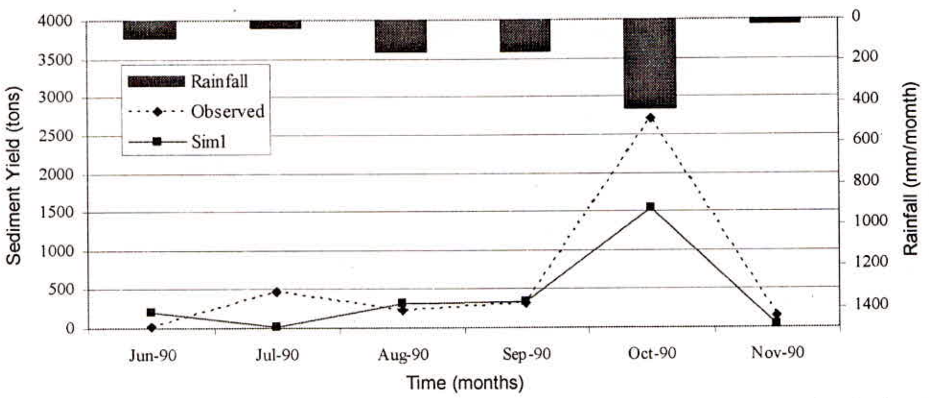

Fig. 4: Comparison of observed and simulated sediment yield by process-oriented model (June–November 1990)

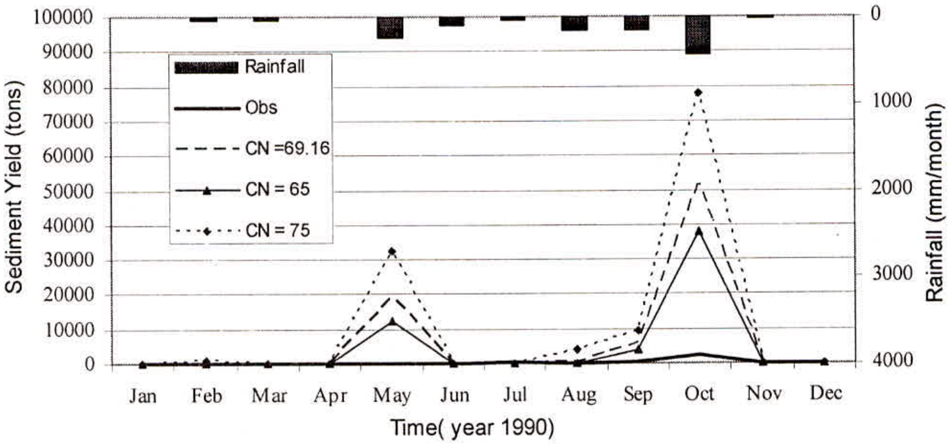

Fig. 5: Comparison of observed and simulated sediment yield by process-oriented model (June–November 1991)

Table 8: Comparison of Performance of the Three Models

Date	*Simulated Sediment Yield (tons)*		*Observed (tons)*	*% Error*	
	RUSLE	*Process-Based*		*RUSLE*	*Process-Based*
Jun-90	1099	120	24	477	400
Jul-90	291	153	469	–38	–67
Aug-90	1716	250	225	663	11
Sep-90	2792	433	327	754	32
Oct-90	7989	1695	2696	196	–37.
Nov-90	122	0.8	159	–23	–100

CONCLUSIONS

This study was an attempt to estimate soil erosion and sediment yield in a river basin using empirical (RUSLE/SEDD) and process-oriented approaches in a distributed manner and compare their performances. The empirical models did not perform well and the outcomes were influenced by DEM resolutions in case of the RUSLE based SEDD model. The error between computed and observed annual average sediment yield was found to be 411% in case of 90 m DEM resolution. After resampling 90 m DEM into 30 m resolution, the computed error was reduced by almost 45%. The improvement was due to the effect of DEM resolution on *L*, *S* and *SDR* factors. The variation in the result may be due to the certain assumptions made during the analysis like computation of soil erodibility value on the basis of soil texture and use of constant *C* values in stead of time varying. In time series computation, the performance of the process-oriented model was better than the empirical (RUSLE/SEDD) model. From June to October 1990 (peak sediment discharge period), the error between simulated results by the process-oriented model and observations was within 70%. Although there are many input parameters for the process-oriented model, it mimics the processes of detachment, erosion and transportation of sediment and hence produces better result than the empirical approach. Though empirical models such as RUSLE/ SEDD) are economic in terms of computational resources and data requirement than the process-oriented model, their applications for temporal analysis of sediment transport is found to be less useful. Another reason behind process-oriented model outperforming empirical models is that the process-oriented model was calibrated before application while empirical models were not. The empirical model may have performed better if proper calibration had been carried out.

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