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Estimation of soil erosion using Revised Universal Soil Loss Equation and GIS

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ABSTRACT

A comprehensive methodology that integrates Revised Universal Soil Loss Equation (RUSLE) model and Geographic Information System (GIS) techniques were adopted to determine the soil erosion vulnerability of a forested mountainous sub-watershed in Kerala, India. The spatial pattern of annual soil erosion rate was obtained by integrating geo-environmental variables in a raster-based GIS method. GIS data layers including, rainfall erosivity (R), soil erodability (K), slope length and steepness (LS), cover management (C) and conservation practice (P) factors were computed to determine their effects on average annual soil loss in the area. The resultant map of annual soil erosion shows a maximum soil loss of 282.2 t/h/yr with a close relation to grassland areas, degraded forests and deciduous forests on the steep side-slopes. The spatial erosion maps generated with RUSLE method and GIS can serve as effective inputs in deriving strategies for land planning and management in the environmentally sensitive mountainous areas.

Keywords— *Soil Erosion, USLE, RUSLE, GIS*

1. INTRODUCTION

1.1 Soil erosion

Soil erosion is the process of detachment, transportation, and deposition of soil particles from the land surface. Agencies or the energy sources involved in the process of soil erosion are mainly water, wind, sea waves, human beings and animals (Judson, 1965; Merritt *et al.*, 2003). Soil erosion as "soil cancer" is a complex process and its multiple obvious and hidden social and environmental impacts are an increasing threat for the human existence (Ownegh, 2003). The soil is naturally removed by the action of water or wind and is called background soil erosion. Natural soil erosion has been occurring since the early period of the earth. But accelerated soil erosion is relatively a recent problem. It is always the result of mankind's unwise actions which leave the land vulnerable during times of erosive rainfall or windstorms.

In India, about 53% of the total land area is prone to erosion and has been estimated that about 5,334 metric tons of soil are being detached annually due to various reasons (Narayana and Babu, 1983). The unprecedented increase in soil loss and its economic and environmental impacts have made erosion one of the most serious global problems of the day (Bewket and Teferi, 2009; Wang *et al.*, 2009; Zhang *et al.*, 2009). Soil erosion is one of the most widespread forms of land degradation resulting from such changes in land use. Soil erosion responds both to the total amount of rainfall and to differences in rainfall intensity, however, the dominant variable appears to be rainfall intensity and energy rather than rainfall amount alone. Every 1% increase in total rainfall, erosion rate would increase only by 0.85% if there were no correspondent increase in rainfall intensity. However, if both rainfall amount and intensity were to change together in a statistically representative manner predicted erosion rate increased by 1.7% for every 1% increase in total rainfall (Pruski and Nearing, 2002).

Soil erosion is more prevalent in the Western Ghats. Mountain sides of Kerala are facing severe soil erosion problem. High-intensity rainfall and steepness of slope have contributed in general to the higher soil loss in certain pockets of the state (Jose *et al*., 2011). Studies showed that the major portion of Kerala (51.98%) falls in 0-5 tones ha/ 1 year / 1 soil loss categories and less than 5% of the area is subjected to a severe form of soil erosion (Jose *et al*., 2011). Soil erosion can be divided into potential erosion and actual erosion. Potential erosion gives an indication of the likelihood and possible intensity of erosion that could occur under given physical and climatic conditions in an area. Actual erosion gives the existing forms and intensity of erosion in an area under the prevailing physical factors and climatic conditions. Erosion can also be characterized by the rates of the erosion processes, and the various factors influencing them in time and space (Angima *et al*., 2003).

1.2 Universal Soil Loss Equations

After 20 years of erosion trials on plots in at least 10 states in the USA, a large amount of data was waiting to be processed. In 1958, Wischmeier, a statistician with the Soil Conservation Service, was put in charge of analyzing and collating over 10000 annual records of- erosion on plots and small catchments at 46 stations on the Great Plains. Wischmeier and Smith's aim (1960 and 1978) was to establish an empirical model for predicting erosion on a cultivated field so that erosion control specialists could choose the kind of measures needed in order to keep erosion within acceptable limits given the climate.

This erosion prediction equation is composed of **five sub-equations**:

$$A = R \times K \times SL \times C \times P$$

Where, R is the rainfall erosivity index, equals E, the kinetic energy of rainfall, multiplied by I30 (maximum intensity of rain in 30 minutes expressed in cm per hour). This index corresponds to the potential erosion risk in a given region where sheet erosion appears on a bare plot with a 9% slope.

K is soil erodibility depends on the organic matter and texture of the soil, its permeability and profile structure. It varies from 70/100 for the most fragile soil to 1/100 for the most stable soil. It is measured on bare reference plots 22.2 m long on 9% slopes, tilled in the direction of the slope and having received no organic matter for three years.

SL is the topographical factor, depends on both the length and gradient of the slope. It varies from 0.1 to 5 in the most frequent farming contexts in West Africa and may reach 20 in mountainous areas.

C is cover management factor, is a simple relation between the erosion of bare soil and erosion observed under a cropping system. The C factor combines plant cover, its production level, and the associated cropping techniques. It varies from 1 on bare soil to 1/1000 under forest, 1/100 under grasslands and cover plants, and 1 to 9/10 under root and tuber crops.

Finally, p is supported practice factor is a factor that takes account of **specific erosion control practices** such as contour tilling or mounding, or contour ridging. It varies from 1 on bare soil with no erosion control to about 1/10 with tied ridging on a gentle slope. Basically, USLE predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system, and management practices (soil erosion factors). By including additional data and incorporating recent research results, the USLE methodology is improved and a revised version of this model (RUSLE) further enhanced its capability to predict water erosion by integrating new information made available through research of the past 40 years (Renard *et al*., 1997; Yoder and Lown, 1995).

The combined use of GIS and erosion models, such as USLE/RUSLE, has been proved to be an effective approach for estimating the magnitude and spatial distribution of erosion (Cox and Madramootoo, 1998; Erdogan *et al*., 2007; Fernandez *et al.*, 2003; Fu *et al*., 2006). In the late 1950s, the Universal Soil Loss Equation (USLE) was developed by W.H. Wischmeier, D.D. Smith, and their associates from the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Soil Conservation Service (SCS) and Purdue University. Its field use began in the Midwest in the 1960s. In 1965 Agriculture Handbook 282 was published, which served as the main reference manual for USLE until it was revised in 1978 as Agriculture Handbook 537 (Deore, 2005).

Although the USLE is a powerful tool that is widely used by soil conservationists in the United States and many other countries, research and experience gained in this field since the 1970s have provided insights to develop improved technology that has led to the designing of modified USLE (Wischmeier and Smith, 1978) and revised USLE (Renard *et al*., 1991). The update is based on an extensive review of the USLE and its database, analysis or data not previously included in the USLE, and theory describing fundamental hydrological and erosion processes. This update of the USLE is so substantial that the result is referred to as RUSLE. RUSLE is an attempt to improve the capability of USLE in using dynamic hydrological and erosional processes and the flexibility of USLE in adjusting process parameters to account for spatial and temporal changes. The modified Universal Soil Loss Equation follows the structure of the USLE, with the exception that the rainfall factor is replaced with the runoff factor. The equation calculates sediment yield for a storm within a watershed that does not exceed 5 square miles. It also includes numerous improvements, such as monthly factors, incorporation of the influence of profile convexity/concavity using segmentation of irregular slopes and improved empirical equations for the computation of LS factor (Foster and Wischmeier, 1974; Renard *et al*., 1991). Such limitations are not at all an indication of the overall performance of the USLE. As an empirical equation derived from experimental data, the USLE adequately represents the first-order effects of the factors that influence sheet and rill erosion. In Asia, several soil erosion studies have been conducted using USLE approach including the soil erosion and risk maps for highlands (Jusoff and Chew, 1998; Mongkolsawat, 1994; Samad and Patah, 1997). The present study envisages the application of USLE method along with remote sensing and GIS techniques in the assessment and quantification of the soil loss in the Neyyar river basin. The present study reveals that Universal Soil Loss Equation along with Geographic Information System and remote sensing is a very powerful tool for quantifying the soil erosion and useful for preparing sustainable soil erosion management strategies. The study prepares the soil erosion prone area map and also quantifies the annual soil erosion map of the study area and its extent in detail.

1.3 Objective of the study

Sediments by soil erosion have been an important factor that affects the morphological changes of river beds and water quality in river systems. The exact estimation of the amount of soil erosion is the basic and essential step not only for the research of river morphology and water quality but also for the appropriate management of sediment. The aim of this project is to calculate the amount of soil erosion more accurately using ArcGIS and Revised Universal Soil Loss Equation (RUSLE). This project would increase the understanding of the water-borne soil erosion directly related to river systems and the GIS combined RUSLE model. Based on the results of this estimation, the area which is vulnerable to erosion can be determined, and the best management plan to reduce soil erosion can be applied to that area.

2. METHODOLOGY

2.1 Study area

The **Neyyar River** is the southernmost river of Kerala state. The river originates from Agastya Hills at about 1860 m above msl. Flows down rapidly along falling terrain in the higher reaches and through almost flat terrain in the tail end. It flows in a southwesterly direction in the mountainous regions and then takes westerly course into Lakshadweep Sea near Poovar.

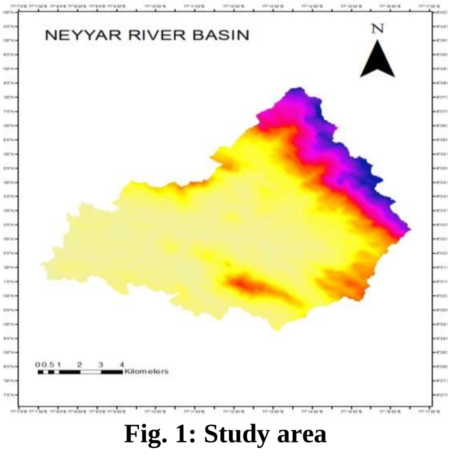

Fig. 1: Study area

2.2. Data used for the study

Table 2.1: Data Required

S. no.	Data	Source
1	Toposheet	Dept. of Civil Engineering (58H2, 58H3, 58H6)
2	Landsat Images And Dem	USGS
3	Soil Map And Soil Details	Directorate of Soil Survey and Soil Conservation Department
4	Land Use Map	Land Use Board
5	Rainfall Data	Indian Metereological Department

2.3 General methodology

In the present study qualitative raster analysis was carried out using different factors influencing soil erosion for the precise identification of erosion proneness area and quantification of erosion. For the study data utilized include a survey of India topographic maps 1:50000 scale, LANDSAT 8 images with a resolution of 30 meters, monthly and annual rainfall data for the year 2013 from Indian meteorological department and Soil data regarding soil type, texture, soil depth etc. Land cover map of the area is prepared by digitizing the land use map of the neyyar river basin. Digital elevation model and slope were generated from the vectorized contour by using spatial analyst extension in Arc GIS software.

This equation is a function of five input factors in raster data format: rainfall erosivity; soil erodibility; slope length and steepness; cover management; and support practice. These factors vary over space and time and depend on other input variables. Therefore, soil erosion within each pixel was estimated with the RUSLE. The RUSLE method is expressed as:

A=R x K x LS x C x P

A is the computed spatial average annual soil loss (tons/ha/yr).
R is the rainfall-runoff erosivity factor (MJ mm/ha/h/yr).
K is the soil erodbility factor (t. ha .h /ha/MJ /yr).
LS is the Slope length and steepness factor (LS).
C is the Cover management factor (C).
P is the Conservation practice factor (P).

2.3.1 Rainfall erosivity Factor (R)

The rainfall factor, an index unit, is a measure of the erosive force of a specific rainfall. This is determined as a function of the volume, intensity, and duration of rainfall and can be computed from a single storm, or a series of storms to include cumulative erosivity from any time period. Raindrop/splash erosion is the dominant type of erosion in barren soil surfaces. Rainfall data of 5 years (2004e2008) collected from Indian Meteorological Department (IMD) were used for calculating R-factor using the following relationship developed by Wischmeier and Smith (1978) and modified by Arnoldus (1980):

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5\, log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right)} \qquad (2)$$

P_i is the monthly rainfall (mm), and P is the annual rainfall (mm).

2.3.1 Soil erodibility factor (K)

The soil erodibility parameter is based on the soil texture, structure, organic matter, and even permeability. The soil erodibility factor, K, in the USLE is a quantitative value experimentally determined. For a particular soil, it is the rate of soil loss per erosion index unit as measured on a "unit" plot, which has been arbitrarily defined as follows: *A unit plot* is 72.6 ft long, with a uniform lengthwise slope of 9 percent, in continuous fallow, tilled up and down the slope. Continuous flow, for this purpose, is land that has been tilled and kept free of vegetation for more than 2 years. The 72.6 ft length and 9 percent steepness were selected as base values for L, S, and K because they are the predominant slope length and about the average gradient on which past erosion measurements in the United States had been made.

For soils containing less than 70 percent silt and very fine sand, the nomograph solves the equation:

$$K= [2.1 \times M^{1.14} \times 10^{-4} \times (12-a) +(3.25 \times (b-2))+(2.5 \times (c-3))]/100 \qquad (3)$$

Where,
M = the particle-size parameter defined above,
a = percent organic matter,
b = the soil-structure code used in soil classification,
c = the profile-permeability class.

2.3.3 Topographic factor (LS)

LS is the expected ratio of soil loss *per* unit area from a field slope to that from a 72.6-ft length of the uniform 9-percent slope under otherwise identical conditions. Length and steepness of a slope affect the total sediment yield from the site and is accounted for by the LS-factor in RUSLE model. In addition to steepness and length, the other factors such as compaction, consolidation, and disturbance of the soil were also considered while generating the LS-factor. Erosion increases with the slope. The combined LS-factor was computed for the watershed by means of ArcInfo ArcGIS Spatial analyst extension using the DEM following the equation as proposed by Moore and Burch (1986a,b). The computation of LS requires factors such as flow accumulation and slope steepness. The flow accumulation and slope steepness were computed from the DEM using ArcGIS Spatial analyst plus and arc hydro extension.

$$LS= 1.4\, [(\text{flow accumulation} \times \text{cell size} /22.13)^{0.4} \times (\sin \text{slope}/0.0896)^{1.3}] \qquad (4)$$

Where flow accumulation denotes the accumulated upslope contributing area for a given cell, LS is the combined slope length and slope steepness factor, cell size = size of the grid cell (for this study 30 m) and sin slope is the slope degree value in sin.

2.3.4 Cover management factor (C)

The C-factor represents the effect of soil-disturbing activities, plants, crop sequence and productivity level, soil cover and subsurface biomass on soil erosion. It is defined as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). Currently, due to the variety of land cover patterns with spatial and temporal variations, satellite remote sensing data sets were used for the assessment of C-factor (Karydas et al., 2009; Tian et al., 2009). The Normalized Difference Vegetation Index (NDVI), an indicator of the vegetation vigor and health is used along with the following formula to generate the C-factor value image for the study area (Zhouet al., 2008; Kouli et al., 2009).

$$c = exp^{[-\propto NDVI/(\beta - NDVI)]} \qquad (5)$$

Where a and b are unitless parameters that determine the shape of the curve relating to NDVI and the C-factor.

2.3.5. Conservation practice factor (P)
The support practice factor (P-factor) is the soil-loss ratio with a specific support practice to the corresponding soil loss with up and downslope tillage (Renard et al., 1997). In the present study, the P-factor map was derived from the land use/land cover and support factors. The values of P-factor ranges from 0 to 1, in which the highest value is assigned to areas with no conservation practices (deciduous forest); the minimum values correspond to built-up-land and plantation area with strip and contour cropping. The lower the P value, the more effective the conservation practices.

Table 2: P Factor Value

Land use	P Factor
Agriculture	0.5
Built up	1
Forest	1
Wasteland	1
Water body	1

3. RESULTS AND DISCUSSIONS
In the present research, annual soil erosion rate map was generated for NEYYAR RIVER BASIN. Several data sources were used for the generation of RUSLE model input factors and are stored as raster GIS layers in the ArcInfo ArcGIS software. Potential annual soil loss is estimated from the product of factors (R, K, LS, C, and P) which represents the geo-environmental scenario of the study area in spatial analyst extension of Arc GIS software. The average soil erosion rate estimated for the upland sub-watershed ranges from 0 to 228.432 tons/ha/year.

3.1 Rainfall runoff erosivity factor
The rainfall runoff erosivity factor calculated using this equation is obtained as 109.924 MJ mm/ha/h/yr.

3.2 Soil erodibility factor (K)

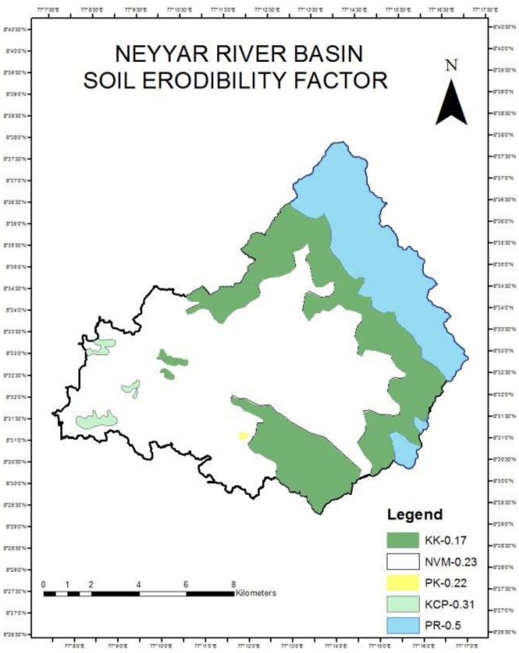

Fig. 2: Soil erodibility map

NVM – Nedumangad vamanapuram mudakkal, KK –Kottur kallar, PR-ponmudi rockland, PK- Palod kodittuki, KCP - Kallar chempakathpara palode.The soil erodibility of the area varies from 0.17 to 0.5 with ponmudi rockland having the highest erodibility factor.

3.3 LS Factor

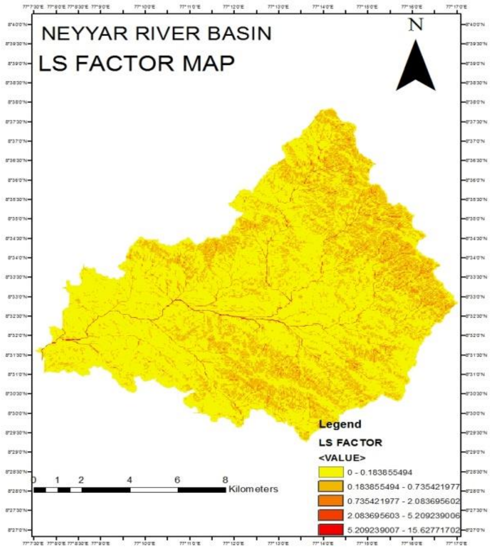

Fig. 3: LS factor map

The LS factor value of the area varied from 0 to 15.62.

3.4 C Factor

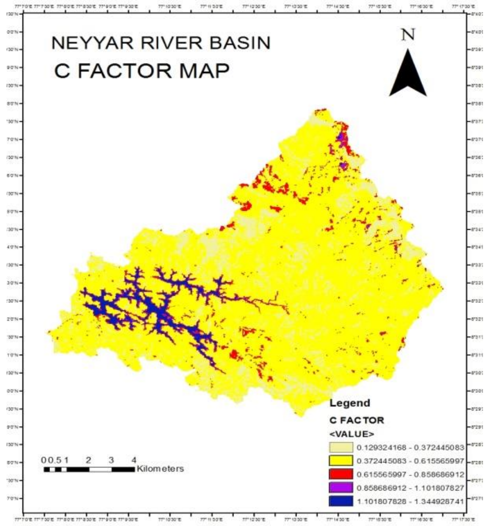

Fig. 4: C factor map

The C Factor of the area varies from 0.129 to 1.344

3.5 P Factor

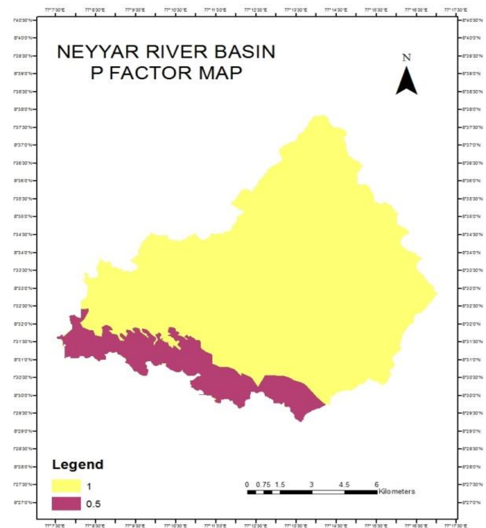

Fig. 5: P factor map

The P factor value adopted is 0.5 for built up and 1 for forest area.

3.6 Soil erosion map

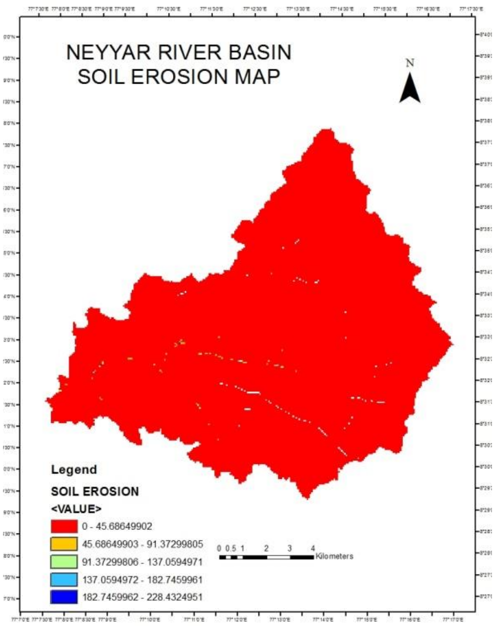

Fig. 6: Soil erosion map

The present study shows that in Neyyar wildlife sanctuary erosion range is 0 - 228.08 tons/ha/yr compared to 0-201 tons ha/yr reported by Suersh *et al*. (2000) in Neyyar wildlife sanctuary. Soil erosion quantification of the present study reveals that the study area is under the threat of soil erosion. The multi-criteria based soil erosion prone area identification will be helpful for the future soil erosion control and to evolve soil erosion management strategies in the study area. The extreme sensitivity of soil erosion was mainly caused not only the strong rainfall and large topography differences but also the intensive human activities.

4. CONCLUSION

A quantitative assessment of average annual soil loss for Neyyar river basin is made with GIS-based well-known RUSLE equation considering rainfall, soil, land use and topographic datasets. In the river basin the land use pattern in areas prone to soil erosion indicates that areas with natural forest cover in the headwater regions have a minimum rate of soil erosion while areas with human intervention have a high rate of soil erosion (up to 228 tons/ha/year)). Terrain alterations along with high LS-factor and rainfall prompt these areas to be more susceptible to soil erosion. It is understood that functions of C and P are factors that can be controlled and thus can greatly reduce soil loss through management and conservational measures. The predicted amount of soil loss and its spatial distribution can provide a basis for comprehensive management and sustainable land use for the watershed. The areas with high and severe soil erosion warrant special priority for the implementation of control measures. While the present analytical model helps to map of vulnerability zones, micro-scale data on rainfall intensity, soil texture and field measurements can augment the prediction capability and accuracy of remote sensing and GIS-based analysis

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