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Estimation of Soil Erosion and Sediment Yield Using GIS at Catchment Scale

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Abstract A GIS-based method has been applied for the determination of soil erosion and sediment yield in a small watershed in Mun River basin, Thailand. The method involves spatial disintegration of the catchment into homogenous grid cells to capture the catchment heterogeneity. The gross soil erosion in each cell was calculated using Universal Soil Loss Equation (USLE) by carefully determining its various parameters. The concept of sediment delivery ratio is used to route surface erosion from each of the discritized cells to the catchment outlet. The process of sediment delivery from grid cells to the catchment outlet is represented by the topographical characteristics of the cells. The effect of DEM resolution on sediment yield is analyzed using two different resolutions of DEM. The spatial discretization of the catchment and derivation of the physical parameters related to erosion in the cell are performed through GIS techniques.

Key words DEM · GIS · soil erosion · sediment delivery ratio · sediment yield

1 Introduction

Soil erosion has been accepted as a serious problem arising from agricultural intensification, land degradation and possibly due to global climatic change (Yang et al., 2003). Not only the deposition of sediment transported by river into a reservoir reduces the reservoir capacity, but also sediment deposition on river bed and banks causes widening of flood plains during floods. Soil erosion is the most significant contributor of off-site ground water pollution on a global scale with most of the contaminants originating within an agricultural setting (Marsh and Grossa, 1996). Since it is not possible to monitor the influence of every land-use practices in all ecosystems under all weather conditions, erosion

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predictions are used to rank alternative practices with regard to their likely impact on erosion. Assessment of soil erosion as to how fast soil is being eroded is helpful in planning conservation work. Modeling can provide a quantitative and consistent approach to estimate soil erosion and sediment yield under a wide range of conditions. Models available in the literature for sediment yield estimation can be grouped into two categories: (1) physically-based models and (2) empirical models. Physically based models are intended to represent the essential mechanisms controlling erosion process by solving the corresponding equations. These models are the synthesis of individual component that affect the erosion process and it is argued that they are highly capable to assess both the spatial and temporal variability of the natural erosion processes. The physically-based models include ANSWERS (Beasley et al., 1980), WEPP (Nearing et al., 1989), KINEROS (Woolhiser et al., 1990) and EUROSEM (Morgan et al., 1998). Although physically-based models emulate the real processes, they suffer from the major drawback of necessity of many parameters related with each processes as these models are organization of different sub-models related to hydrology, hydraulics, meteorology and soil mechanics. For example, WEPP model (Nearing et al., 1989) requires as many as 50 input parameters which can cause the problem of equifinality (condition in which different combination of model parameters lead to similar output) (Brazier et al., 2000). A decade ago, Beven (1989) and Grayson et al. (1992) initiated a meaningful debate to highlight the current limitations of distributed physically-based models. It has been shown that the process descriptions used in the current models may not be appropriate; that the appropriate model parameter values may vary with grid scale; that techniques for parameter estimation are often at inappropriate scales; and that there is sufficient uncertainty in model structure and spatial discretization in practical applications that these hydrologic models are difficult to validate (Beven, 1996). And, the application of process-based models in many areas is further limited due to lack of data set required for the model simulation.

Simple empirical methods such as the Universal Soil Loss Equation (USLE) (Musgrave, 1947; Wischmeier and Smith, 1965), the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), or the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) are 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 simple structure and ease of application. Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1984) and Agricultural Non-Point Source Pollution Model (AGNPS) (Young et al., 1987) are the examples of commonly used watershed models based on USLE methodology to compute soil erosion. Although USLE/RUSLE may not replicate the real picture of erosion process as they are based on coefficients computed or calibrated on the basis of observations, it has been extensively applied all over the world mainly due to the simplicity in the model formulation and easily available data-set (Bartsch et al., 2002; Jain and Kothyari, 2001; Jain et al., 2001). USLE has been proved to provide good estimate of soil erosion at plot scale (Wischmeier and Smith, 1978). In case of catchment, part of eroded soil is deposited within catchment before it reaches the catchment outlet. Nevertheless, soil erosion computed by USLE can be routed to catchment outlet using the concept of sediment delivery ration by applying appropriate procedure.

Due to the spatial variation in rainfall and catchment heterogeneity, both soil erosion and sediment transport processes are spatially varied. Such variability has promoted the use of data intensive distributed approach for the estimation of catchment erosion and sediment yield by discretizing a catchment into sub-areas each having approximately homogeneous characteristics and uniform rainfall distribution (Young et al., 1987; Beven, 1989). To encapsulate the spatial variation of the parameters like topography, soil and land use in a watershed, the use of Geographical Information System (GIS) methodology is well suited. GIS can be used for the discretization of the catchment into small grid cells and for the computation of such physical characteristics of these cells as slope, land use and soil type, all of which affect the processes of soil erosion and deposition in the different sub-areas of a catchment. A number of different GIS based models (both empirical and process-based) have been developed to interpret soil loss data as it becomes an increasing concern on a global scale (Marshringni and Cruise, 1997; Rewarts and Engel, 1991; Srinivasan and Engel, 1994). Jain et al. (2001) compared the Morgan model and Universal Soil Loss Equation (USLE) model to estimate soil erosion from a Himalayan watershed using remote sensing and ancillary data in GIS mode. The soil erosion estimated by Morgan model was found to be within the limits reported for the region while the soil erosion estimated by USLE gave a higher rate. Fistikoglu and Harmancioglu (2002) integrated GIS with the USLE (Universal Soil Loss Equation) model in identification of rainfall-based erosion and the transport of non-point source pollution loads to the Gediz River, Turkey. They have used empirical relationship between Delivery Ratio (DR) and catchment area in order to compute sediment load. Jain et al. (2003) made an assessment of sediment yield for the Satluj River using two approaches: (1) relationship between suspended sediment load and discharge and (2) empirical relationship. The sediment–discharge relationship was developed using daily data. For estimation of the sediment yield using the empirical relationship, various geographical parameters such as land use and topography were generated using Geographic Information System (GIS) technique. Onyando et al. (2005) used Universal Soil Loss Equation (USLE) in conjunction with GIS Arc/Info and Integrated Land and Water Information Systems (ILWIS) to estimate potential soil loss from River Perkerra catchment, Kenya. They also utilized empirical equation to estimate sediment delivery ratio in order to compute sediment yield at catchment outlet. Panday et al. (2006) combined GIS, Remote Sensing (RS) with Universal Soil Loss Equation (USLE) to identify the critical erosion prone areas of watershed for prioritization purpose. Most of the previous studies have either computed only soil erosion (not sediment yield) or used lumped empirical relationship to compute Delivery Ratio (DR) in order to calculate sediment yield the catchment outlet.

The aim of this study was to use GIS technique to model soil erosion and sediment yield in distributed manner using minimum available dataset using USLE approach. GIS techniques have been used for the descritization of the catchment into small grid cells and computation of different physical characteristics of these cells such as slope, land use, soil type, all of which affect the processes of soil erosion and deposition in different sub-areas of catchment. And, GIS technique is further utilized to separate cells into overland and channel component, to estimate soil erosion in individual cell and to determine the catchment sediment yield by using the concept of sediment delivery ratio.

2 Study Area

The study area is the M91 sub-watershed of the Mun River as shown in Figure 1. The Mun River basin lies between latitude 14°N and 16°N, and longitude 101°E and 105°E. It 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

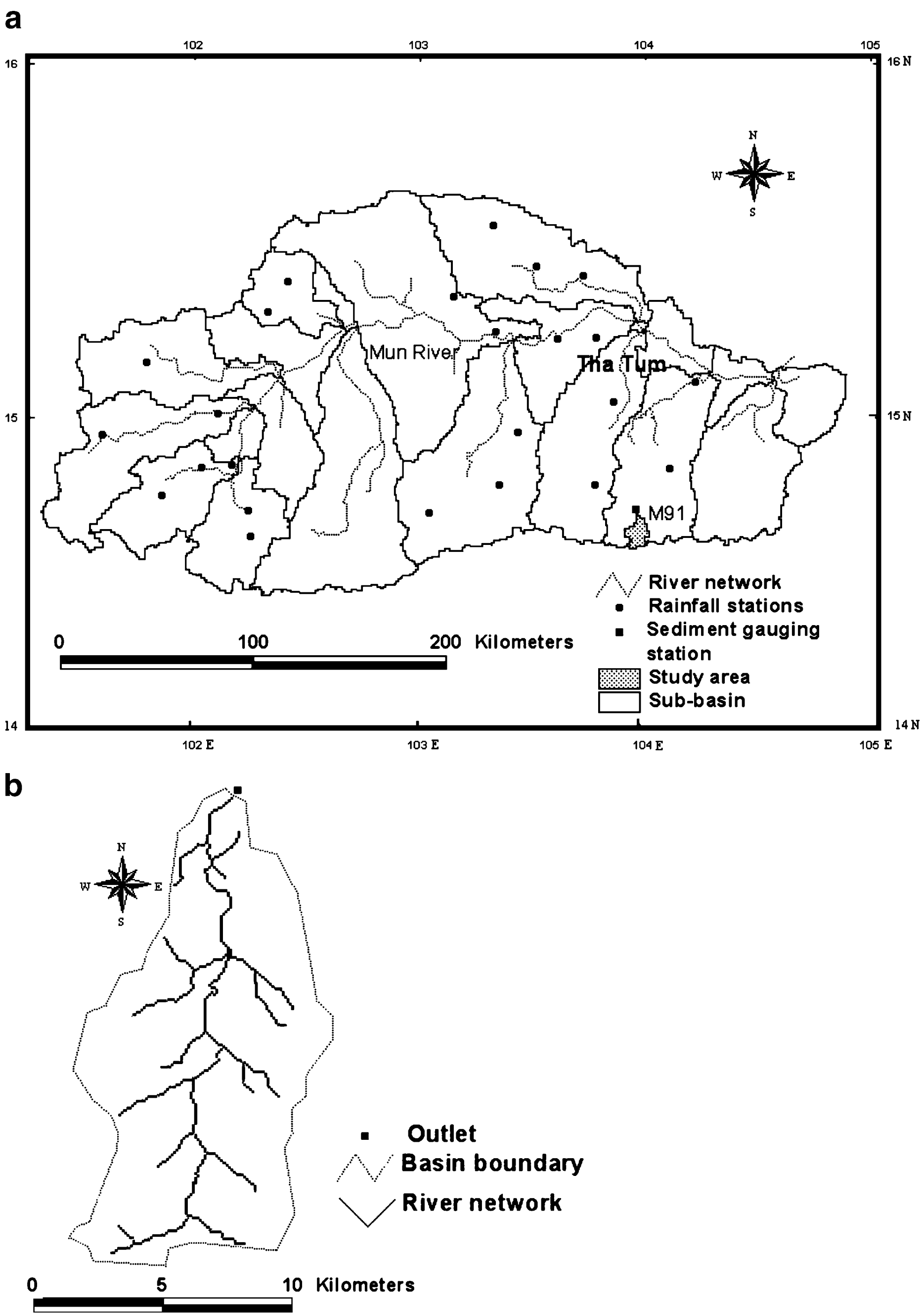

Figure 1 **a** Mun river basin, Thailand **b** Study area (M91 sub-basin).

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 MCM (Million Cubic Meter), which is equivalent to an annual runoff of 210 mm or 800 m^3/s. Roughly two third of this comes from the Mun River. The average annual rainfall in the basin is 1,200 mm which varies from 1,600 mm in the east and 1,000 mm in the west part of the basin. It covers five provinces (Nakhon Rathchasima, Buri Ram, Surin, Sisaket and Ubon Ratchathani) entirely and three (Maha Sarakham, Rio Et and Yasothom) partly in Thailand.

Between 1990 and 1995, the average deforestation rate in the Lower Mekong basin was 1.6% PA – one of the highest rates in the world. The erosion in the basin is mainly rainfall based runoff erosion subjected to the effects of land use (MRC – Mekong River Commission, 2003). Chi-Mun basin comprises of more than 20 dams. And, the deposition of sediment transported by river into the reservoir is reducing the reservoir capacity. The average annual loading of the suspended sediments during the 90 s at the Chi-Mun/Mekong Junction was 0.96 million tons/year (Al-Soufi, 2004). The M91 sub-watershed is selected for this study based on the location of the sediment gauging station M91, which is not affected by the reservoir located in the downstream. The size of the M91 sub-watershed is about 128 km^2 with an average annual sediment yield of 12,648 tons. The elevation varies from 183 to 483 m above msl in the watershed. Digital elevation model (DEM) of the study area is shown in Figure 2. Cultivated land and forest are two major land uses in the study area where cultivated land accounts for 62% area of total watershed. The major soil types in the study area are sandy loam and silty clay loam in which sandy loam soil covers 93% of watershed area. Structurally, the basin consists of gently folded to near horizontal sequences of shale and sandstones. Surface sandy loam and clay generally extends 2 to 4 m deep up to a maximum of 10 m. Medium sand fraction is dominant in river sand compared to silt and clay. Soil analysis from river back showed 80% fine sand, 10% silt and 10% clay (Suntaree 1993).

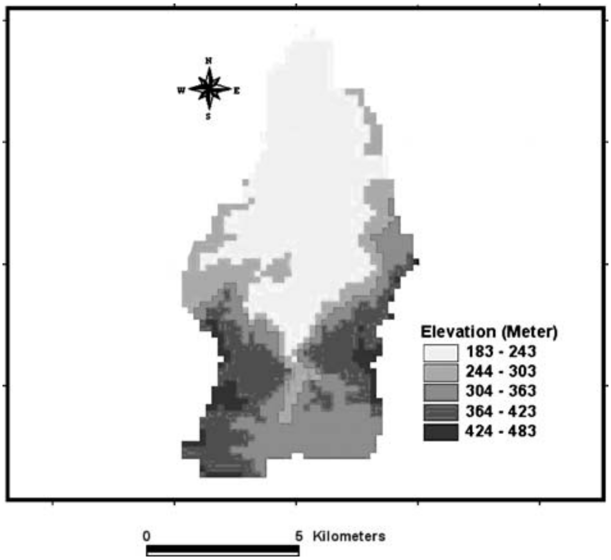

Figure 2 Digital Elevation Model (*DEM*) of the study area (resolution of 90 m).

3 Methodology

The rate of soil erosion from an area is strongly dependent upon its soil, vegetation and topographic characteristics beside rainfall and runoff. These factors are found to vary greatly within the various sub-areas of a catchment. Therefore, the catchment needs to be discritized into smaller homogeneous units before making computations for soil loss. A grid-based discretization is found to be the most reasonable procedure in both process-based models as well as in other simple models (Beven, 1996; Kothyari and Jain, 1997).

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:

$$A = R^{*}K^{*}L^{*}S^{*}C^{*}P \tag{1}$$

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 on the methods described by Agricultural Handbook 703 (Renard et al., 1996). Rainfall Erosivity Index (R) is generally calculated from an annual summation of rainfall data using rainfall energy over 30-min duration. The relative fall velocity of the single droplet and the overall rainfall intensity determines the erosive properties of rain droplets (Hrissanthou et al., 2003).

$$R = \frac{1}{n}\sum_{i=1}^{n}\left(\sum_{j=1}^{m} E_j (I_{30})_j\right) \tag{2}$$

Where n = Total number of years, m = Total number of rainfall storms in ith year, I_{30} = Maximum 30 min intensity (mm hr $^{-1}$), E_j = Total kinetic energy (MJ ha^{-1}) of jth storm of ith year and is given as:

$$E_j = \sum_{i=1}^{p} e_k {}^{*} d_k \tag{3}$$

Where p = Total number of divisions of jth storm of ith year, d_k = Rainfall depth of kth division of the storm (mm), e_k = Kinetic energy (MJ ha^{-1} mm^{-1}) of kth division of the storm and is given as: (Renard et al., 1996)

$$e_k = 0.29\left(1 - 0.72e^{(-0.05 i_k)}\right) \tag{4}$$

Where i_k = Intensity of rainfall of kth division of the storm (mm hr^{-1}). If λ is the horizontal projection of the slope length (in meter), then L factor is given as,

$$L = \left(\frac{\lambda}{22.1}\right)^{m} \tag{5}$$

Where m = Variable slope length exponent

The slope-length exponent m is related to the ratio β of rill erosion (caused by flow) to interrill erosion (principally caused by raindrop impact) by the following equation:

$$m = \beta/(1+\beta) \tag{6}$$

For moderately susceptible soil in both rill and inter-rill erosion, McCool et al. (1989) suggested the equation:

$$\beta = \frac{11.1607(\mathrm{Sin}\theta)}{3.0\left((\mathrm{Sin}\theta)^{0.8} + 0.56\right.} \tag{7}$$

Where θ = Slope angle (degrees)

The slope steepness factor S is evaluated from (McCool et al., 1987).

$$\begin{aligned} S &= 10.8 \sin\theta + 0.03 \text{ for } s < 9\% \\ S &= 16.8 \sin\theta - 0.50 \text{ for } s \geq 9\% \end{aligned} \tag{8}$$

Where θ = Slope angle (degrees)

C and P factors were assigned to different grid according to land cover data while K factor was estimated using the soil data.

4 Sediment Delivery Ratio (SDR)

In a catchment, part of the soil eroded in an overland region deposits within the catchment before reaching its outlet. The ratio of sediment yield to total surface erosion is termed as sediment delivery ratio (D_R). Values of 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 (Kothyari and Jain, 1997; Williams and Berndt, 1972; Hadley et al., 1985).

Ferro (1997) and Ferro and Minacapilli (1995) hypothesized that D_R in grid cells is a strong function of the travel time of overland flow within the cell. The travel time is strongly dependent on the topographic and land cover characteristics of an area and therefore its relationship with D_R is justified. Based on their studies, the following empirical relationship was assumed herein for a grid cell lying in an overland region of a catchment:

$$D_R = \exp(-\gamma t_i) \tag{9}$$

Where t_i is the travel time (h) of overland flow from the ith overland grid to the nearest channel grid down the drainage path and γ is a 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 one knows the lengths and velocities for the flow paths. In grid-based GIS analysis, the direction of flow from one cell to a neighboring cell is ascertained by using an eight direction pour point algorithm. 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. If the flow path from cell i to the nearest channel cell traverses m cells and the flow length of the ith cell is l_i (which can be equal to the length of a square side or to a diagonal depending on the direction of flow in the ith cell) and the velocity of flow in cell i is v_i, the travel time t_i from cell i to the nearest channel can be estimated by summing the time through each of the m cells located in that flow path:

$$t_i = \sum_{i=1}^{m} \frac{l_i}{v_i} \tag{10}$$

For the present study, the method for the determination of the overland flow velocity proposed by the US Soil Conservation Service was chosen due to its simplicity and to the availability of the information required (SCS – Soil Conservation Service, 1975). The flow velocity is considered to be a function of the land surface slope and the land cover characteristics:

$$v_i = a_i {}^* S_i^b \tag{11}$$

Where b is a numerical constant equal to 0.5 (Ferro and Minacapilli 1995; SCS – Soil Conservation Service, 1975), S_i is the slope of the ith cell and a_i is a coefficient related to land use (Haan et al. 1994). Introducing Eqs. 10 and 11 into Eq. 9 gives

$$D_{\mathrm{R}} = \exp\left(-\gamma \sum_{i=1}^{m} \frac{l_i}{a_i S_i^{0.5}}\right) \tag{12}$$

Note that $l_i / S_i^{0.5}$ is the definition of travel time used by Ferro and Minacapilli (1995). Values of the coefficient a_i for different land uses were adopted from Haan et al. (1994).

If S_{E} is the amount of soil erosion produced within the ith cell of the catchment estimated using Eq. 1, then the sediment yield for the catchment, S_{y}, was obtained as below:

$$S_{\mathrm{y}} = \sum_{i=1}^{n} D_{\mathrm{R}} {}^* S_{\mathrm{E}} \tag{13}$$

Where n is the total number of cells over the catchment and the term D_{R} is the fraction of S_{E} that ultimately reaches the nearest channel. Since the D_{R} of a cell is hypothesized as a function of travel time to the nearest channel, it implies that the gross erosion in that cell multiplied by the D_{R} value of the cell becomes the sediment yield contribution of that cell to the nearest stream channel. The D_{R} values for the cells marked as channel cells are assumed to be unity.

5 Data Preparation and Simulation

For modeling, three hourly rainfall data from year 1985–2000 was obtained from Thailand Meteorological Department (TMD). R value was computed using Eqs. 2, 3 and 4. The long term annual averaged R value for the station Tha Tum was computed to be 968.14.

Table I 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	0.0356	0.0316	0.0250
Silty clay loam	0.0487	0.0422	0.0343

Table II Cover management factor (C) and a value on the basis of land use type

S N	Land use	C value basis	C value	a value
1	Cultivated land	Crops, disturbed land	0.4000	1.55
2	Forest land	Forest	0.0020	0.76

Topographical parameters (L, S) were extracted by using SRTM-DEM (http://edc.usgs.gov/products/elevation/srtm.html) of resolution 90 m. Eq. 5 was used for L factor calculation while S factor was computed using Eq. 8 for each cell. The values for the factors K, C and P were estimated for different grids using the soil and land cover data. The data in the Land Use and Soil layers were obtained from the CDROM "Thailand on a disc." These data were provided by the Department of Land Development (DLD) 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 I. The major soil types in the study area are sandy loam and silty clay loam. C value, which depends on land use, was obtained from different literature (Morgan, 1995; Schwab et al., 1981). Cultivated land and forest are two major land uses in the study area. The C values used in the study are shown in Table II. In case of P factor, the value is taken 0.5 for agricultural land and for rest of the land use; P value is assigned to be 1. a values for different land-use used to compute SDR is presented in Table II. Monthly sediment yield data was obtained from Royal Irrigation Department (RID), Bangkok for year 1987–2000.

The drainage map of the watershed (Figure 1b) was prepared using GIS technique based on DEM data. The GIS-based drainage map was verified and corrected with the river network map from the CDROM "Thailand on a disc" for the watershed. For the determination of stream order, Strahler's system was followed which showed that the watershed was of order three. The total length of stream order is obtained by adding the length of streams with same order. Order one stream network covers about 43.5 km while order two network measures about 16 km in length. Similarly, order three network covers the length of 7 km.

6 Results and Discussion

During SDR calculation, the sensitivity analysis of the parameter γ showed that the computed values of S_y were not very sensitive to the value of γ used in Eq. 12. γ value was varied from 0.1 to 1.5 and it was observed that S_y value varied by only 10%. So, γ value is taken equal to 1 in the computation for the simplicity. The sediment contribution of each grid to the outlet was computed with the help of erosion potential map and SDR map. And, the sediment yield at the outlet was compared with the field measured data which was obtained from Royal Irrigation Department (RID), Thailand.

Table III Computed and observed value of sediment yield

Duration	Observed (tons/km^2)	Computed for 90 m DEM resolution (tons/km^2)	Computed for 30 m DEM resolution (tons/km^2)	Percent (%) error for 90 m DEM	Percent (%) error for 30 m DEM
Year 1990	72.12	206.65	150.54	186.53	108.73
Annual average (1987–2000)	98.81	505.41	322.46	411.49	226.34

Table IV DEM effect on USLE parameters and SDR

DEM resolution	*L* factor	*S* factor	SDR
90 m	1–3.38	0.03–6.73	0.78–1
30 m	1–1.61	0.03–11.98	0.83–1

The simulation was carried out for two DEM resolutions: 90 and 30 m (re-sampled from 90 m). The computed and observed value of sediment yield for year 1990 and average annual for 14 years (1987–2000) at the catchment outlet is presented in Table III. In case of 30 m resolution, the simulated yield is closer to the observation than the value obtained using 90 m DEM resolution. These results show that the DEM resolutions greatly influence the outcomes of the models. Table IV shows the effect of DEM resolution on different USLE parameters and SDR values and it can be seen from this table that the *L* and *S* factors are different for these two DEMs of different resolutions. Change in grid size affects slope

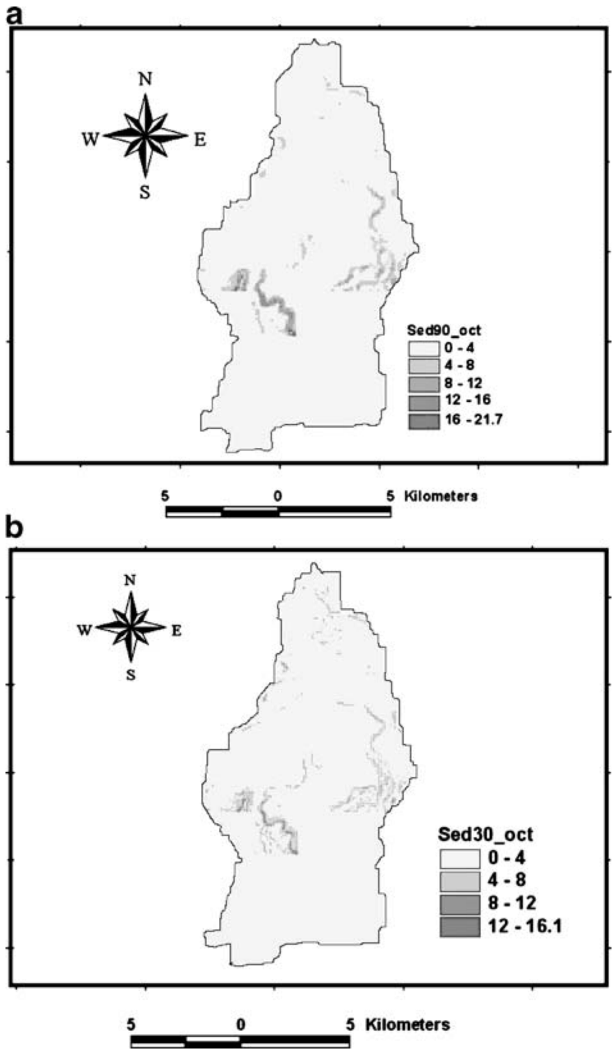

Figure 3 **a** Simulated sediment yield map for October 1990 with *DEM* resolution of 90 m **b** Simulated sediment yield map for October 1990 with *DEM* resolution of 30 m.

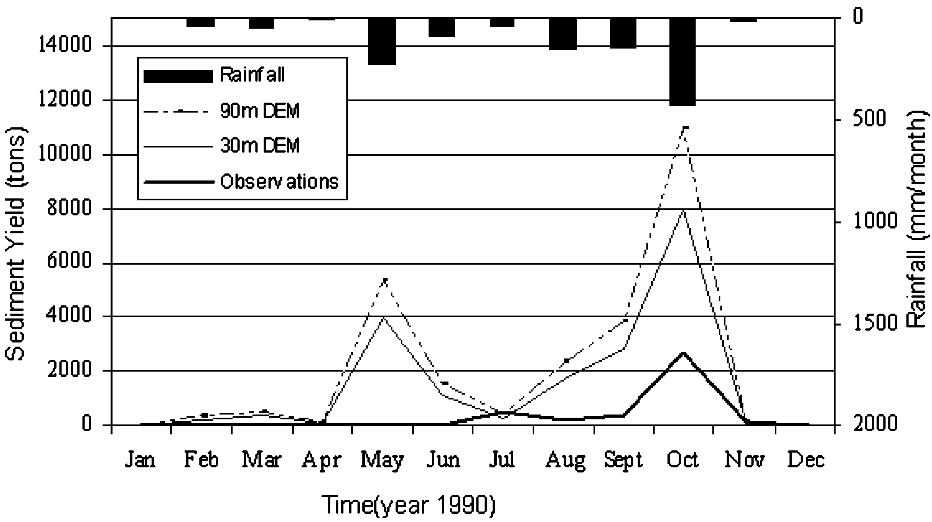

Figure 4 Time series of observed and simulated yield by *RUSLE* based model.

values and ultimately affects the values of *L* and *S* factors. *L* factor is dependent on grid size and slope, whereas *S* factor depends on slope only. The sediment yield maps (for October 1990) obtained using 90 and 30 m DEM resolution are shown in Figure 3a, b. Annual sediment yield for 1990 is closer the observation compared to long-term annual average. Simulation was also carried for monthly basis for year 1990 and the time series of computed and observed sediment yield is shown in Figure 4. The monthly sediment yield simulation was limited to year 1990 because the land-use map used in the study was based on land-use of the year 1990. It should be noted that two USLE parameters *C* and *P* along with Sediment Delivery Ratio (SDR) computation were based on land-use map. For the year 1990, error between computed and observed sediment yield was found to be 186.53 and 108.73% for DEM resolution of 90 and 30 m, respectively. Similarly, the error between computed and observed long-term annual average sediment yield was found to be 411.49% in case of 90 m DEM resolution. After resampling 90 m DEM into 30 m resolution, the computed error was 226.34%. The high level of discrepancy between observed and computed long-term average sediment yield might be resulted by different dynamic processes occurring within the catchment. While computing long-term annual average sediment yield, the only parameters varied was *R* factor (of USLE) while others factors were assumed to be constant. In real world, there are many other processes that vary temporally, not only rainfall within a catchment. The improvement in result for 30 m resolution compared to 90 m is due to the effect of DEM resolution on *L, S* and SDR factors. It was observed that USLE based model over-estimated sediment yield.

7 Conclusion

This study is an attempt to estimate soil erosion and sediment yield in one small sub-basin of Mun River basin using existing conceptual methods and GIS. This methodology can be used for the identification of sediment source areas and prediction of sediment yield at a catchment scale with available optimum data sets. Arc/Info was used for discretizing the catchment into grid cells of different resolutions. Grid cell slope, drainage direction and catchment boundary were generated from DEM using pour point method. The DEM was further analyzed to classify the grid cells into overland flow and channel region by using channel initiation threshold area approach. After preparing different USLE parameter layers, the gross surface erosion map was computed. The sediment delivery ratio of overland flow cell was assumed to be a function of the travel time of overland flow from given cell to the nearest downstream channel cell. For channel cells, the sediment delivery ratio was assumed to be unity.

The computed and observed values were observed to have some discrepancy for both annual and monthly sediment yield. The variation is resulted by the few assumptions made during the analysis. In the study, computation of soil erodibility value (K) was based on soil texture only. Similarly, constant cover management factor (C) values were used in stead of time varying because of the lack of series of land-use map for different years. Improved results can be expected if these enhancements are incorporated.

Better estimates of sediment yield were obtained using 30 m DEM than 90 m because of the effect of DEM resolution on different USLE parameters like L, S factors and Sediment Delivery Ratio (SDR). The slope for a cell is calculated from the 3×3 neighborhood using the average maximum technique in Arc Info. The improved result for 30 m DEM resolution compared to 90 m resolution using USLE method bolsters the fact that better results can be expected for the resolution which is closer to the slope length of 22.4 m, slope length used in the derivation of USLE relationship.

References

Al-Soufi R (2004) Soil erosion and sediment transport in the Mekong basin. In: Proc. of 2nd APHW conference, Singapore, pp 47–56

Bartsch KP, Mietgroet HV, Boettinger J, Dobrowolski JP (2002) Using empirical erosion models and GIS to determine erosion at Camp William, Utah. J Soil Water Conserv 57(1):29–37

Beasley DB, Huggins LF, Monke EJ (1980) ANSWERS: a model for watershed planning. Trans ASAE 23 (4):938–944

Beven KJ (1989) Changing ideas in hydrology: the case of physically-based models. J Hydrol 105:157–172

Beven KJ (1996) A discussion of distributed hydrological modeling. In: Abott MB, Refsgaard JC (eds) Distributed hydrological modeling. Kluwer, Dordrecht, The Netherlands, pp 278–255

Brazier RE, Beven KJ, Freer J, Rowan JS (2000) Equifinality and uncertainty in physically-based soil erosion models: application of the GLUE methodology to WEPP, the Water Erosion Prediction Project for sites in the UK and USA. Earth Surf Process Landf 25:825–845

Ferro V (1997) Further remarks on a distributed approach to sediment delivery. Hydrol Sci J 42(5):633–647

Ferro V, Minacapilli M (1995) Sediment delivery processes at basin scale. Hydrol Sci J 40(6):703–717

Fistikoglu O, Harmancioglu NB (2002) Integration of GIS with USLE in assessment of soil erosion. Water Resour Manag 16:447–467

Grayson RB, Moore ID, McMahon TA (1992) Physically based hydrologic modelling 2: is the concept realistic? Water Resour Res 26(10):2659–2666

Haan CT, Barfield BJ, Hayes JC (1994) Design hydrology and sedimentology for small catchments. Academic, New York

Hadley RF, Lal R, Onstad CA, Walling DE, Yair A (1985) Recent developments in erosion and sediment yield study. UNESCO (IHP), Paris, France

Hrissanthou V, Mylopoulos N, Tolikas D, Mylopoulos Y (2003) Simulation modeling of runoff, groundwater flow and sediment transport into Kastoria Lake, Greece. Water Resour Manag 17:223–242

Jain MK, Kothyari UC (2001) Estimation of soil erosion and sediment yield using GIS. Hydrol Sci J 45 (5):771–786

Jain SK, Kumar S, Varghese J (2001) Estimation of soil erosion for a Himalayan watershed using a GIS technique. Water Resour Manag 15:41–54

Jain SK, Singh P, Saraf AK, Seth SM (2003) Estimation of sediment yield for a rain, snow and glacier fed river in the Western Himalayan Region. Water Resour Manag 17:377–393
Kothyari UC, Jain SK (1997) Sediment yield estimation using GIS. Hydrol Sci J 42(6):833–843
Marsh WM ,Grossa JJ (1996) Environmental geography: science land use, and earth systems. Wiley, Toronto, Canada
Marshringni HS, Cruise JF (1997) Sediment yield modeling by grouped response units. J Water Resour Plan Manage 123(2):95–104
McCool DK, Brown LC, Foster GR, Mutchler CK, Mayer LD (1987) Revised slope steepness factor for the Universal Soil Loss Equation. Trans ASAE 30:1387–1396
McCool DK, Foster GR, Mutchler CK, Mayer LD (1989) Revised slope length factor for Universal Soil Loss Equation. Trans ASAE 32:1571–1576
Morgan RPC (1995) Soil erosion and conservation. Longman, Essex, UK
Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME (1998) The European soil erosion model (EUROSEM): a process-based approach for predicting sediment transport from fields and small catchments. Earth Surf Process Landf 23:527–544
MRC – Mekong River Commission (2003) State of the basin report, Mekong River Commission, Phnom Penh
Musgrave GW (1947) The quantitative evaluation of factors in water erosion – a first approximation. J Soil Water Conserv 2(3):133–138, 170
Nearing MA, Foster GR, Lane LJ, Flinkener SC (1989) A process based soil erosion model for USDA water erosion prediction project technology. ASCE 32(5):1587–1593
Onyando JO, Kisoyan P, Chemelil MC (2005) Estimation of potential soil erosion for River Perkerra catchment in Kenya. Water Resour Manag 19:133–143
Panday A, Chowdary VM, Mal BC (2006) Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. Water Resour Manag DOI 10.1007/s11269-006-9061-z (in press)
Renard KG, Foster GR, Weesies GA, Porter JP (1991) RUSLE, Revised Universal Soil Loss Equation. J Soil Water Conserv 46(1):30–33
Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1996) Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation, US Department of Agriculture, Agricultural Research Services, Agricultural handbook, p 703
Rewarts CC, Engel BA (1991) ANSWERS on GRASS: Integrating a watershed simulation model with a GIS. In: Proc. of American Society of Agricultural Engineers, St. Joseph, Michigan, USA. (ASAE paper no. 91-2621)
Schwab GO, Frevert RK, Edminster TW, Barnes KK (1981) Soil and water conservation engineering, 3rd edn. Wiley, New York, USA
SCS – Soil Conservation Service (1975) Urban hydrology for small watersheds. Technical release no. 55, Soil Conservation Service, United States Department of Agriculture, Washington, DC, USA
Srinivasan R, Engel BA (1994) A spatial decision support system for assessing agricultural non point source pollution. Water Resour Bull 30(3):441–452
Suntaree Y (1993) A catalogue of water retention functions of major soil series of Thailand, Department of Soil Science. Kasetsart University, Thailand
Walling DE (1983) The sediment delivery problem. J Hydrol 65:209–237
Walling DE (1988) Erosion and sediment yield research – some recent perspectives. J Hydrol 100:113–141
Williams JR (1975) Sediment routing for agricultural watersheds. Water Resour Bull 11:965–974
Williams R, Berndt HD (1972) Sediment yield computed with universal equation. J Hydrau Div, ASCE 98 (HY12):2087–2098
Williams JR, Jones CA, Dyke PT (1984) A modeling approach determining the relationship between erosion and soil productivity. Trans ASAE 27:129–144
Wischmeier WH, Smith DD (1965) Predicting rainfall-erosion losses from cropland east of Rocky Mountains: guide for selection of practices for soil and water conservation. US Department of Agriculture, Agricultural handbook 282
Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses – a guide to conservation planning. US Department of Agriculture, Agricultural handbook 537
Woolhiser DA, Smith RE, Goodrich DC (1990) KINEROS, A kinematic runoff and erosion model: documentation and user manual. USDA-Agricultural Research Service, ARS-77, p 130
Yang D, Kanae S, Oki T, Koikel T, Musiake T (2003) Global potential soil erosion with reference to land use and climate change. Hydrol Process 17(14):2913–2928
Young RA, Onstad CA, Bosch DD, Anderson WP (1987) AGNPS: an agricultural non point source pollution model. Conservation research report 35, US Dept. Agric. Res. Services, Washington, DC, USA