EVALUATING LS-FACTOR OF USLE FOR GRID BASED SOIL EROSION MODELING AT CATCHMENT SCALES

Habib-ur-Rehman *Abdul Ghaffar* *M. Kamran Ali*
UET, Lahore. *BZU, Multan* *BZU, Multan*

ABSTRACT

Although Universal Soil Loss Equation (USLE) was developed in United States, it has been used throughout the world. Basically USLE is a plot scale model, where slope length can easily defined or measured directly from the field. When USLE is being applied at catchment scales to assess the soil erosion, it needs to discritize the spatial information by some way, usually a slope based approach is widely used for modeling. In the present study, USLE has been applied by discritizing the topography of the watershed by using a grid based approach. While using this approach, the contributing slope length becomes one of the most difficult USLE parameter to assess. Its definition implies that it is virtually impossible to simply derive slope length values from a DEM, even if the DEM is highly detailed. A sole DEM does not tell where deposition of sediment or runoff concentration occurs. In some cases it is also difficult to estimate in the field, because signs of runoff concentrations are often removed by soil tillage. This paper describes the application of USLE by selecting suitable slope lengths for a grid based model to the Mae Taeng river basin of Thailand to estimate the rate of soil erosion and its spatial distribution over the catchment. Results of the model reveal that the grid size either in cardinal or diagonal direction can be used as the slope length and the slope derived by the same coarser resolution data of the DEM cab be used as the slope angle for the cell under considerations.

INTRODUCTION

Soil erosion is causing the degradation and loss of one of the critical natural resources necessary for sustenance of human life on the planet. The GLASOD (Global Assessment of Soil Degradation) survey[1] has indicated that more than 10^9 ha of the land surface of the earth are currently experiencing serious soil degradation as a result of water erosion. For total suspended sediment transport from the land to the oceans, average values ranging from 15 – 20 G tons year^{-1} are frequently cited, whereas average global specific sediment load is approximately 140 – 188 tons / km^2 / year^2. As for as total global sediment flux to oceans is concerned, a sediment delivery ratio (SDR) of 13 – 20 % is in turn consistent with existing information on the magnitude of SDRs[3]. The loss of the regional soil resource is insidious, and that resource once lost is forever lost. We often don't see the direct results of the soil erosion either in terms of the physical markings on the land or on the human population. Earth is eroded at an average rate of 3 cm /1000 years and may take about 28 M years to be reduced to sea level[4]. As thin layers of soil are stripped away in scales on the orders of millimeters or centimeters, the process of erosion is like a disease which remains undetected until the last stages – in other words - until it is too late. Human population is increasing at a frighteningly high rate and the soil resource necessary to sustain that population is steadily decreasing.

Universal Soil Loss Equation (USLE) is the most widely used regression model for predicting soil erosion. The equation was developed from over 10 000 plot-years of runoff and soil loss data, collected on experimental plots of agricultural land in 23 States by the U.S. Department of Agriculture. This effort began about 1930 when the first 10 Federal-State Cooperative Stations began operation. Thirty-two additional stations were established in the next 25 years. Measurements of precipitation, runoff, and soil loss associated with these 42 stations were collected continuously for periods of from 5 to 30 or more years. Field plots were rectangular to facilitate typical flow row spacing for cultivated units[5].

Edwards and Owens[6] reported that Wischmeier and Smith had used 250 000 individual soil loss measurements from small field plots at 45 research stations while developing the model. Several empirically developed equations were used to estimate the individual factors.

Although USLE was developed in United States, it has been used throughout the world[7] because it seems to meet the need of researchers better than any other available tool [8].

The major objective of the study is to assess the soil erosion rate using USLE emphasizing on evaluation of *LS* factor with grid based discritization system for spatial information of the watershed.

SOIL EROSION MODEL

USLE[9] model was used to estimate the annual soil loss from the catchment area. The general form of the model is expressed as:

$$A = R\ K\ LS\ C\ P \qquad (1)$$

Where, A is the average annual soil loss (tons ha^{-1} year^{-1}), R is the rainfall erosivity factor (KJ mm ha^{-1} hr^{-1}), K is the soil erodibilty factor ((tons ha^{-1})/(KJ mm ha^{-1} hr^{-1})), L is the slope length factor, S is the slope steepness factor, C is the cropping and management factor, P is the erosion control practice factor.

For the estimation of soil erosion, the Mae Taeng river basin was modeled by the regular square grid descritizing system. Each grid is of 1km size, the slopes were determined in the steepest descent direction from a processing cell to its eight neighboring cells. The steepest descent direction was assessed by the flow direction grid of the catchment.

Assessment of the Model Factors

Though equation (1) seems to be much simpler, but its factors are difficult to assess particularly when modeling soil erosion by using a grid based approach. The detailed discussion about each factor is given below:

Rainfall Erosivity Factor

Wischmeier and Smith[9] found the average annual soil loss *A* to be proportional to *R*, the rainfall erosivity factor. The *R* factor is the sum of the product of rainfall energy and maximum 30 minute intensity (mm hr^{-1}) of all events during a year and can be computed rather accurately from detailed precipitation time series, using relationship as given in equation (2).

$$R = \frac{\sum_{i=1}^{j} (EI_{30})_i}{N} \quad (2)$$

Where $(EI_{30})_i$ is EI_{30} for storm i, *j* is number of storms in an *N* year period. Where I_{30} is the maximum 30 minutes rain intensity (mm hr^{-1}) of the rainstorm, *E* was evaluated using the Brown and Foster[10] relationship.

$$E = 0.29 \; [1 - 0.72 \; \exp(-0.05 \; i)] \quad (3)$$

Where i has the units of mm hr^{-1} and units of E is MJ ha^{-1}.

As for Mae Taeng river basin, 30 minutes or hourly rainfall data was not available for the estimation of rainfall erosivity factor, the hourly rainfall data was estimated by disaggregating the daily rainfall at an hourly level on proportional basis, maintaining the correct daily volumes of rainfall over the period. There were three rain gauges, which contribute the daily rainfall over the catchment.

Soil Erodibility Factor (K-Factor)

Soil erodibility is a term, which is used to describe the relative inherent resistance of a soil to the forces of detachment, entrainment and transport resulting from raindrop impact and shear of surface flow[11]. In USLE, the soil erodibility factor is defined as the rate of soil loss per unit rainfall erosivity as measured on a unit plot[9].

The soil erodibility factor is primarily determined by the soil texture, the high sand and the high clay content soils having lower values and the high silt content soils having higher values. Other soil conditions that affect the K-factor are organic matter content, soil structure and permeability.

For present application, following relationship

$$K = \left\{ 0.2 + 0.3 \ \exp\left[-0.0256 \ S_a \ \left(1 - S_i / 100\right)\right] \right\} \left(\frac{S_i}{C_l + S_i} \right)^{0.3}$$
$$\left(1.0 - \frac{0.25C}{C + \exp\ \left(-3.72 + 2.95 \ C\right)}\right) \left(1.0 - \frac{0.7 \ S_n}{S_n + \exp\left(-5.51 + 22.9 \ S_n\right)}\right) \qquad (4)$$

as given in EPIC model documentation[12] has been used.

Where S_a, S_i, C_l & C are the percentages of sand, silt, clay and organic carbon content respectively. And S_n is defined as:

$$S_n = 1 - \frac{S_a}{100} \qquad (5)$$

Equation (4) allows *K* to vary from about 0.1 to 0.5. The first term gives low *K* values for soils with high coarse sand contents and high values for soils with little sand. The second term reduces *K* for soils that have high clay to silt ratios. The third term reduces *K* for soils with high organic carbon contents, the fourth term reduces *K* further for soils with extremely high sand contents (S_a > 70%).

LS Factor

The *LS* factor mainly depends on slope length λ and slope angle *s*. The contributing slope length is one of the most difficult USLE parameters to assess. In fact λ is also difficult to estimate in the field, because signs of runoff concentrations are often removed by soil tillage. Renard *et al [13]* argue that “the considerable attention paid by many researchers to the *L*-factor is not always warranted, because soil loss is less sensitive to slope length than to any other USLE-factor”.

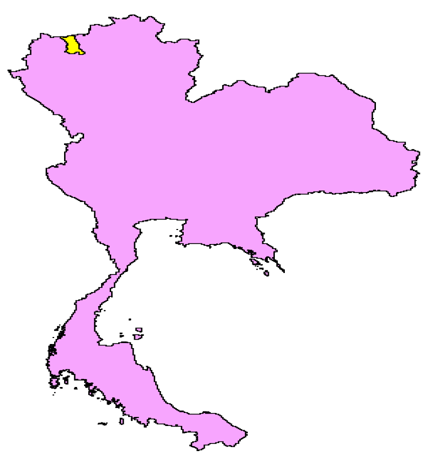

Figure 1: *Location of Mae Taeng river basin in Thailand*

Therefore, the contributing slope length was set to a fixed value of 1000 m when the flow is in cardinal direction (flow direction values 1, 4, 16 and 64), and 1414.21 m when the flow is in diagonal direction (for flow direction values 2, 8, 32 and 128), for the entire basin.

Many authors argue to use a smaller slope lengths values ranging from 50 to 300 m as they have shown this range in their field observations. Paul[11] used a fixed value of 100 m for slope lengths while modeling with 1 km grid. Prasad[14 had also used a land use and slope algorithm for the estimation of slope lengths (4-90 m) with 1km grid size. Though these algorithms are highly justified as far as the slope lengths are concerned, but what about the slope angles? These were estimated by using 1km DEM, which gives very low slope angles, because there is high scaling effect. When smaller slope lengths are multiplied with the smaller slopes (scale effected), the resulting *LS* factor and soil erosion would be very low. For the estimation of slope angle factor, the slope angles (*s*) were derived from a DEM of 1 km resolutions. In fact, these slope values are relatively much lower than the true slopes of the landscape, which is affected by the resolution of the DEM. There would be two possibilities to cater this problem, one is the re-sampling of the DEM to higher resolutions, and estimate the slope angles, but in this approach elevations are determined simply by some interpolation methods which may not guaranty the true slopes of the landscape, though the values will be definitely higher. The other approach is the downscaling the slopes to finer resolutions using Fractal approach. On the other hand in the used approach, i.e. slope lengths 1 km which are relatively higher are compensated with the lower values of the slopes, which are derived from the lower resolution DEM (1km).

The combined *LS* factor was obtained by using relationship proposed by Wsichmeier and Smith[9], and its spatial distribution over the catchment is shown in Figure 3 (c).

$$LS = \left(\frac{\lambda}{22.1}\right)^{\xi}\left(65.41 * s^2 + 4.56 * s + 0.065\right) \qquad (6)$$

Where *s* is land surface slope (m/m), λ is the slope length (m), and ξ is a parameter dependent upon slope and was estimated with the equation (7).

$$\xi = \frac{0.30\ s}{\left[s + \exp\left(-1.47 - 61.09\ s\right)\right]} + 0.20 \qquad (7)$$

C and P Factors

The factor *C* depends on the type of land cover, type and height of vegetation, canopy cover and cover that contacts the soil surface. Similarly *P* factor depends on the conservation planning adopted like contouring, strip cropping or terracing and the land surface slope. For this application, the values of *C* and *P* factors are assigned directly with the land cover type as adopted from Mckendry *et al*. [15].The values for five land use types in the Mae Taeng river basin are given in Table 1.

Table 1: C and P factors based on land cover

Land cover	C Factor	P Factor
Forest	0.001	1.0
Agricultural area	0.650	0.5
Paddy field	0.100	0.5
Grassland/shrub	0.150	0.5
Orchard	0.400	0.5

DATA SOURCES & STUDY AREA

Daily-suspended sediment discharge data was obtained from the Thailand hydrological yearbooks, volume 24-40 for the water years (April to March) of 1981-1997. These data books are published by the Royal Irrigation Department[16], Hydrology Division Bangkok, Thailand. Daily rainfall data too were obtained from the RID for the nineteen years from 1980-1999. Whereas Landuse data was obtained from USGS (United States Geographical Survey's) of about 1 km resolution. Soil data source used in the study was ISRIC (International Soil Reference and Information Center). Topographic data was obtained from GTOPO30 (of about 1 km resolution). For the validation of the estimated soil erosion, average annual soil erosion values estimated by the Prasad[14] were collected for the study area location.

The USLE model was applied to the Mae Taeng river basin, up to Mae Taeng Chiang Mai (P.4A), located at a latitude of 19^o 07' 15" N and a longitude of 98^o 56' 51" E, Thailand as shown in Figure 1. The drainage area of the catchment is 1910 km^2. The major land use types are grassland and forest in the catchment, major soil type is sandy clay loam as shown in Figure 2. Maximum elevation difference in the catchemnt is 1145 m, on the basis of 1 km DEM. The annual rain is about 1300 mm per year and maximum daily rain is 153 mm day^{-1}, and suspended sediment yield is 61.62 tons km^{-2} $year^{-1}$ on the average basis of the available sediment discharge data record.

RESULTS & DISCUSSIONS

The prepared rainfall erosivity spatial distribution on the basis of nineteen years precipitation data record is shown in Figure 3 (a). Using equation (4) and (5), the derived soil erodibility spatial distribution is shown in Figure 3 (b). Applying equation (6), the *LS* factor is computed and its spatial distribution is shown in Figure 3 (b). The used *C* and *P* Factor's spatial distributions are shown in Figure 3 (d) and (e), respectively.

The average annual soil loss for the Mae Taeng river basin has been estimated as 36 tons ha^{-1} $year^{-1}$. The predicted value for annual soil erosion is much higher as compared to the annual sediment yield (0.6162 tons ha^{-1} $year^{-1}$). It is due to the fact that USLE does not estimate the sediment yield, it simply gives the on-site soil erosion from each cell with its transport to a very limited length only. Secondly USLE calculates the soil erosion in units of tons ha^{-1}, which is assumed to be spread uniformly on the entire 1 km grid. Scale seriously affects the result of the soil erosion. And also there is quite high non-linearity of sediment discharge along the longer hill-slopes.

Figure 4 shows the results of estimated soil erosion for each land use of the Mae Taeng river basin, showing the average slopes for each land use too. This figure indicates that soil erosion is highest for the grasslands, then orchard, cropland, paddy and forestland classes.

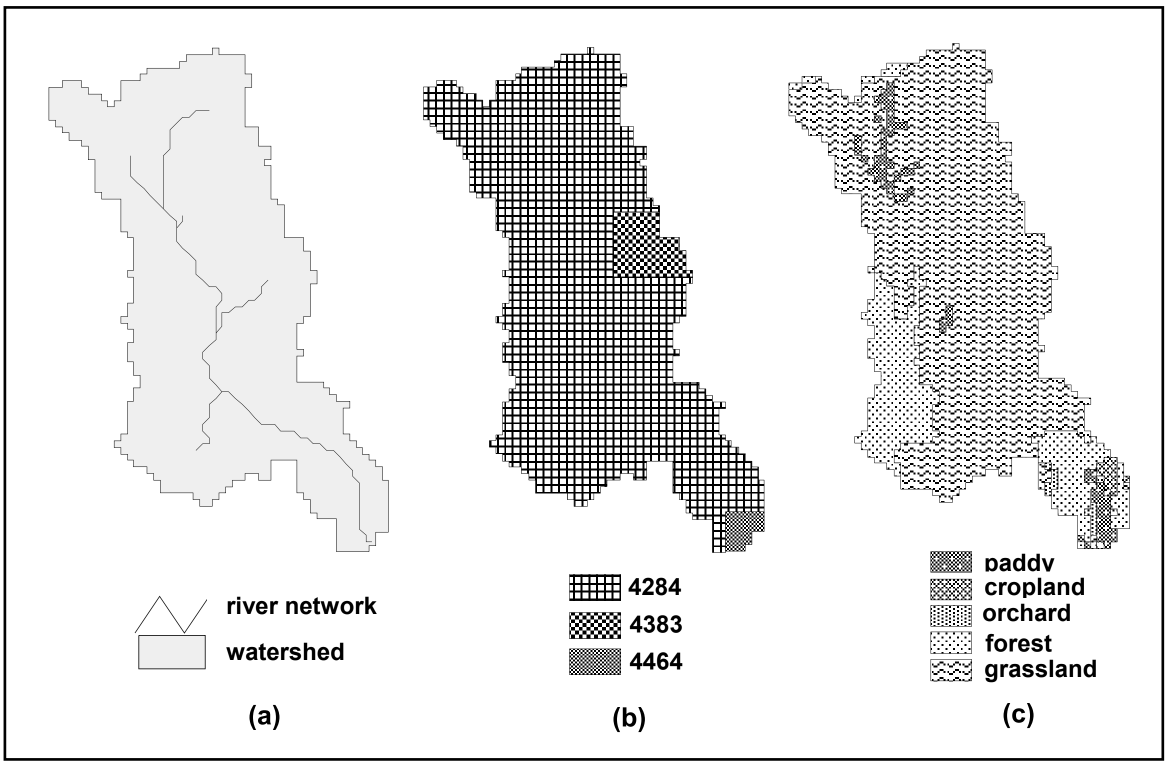

Figure 2: *(a) Watershed and river network, (b) soil map, (c) land use map of Mae Taeng river basin, Thailand*

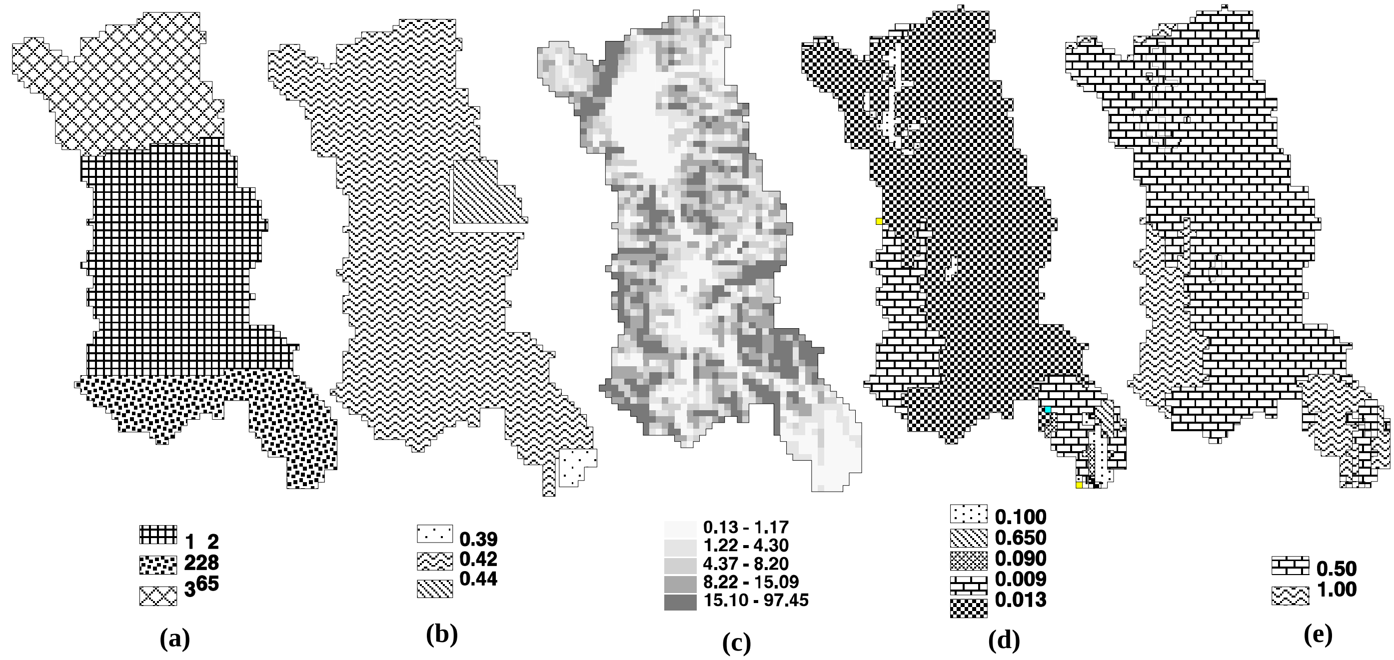

Figure 3: *Spatial distributions of (a) Rain factor (MJ mm km^{-2} hr^{-1}), (b) soil erodibility factor (tons km^{-2} hr km^{-2} MJ^{-1} mm^{-1}), (c) topographic factor, (d) Cropping management factor, (e) support practice factor, (f) Annual soil loss (tons km^{-2})*

Although it is true that the slopes are higher for grassland, on the other hand slopes are highest for forestlands but erosion is lowest, it is due to the selection of *C* and *P* factors for respective land use types as given by the Meckendry *et al.*[15].

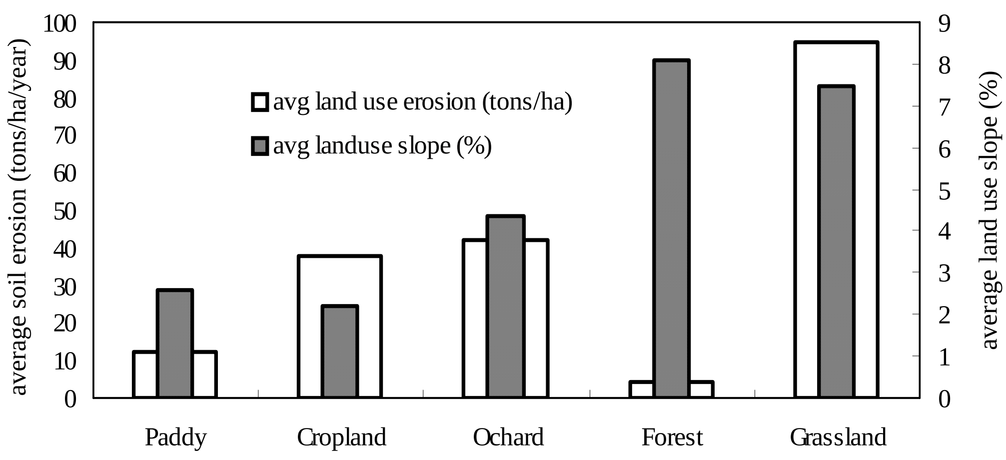

Figure 4: *Average slopes and average soil erosion in each land use of Mae- Taeng*

It apparently seems that USLE underestimates soil erosion rates for forestlands. Actually forestlands are patchy in nature, soil erosion is much higher from the bare soil but relatively lesser under the vegetation cover. As effective canopy heights are higher, due to which there is higher tendency of leaf drip impacts despite of the vegetation cover. On the contrary, grasslands are assumed to be ground covers, and in reality soil erosion values should be very less from this land use type, it has canopy heights usually less than 0.5 m, almost no leaf drips, and its biomass above the soil surface acts as a shield to raindrop impact, roots reinforce the soil top surface continuously, thus increasing the shear strength of the soil, and moreover, this land use class increases the permeability of the soil, which diminishes the chances of eroded sediment to transport to down stream of hill slopes, and grasslands have a tendency to mechanically entrap sediments.

Similar results of average soil loss in Thailand for different land uses are reported by the Prasad[14], i.e., the average values for grassland is 85.049 tons ha^{-1} $year^{-1}$, whereas for forest average value is 3.512 tons ha^{-1} $year^{-1}$ as the results were obtained using the similar *C* and *P* Factor values.

VALIDATION OF THE EROSION ESTIMATION

Prasad[14] studied the National level soil erosion estimation for developing countries. The focus of his research was soil erosion estimation within the national boundaries of Thailand. He applied USLE to assess soil erosion rates. According to his results the soil erosion from Northern Thailand is ranging from 0.001 to 4940 tons ha^{-1} $year^{-1}$. The average value is cited as 25.19 tons ha^{-1} $year^{-1}$ with a standard deviation value of 118.273 tons ha^{-1} $year^{-1}$.

The average estimated soil loss is 36 tons ha^{-1} yr^{-1} for the Mae Taeng river basin, whereas average reported soil erosion as estimated by Prasad[14] is 25.19 tons ha^{-1} yr^{-1} for the Northern Thailand, which shows overestimation of the estimated results. This overestimation may have several reasons, one is very clear, that Prasad[14] results are average for the entire Northern Thailand, whereas presented are only for Mae Taeng river basin. Secondly, overestimation may be due to using slope lengths as grid size in cardinal and diagonal directions depending on the direction of flow for the processing cell, whereas Prasad[14] had estimated the slope lengths based on land use and slope algorithms.

CONCLUSIONS

Estimated soil erosion values are compared with the available estimated results on average basis, and it is found that estimated soil loss values are relatively higher with a percentage error of 30 which seems to be acceptable while modeling soil erosion at catchment scales. This also proves that the grid size may be taken as the slope length for modeling soil erosion at catchment scales. The estimated values were also compared with the observed sediment yield at the outlet of the basin. The total soil erosion is about 58 times higher as compared to the sediment yield, indicating the deposition of the sediments over the bottom of hillslopes, in depressions and in the riverbeds. The sediment delivery ratio for the catchment was found as 1.7%.

REFERENCES

[1] Oldeman, L. R., Hakkeling, R.T.A. & Sombroek, W. G. (1991), *World map of the status of Human-Induced Soil Degradation: An Explanatory Note.* ISRIC, Wageingen.

[2] Walling D. E. & B.W.Webb. (1996, July), Erosion and sediment yield: a global overview, Global and regional perspectives, *Proceedings of the Exeter Symposium, IAHS Publication no. 236,* 3-17.

[3] Walling DE. (1983), The sediment delivery problem, *Journal of Hydrology 65*, 209-237.

[4] Garde, R.J. (1991), *Erosion and sediment yield from catchments*. Lecture Notes of Regional Training Course on Reservoir Sedimentation and Control, CWC, New Dehli, India, 2.1-2.16.

[5] Simons Daryl B. and Fuat Senturk (1992), *Sediment Transport Technology, Water and Sediment Dynamics,* Water Resources Publications, 897 pp.

[6] Edwards, W.M. and L.B. Owens (1991), Large Storm Effects on Total Soil Erosion, *Journal of Soil and water Conservation, Vol. 46, No. 1*, 75-78.

[7] Albaladejo-Montero, J. and Stocking, M. A.(1989), Comparative evaluation of two models in predicting storm soil loss from erosion plots in semi-arid spain: *Catena, 16*, 227-236.

[8] Risse, L. M., Nearing, M.A., Nicks, A. D. and Laflen, J, M. (1993), Error assessment in the Universal Soil Loss Equation, *Soil Science Society of American Journal, 57*, 825-833.

[9] Wischmeier W.H. and D.D. Smith (1978), Predicting Rainfall-erosion losses, a guide to conservation planning, Agricultural Handbook No. 537, USDA, Washington.

[10] Brown, L. C., McCool, D. K., Foster, G. R., Muthcher, C. K. and Meyer, L. D. (1987), Revised slope steepness factor for the Universal Soil Loss Equation, *Transactions of American Society of Agricultural Engineers, 30*, 1387-1396.

[11] Paul Van Dijk. (2001). *Soil erosion and associated sediment supply to rivers, Seasonal dynamics, soil conservation measures and impacts of climate*

change, Ph.D-Thesis, University Van Amsterdam, 211 pp.

[12] Williams, J.R., C.A. Jones, and P.T. Dyke. (1984), A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE,* 27, 129-144.

[13] Renard, K. G., Foster, G.R., Weesies, G.a. and J.P. Porter (1991), RUSLE Revised Universal Soil Loss Equation, *Journal of Soil and Water Conservation, Vol. 46, No. 1*, 30-33.

[14] Prasad Sah, (2000), National level soil erosion estimation method for developing countries, *Ph.D. research thesis*, University of Tokyo, Japan.

[15] Meckendary J. E., Eastman J. R., martin K. St., and Fulk M. A. (1992), exploration in geographic Information Systems Technology Vol.2, Application in forestry, *UNITAR Euroean office*, pp. 92-112.

[16] RID (1999), *Thailand Hydrological Yearbook*, Royal Irrigation Department, Hydrology Division Bangkok, Water year 1997, Volume 40, pp. 597.