

# Application of GIS in Hydrology and Estimation of Soil Erosion Using USLE Model

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**Abstract:** *The problem of soil erosion is prevalent over about 53% of the total land area of India. Soil erosion is a worldwide growing problem especially in agricultural productions where soil erosion not only leads to decrease the productivities of agriculture but also reduces the availability of water. Hence accurate estimation of soil erosion due to water is very important in several environmental aspects, such as the assessment of potential soil loss from agricultural land and evaluation of the loss of water storage capacity in reservoirs due to sediment depositions. The most popular empirical method to estimate the soil erosion is Universal Soil Loss Equations (USLE). This equation was first developed by Wischmeier and Smith in (1960s) of United States Department of agricultural as a field scale model, to predict the long term average soil loss under specified conditions and estimate erosion rates for different combinations of crops and management practices. The soil erosion rate was determined as a function of land, topography, soil texture, lu/lc, rainfall erosivity, crop management and practice management in the watershed. In the present study an attempt has been made to assess the annual soil loss in Vamanapura River basin, Kerala State, using Universal Soil Loss Equation (USLE) in ArcGIS framework. Each one of the USLE parameters (Rainfall Erosivity R, Soil Erodibility K, Slope LS, Land use C and Conservation Practice P) were represented by thematic raster layers in the GIS. The GIS interface permits the generation of detailed information required for USLE and presents the output as a distributed soil loss pattern over the river basin surface. GIS generated outputs can be used to identify critical erosion zones and to concentrate proper management activities on such areas*

**Keywords:** Soil erosion, USLE model, ArcGIS, DEM

## 1. Introduction

Erosion is a natural geological phenomenon resulting from removal of topsoil by natural agencies like wind, water transporting them elsewhere while some human intervention can significantly increase erosion rates. It is a major agricultural problem and also one of the major global environmental issues. Erosion is triggered by a combination of factors such as slope steepness, climate, inappropriate land use, land cover patterns and ecological disasters (e.g. forest fires). Soil erosion is one form of the soil degradation along with soil compaction, low organic matter, and loss of soil structure, poor internal drainage, and salinization and soil acidity problems. Soil erosion is a naturally occurring process on all land. Soil Erosion may be a slow process that continues relatively unnoticed, or it may occur at an alarming rate causing serious loss of topsoil. The loss of soil from farmland may be reflected in reduced crop production potential, lower surface water quality and damaged drainage networks.

Water erosion can occur in many ways, for example coastal erosion by waves, splash erosion from the impact of precipitation and irrigation water, erosion due to overland flow (also called sheet erosion or rill/inter-rill erosion), stream channel erosion or erosion by percolating water. Basically the impact of water droplets and/or the sheer stress caused by water in motion detaches soil particles, followed by transport and finally deposition of the particles eroded.

During storm events, rainfall intensity can exceed the infiltration capacity of the soil and the excess water will form a runoff directed downslope. The magnitude of the runoff varies due to different factors such as the initial soil moisture, the infiltration capacity and the variations in

precipitation intensity. The runoff will cause sheet erosion, which is more or less spatially uniform removal of soil, or rill erosion which occurs in small closely related channels called rills. With time rill erosion will progress to gully erosion as the channel increases in size and is defined as a gully.

## 2. Literature Review

Erosion and sediment transport are complex natural processes that are strongly influenced by human activities such as deforestation, agriculture and urbanization. Eroded sediments act as both physical and chemical pollutant and have far-reaching environmental and economic impacts. Significant efforts are being directed towards developing analytical tools that predict erosion and sediment yield on plot or small watershed scale. With the advancement of GIS technology, development and use of these models have become more efficient and economically feasible. GIS also allows visualization of the results from models as maps rather than mere columns of numbers.

One of the most popular empirical models is the Universal Soil Loss Equation (USLE) by Wischmeier and Smith, (1965). It is designed to predict long-term average soil loss under specified conditions and used to estimate erosion rate for different combinations of crops and management practices. Since 1965, efforts were gone into the improvement of USLE to suit additional types of land use, climatic conditions and management practices (Blackburn, 1980; Hadda & Sandhu, 2001; Kurothe et al., 2001; Mikos et al., 2006). Onstad and Bowie (1977) modified the USLE to include both rainfall and runoff energy terms. Renard et al. (1991) revised the USLE to RUSLE by for use in computer based models.

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Williams (1975) modified USLE as MUSLE, by using a runoff factor instead of rainfall energy factor for predicting individual storm sediment yield (Sadeghi et al., 2004; Hrissanthou, 2005; Sadeghi et al., 2007). Sadeghi (2004) has made certain revisions by changing the power quotient in the MUSLE equation using observed soil loss and MUSLE parameters. Sadeghi et al. (2007) also reported that rainfall oriented soil erosion models are preferred to runoff based models for small watersheds and experimental plots.

Integration of GIS with the USLE model improved the prediction accuracy of the model and areal coverage of the results. Since GIS handles data in pixel scale, the outputs generated by a GIS in conjunction with USLE gave a better picture of erosion activities taking place in the watershed surface and also enabled many scenario analyses (Andersson, 2010; Reshma and Kumar, 2012; Kim, 2014; Chandramohan et al., 2014)

### 3. Soil Erosion Modelling in GIS Environment

Estimation of soil erosion there are different type of models available, most of them are physical based models such as

Empirical and Mechanistic models. The empirical models describe a process based on empiricism. In contrast mechanistic model attempts to represent the physical causes of response to conditions.

Statics and Dynamic models. The difference between static & dynamic model is that dynamic models takes into accounts time is an extra variables.

Deterministic and Stochastics: Deterministic models make definite prediction for quantities without any associated probabilities distributions stochastics models on the other hand contain some random elements or probabilities distributions. Except for the predicted values, stochastic models can also predict the variance. Spatial dimensions in models any models can be distinguished between 1D, 2D & 3D models. Qualitative and Quantitative Qualitative models predict values on quality level such as not risky or highly risky. The input data for a qualitative model can be both qualitative & Quantitative. On the other hand, a qualitative model produces a numerical output.

In empirical model different types of models they are as follows

### 4. Modified Universal Soil Loss Equation (MUSLE)

Geographical Information System is a system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data which are spatially referenced to the Earth. This is normally considered to involve a spatially referenced computer database and appropriate applications software. Hydrology is one of the fields where the use of GIS facilitated better and faster

applications and scenario generation. Currently many hydrological models are generated working in a GIS environment. Remote sensing and GIS techniques have become valuable tools specially when assessing erosion at larger scales due to the amount of data needed and the greater area coverage. For this reason, use of these techniques have been widely adopted and currently there are several studies that show the potential of remote sensing techniques integrated with GIS in soil erosion mapping.

Advantages of estimation of soil erosion by GIS:

- Exploring both geographical and thematic components of data in a holistic way
  - Stresses geographical aspects of a research question
  - Allows handling and exploration of large volumes of data
  - Allows integration of data from widely disparate sources
  - Allows analysis of data to explicitly incorporate location
  - Allows a wide variety of forms of visualization
- 1) Universal Soil Loss Equation (USLE) – this equation is popularly used in worldwide to estimate the annual soil loss.
  - 2) Revised Universal Soil Loss (RUSLE) – this is an improved and modified equation of USLE.

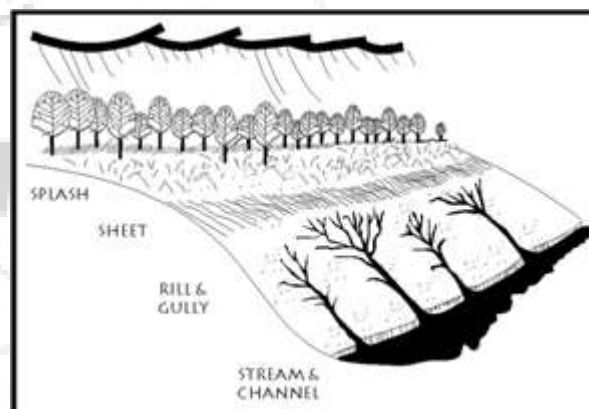


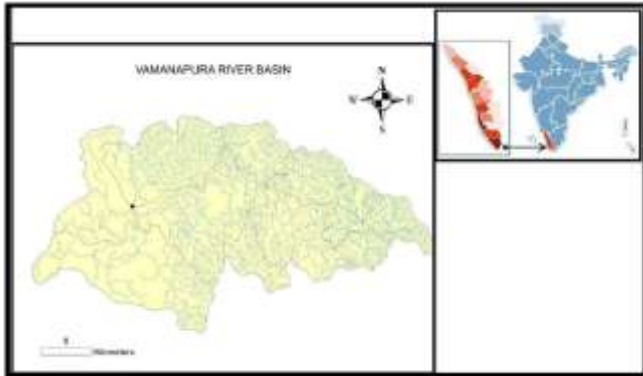
Figure 1: Types of soil erosion

### 5. Study Area

The watershed taken up in the present study is Vamanapuram river basin, the catchment area of the watershed is about 787km.sq is located mainly in Thiruvananthapuram district and a small part falls in Kollam district of Kerala state. The basin is bounded by latitudes of 8° 35' 24'' N and 8° 49' 13'' N and longitudes of 76°44' 24'' E and 77°12' 45'' E. The area forms part of the midland terrain of the state, characterized by lateritic uplands with undulating topography and intermittent valleys.

The river Vamanapuram is a major river in South Kerala with its network of tributaries. The trunk stream originates from the foothills of the Ponmudi hills (1074 m above msl) and the tributaries from the surrounding hills like

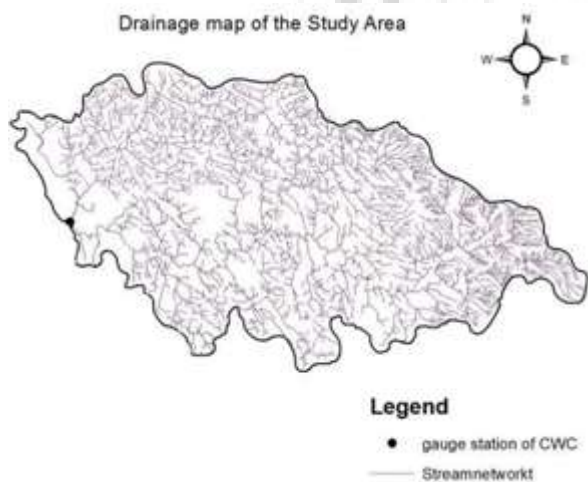
Kallar. The river then flows onwards through Vamanapuram town and two-branch stream join at Attaramoodu where the mainstream is called Kilimanur River. From there the master stream flows onward and joins the Kadinamkulam backwater at the northern most Extremity. It debouches into the Arabian Sea at Mudalapallipozhi near Perumathura, 25 km north of Thiruvananthapuram city. The two tributaries of this river are the Upper Chittar & Manjaprayar streams. The major portion of the Vamanapuram River flows through midland terrain and the remaining through highlands and lowlands areas.



**Figure 2:** Location map of the study area

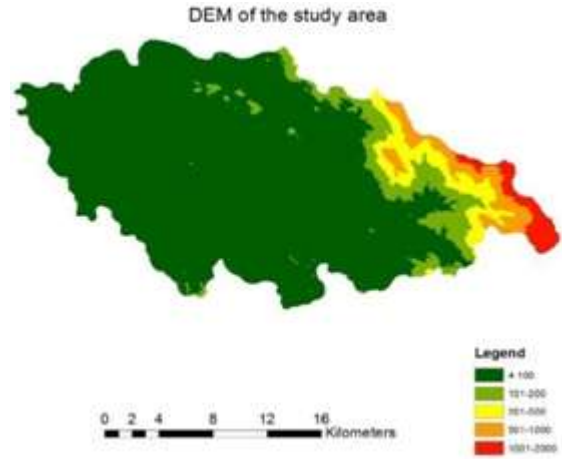
The climate is generally hot with humidity throughout the coastal belt and in mid land, where as in hilly region of the basin it is very cool, for most of the period in the year. As per the I.M.D observations, the normal mean daily temperature of the basin varies from 26.2°C to 28.8°C. The basin experiences annual rainfall between 1836 mm and 4651 mm.

965 MCM and the sediment yield is 112355 tons.



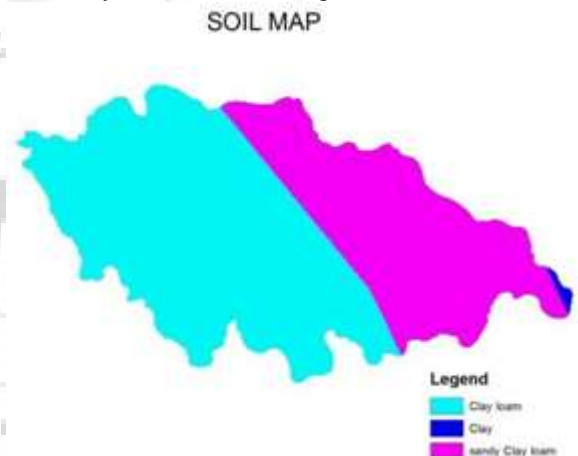
**Figure 3:** Drainage map of the study area

Majority of the area falls within midland zone of the State with elevational varies from about 4 m above msl near the gauge site to 75 m. The upstream region falls within the hilly zone of the The Central Water Commission (CWC) is maintaining a gauge site at Aylima, where daily discharge and sediment data is being monitored.

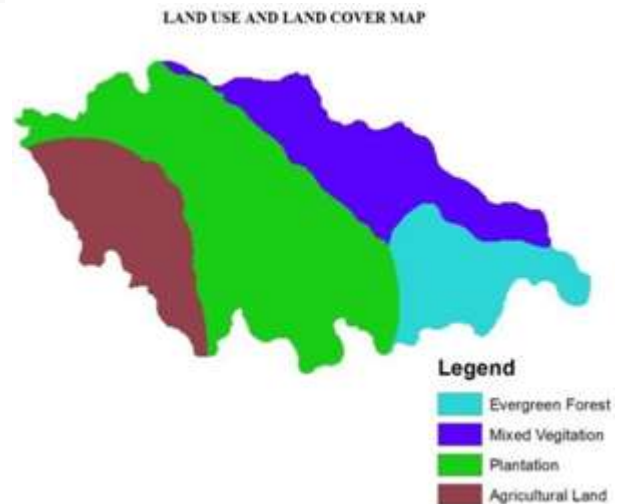


**Figure 4:** DEM of the study area

The present study area the catchment of the river above the CWC gauge station at AYILAM, catchment area of which is 490 sq. km. The study area with its drainage pattern is shown in Figure .3 the average annual discharge at this site is State, part of the Western Ghats, with large slopes and elevation upto 1900 m, as shown in the DEM of the study area. Three types of soil covers the area, maximum amount of area covered by Clay loam soil (55% of the total area), Sandy clay loam soil covers 40% of the area and Clay soil covers the rest of the area. The soil map for the study area is shown in figure5



**Figure 5:** Soil map of the study area



**Figure 6:** Land use / Land cover map of the study area



From the land use / Land cover map we can develop the crop management factor (C-Factor map) and practice management factor ( P-Factor map), in this map plantations covers more than 45% of catchment area and about 20% area covered by mixed vegetation's i.e. (vegetables, plants and trees).Agriculture land covers very less catchment area.

## 6. Methodology

In this study the Universal Soil Loss Model (USLE) has been developed by using the following equation, the application of the Universal Soil Loss Equation (USLE) is often recommended as a valuable tool to estimate water erosion. The soil loss of the watershed was calculated using USLE with some modification in its parameter estimation to suit Indian conditions

$A = R * K * LS * CP$  Whereas,

A = Average annual soil loss (ton/ha/year). R = Rainfall-runoff erosivity index (in MJ Mm/ha/ hr. /yr.)

K = Soil erodibility factor (ton/MJ/mm). L = Length factor.

S = Slope factor.

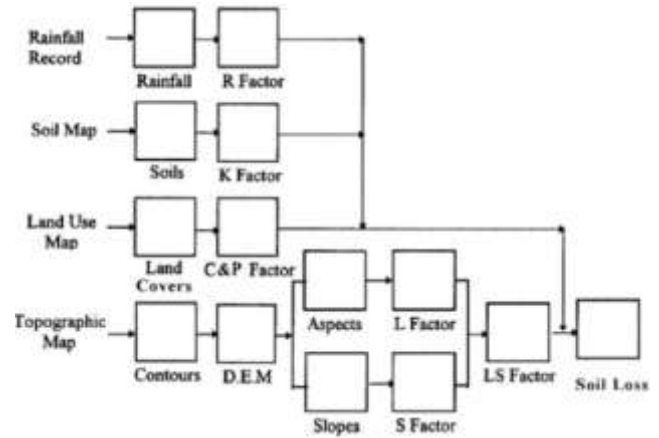
C= Crop management factor.

P = Practice management factor.

In order to apply the USLE in a GIS, every parameter is organized as a thematic layer which provides a spatial distribution. The layers need to be of the type 'raster', which means that they are in the form of grid nets (matrixes). In the spatial distribution of the raster, every grid cell has a unique parameter value and the model is executed by an overlay operation that multiplies all the parameter layers mathematically. This means that every single cell is overlaid (multiplied) with its spatially corresponding cells in the other parameter layers, completing the multiplication of the equation. The output of the model is a combined layer where every single cell value is the product of the equation. Finally the whole layer is summed and the average annual soil loss per hectare is calculated by taking the total catchment area in consideration.

The topo-sheet for the Vamanapuram River basin was geo- referenced with respect to the coordinate system (WGS 1984 UTM ZONE 43N). A coordinate system defines x-y coordinates of map and projection of map. It is used by all vector and raster maps generated within GIS. The base shape map of the river basin boundary and drainage up to the CWC Gauge site were generated from the imported topo-sheet. Different thematic maps, such as DEM, land use map, soil, etc. were prepared.

ASTER (30 m) DEM layers were downloaded two 1° x 1° squares from Aster Gdem web site, which covers the entire study area. The DEM (Digital Elevation Model) for the study area was extracted from the Raster data. Raster layers for Slope, flow direction and flow accumulation were prepared from the spatial analysis tool (Hydrology) in the Arc Tool box.



**Figure 7:** Procedure to develop USLE model in ArcGIS software

## 7. Analysis

R-Factor: Monthly rainfall data were collected for the rain gauge stations within the study area. The annual and seasonal average rainfall values for these stations are listed in the table.

**Table 1:** Average Annual Rainfall for the Selected Rain gauges

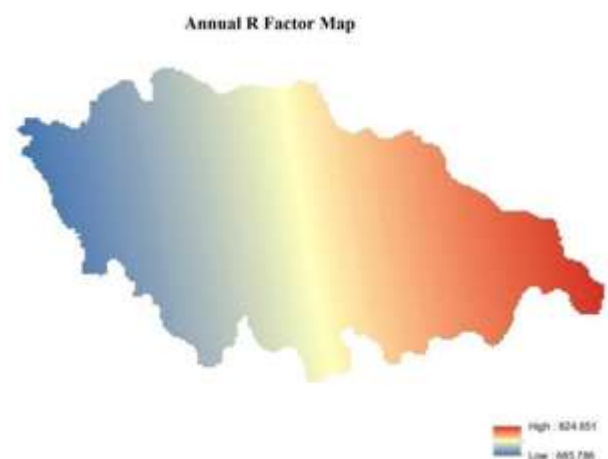
| Sl. No. | RG Station Name | Latitude | Longitude | Annual Average Rainfall in mm |
|---------|-----------------|----------|-----------|-------------------------------|
| 1       | Attingal        | 8.69     | 76.8      | 1921.00                       |
| 2       | Valayankil      | 8.69     | 77.1      | 3932.85                       |
| 3       | Brymore Estate  | 8.76     | 77.1      | 4407.25                       |
| 4       | Ponmudi         | 8.7      | 77.15     | 3139.47                       |
| 5       | Thenmala        | 8.96     | 77.06     | 3201.10                       |

Rain gauge stations were represented as point map in ArcGIS. The average annual and seasonal rainfall values in the attribute table and point map were used to create rainfall distribution maps using the interpolation (Kriging) techniques in the GIS.

R-factor maps were prepared using raster calculator using the equation.

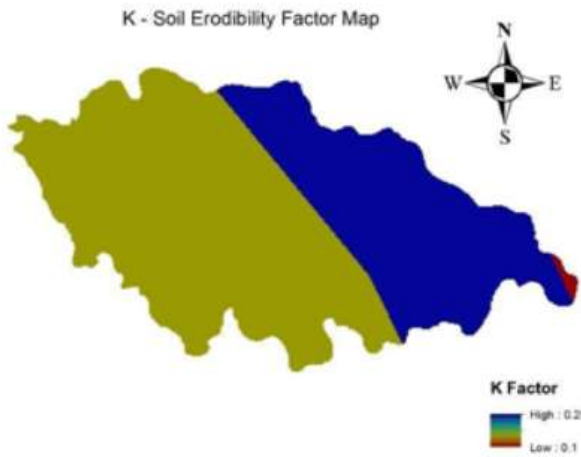
$$R\text{-factor} = 79 + 0.363 * RN$$

RN = Average annual/seasonal rainfall in mm.



**Figure 8:** Annual Rainfall erosivity map

K-Factor: Soil erodibility nomograph (Wischmeier and Smith, 1978) was used for determining K-factor based on particle size, organic matter present, and permeability class. The soil erodibility nomograph is shown in figure 8. These K values were added to the soil attribute table and the soil erodibility factor map was prepared using the soil map and soil classification table



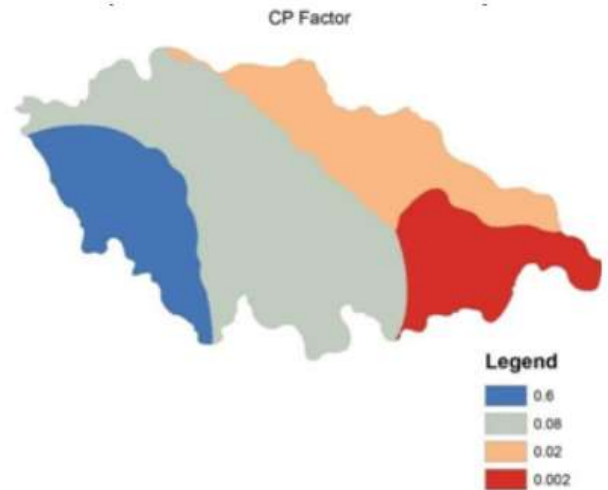
**Figure 9:** K-Soil Erodibility map

$$LS = (L/22)^{0.5} \{ (0.065 + 0.045 * S) + (0.006 * S^2) \}$$

Where, LS = slope length & slope steepness factor  
 L = slope length (m) S = slope steepness

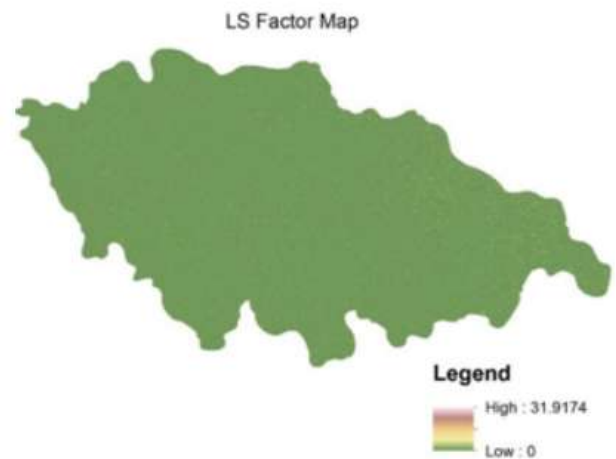
From the slope and flow accumulation maps, using the above equation in raster calculator tool, LS-factor map was created. The LS factor map for the study area is shown in figure 9.

CP-Factor: The calculation of CP factor for each cover unit was made on the basis of management practices, physical conditions and characteristics of cover units. The conservation practice represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. For this project, the ratio is kept at 1, indicating straight-row farming. CP factor for various cropping and management practices for the study area are given in table 3. CP factor map was created by linking the attribute table for the land use layer and CP factor. The CP-factor map for the present study is shown in figure 10.



**Figure 10:** Soil erodibility factor map

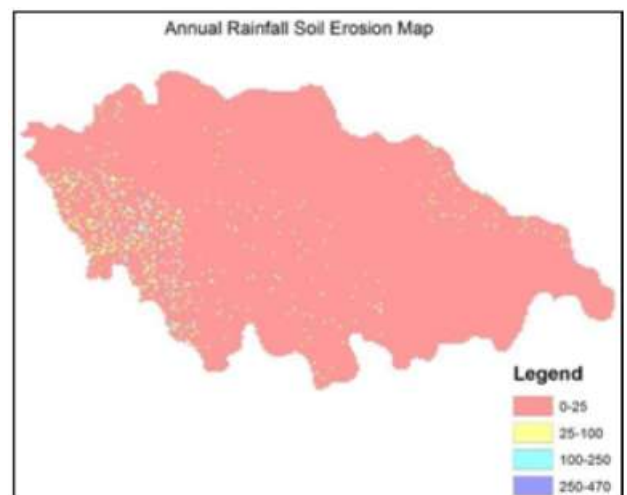
LS-Factor: For slope steepness up to 21%, the original USLE formula for estimating the slope length and slope steepness was used. The equation used was,



**Figure 11:** LS factor map

**Table 3:** CP factor for different type of land

| Soil type         | Area km <sup>2</sup> | % of area | CP Factor |
|-------------------|----------------------|-----------|-----------|
| Mixed Vegetation  | 107.80               | 22        | 0.02      |
| Evergreen forest  | 73.50                | 15        | 0.002     |
| Plantation        | 220.50               | 45        | 0.08      |
| Agricultural land | 88.20                | 18        | 0.6       |



**Figure 12:** Estimated annual soil erosion map

## 8. Expected Soil Loss (A) Calculation

Using the raster calculator tool( Spatial Analysis Tool, Map Algebra) in ArcGIS, R, K, LS and CP maps were multiplied to get the RKLSCP map, which shows the distributed soil erosion map (showing pixel wise soil erosion of the study area). The soil erosion maps were developed for Annual, SW monsoon and NE monsoon rainfall. These maps are shown in Figure 11. Table 4 shows the maximum and average erosion values for the three seasons. These values were compared with the observed sediment data of the CWC gauge site. The comparison of observed and predicted soil erosion values are shown in Table 5. It seems that the predicted values are fairly matching the observed sediment yield rates at the gauge site. It is also to be mentioned that the sediment yield values obtained by using USLE and ArcGIS represents the gross erosion rate over the entire river basin surface. However, only a fraction of these eroded materials reaches the outlet because of the partial storage of these sediments along the course of its movement towards the outlet. This fraction is termed as sediment delivery ratio.

**Table 4:** Comparison of Observed (CWC) and Predicted Soil erosion rate

| Seasons    | Average soil loss Observed (ton/ha/season) | Average soil loss Predicted (ton/ha/season) |
|------------|--|---|
| SW Monsoon | 1.72                                       | 2.04  |
| NE Monsoon | 0.30                                       | 0.90  |
| Annul      | 2.29                                       | 3.29  |

## 9. Conclusions and Discussions

The USLE model combined with GIS is effective in estimating the potential of soil erosion for the Vamanapuram River Basin up to the CWC gauge site Ayilam. From basic overlays of the 5 variables and the raster calculator, the model was accurately illustrated.

USLE was tested for its prediction capability in a GIS environment using the available information on rainfall, soil, topography and land use, prevailing in the study area. The efficiency of soil loss simulation is satisfactory and generally the model tends to slightly over-predict the soil loss.

However, application of the model in a GIS framework resulted in creating a distributed visualization of the actual erosion activities taking place on the watershed surface. Hence GIS can be effectively used in conjunction with soil erosion models so that the results could be used for precisely locating the problem areas. Such output maps can assist planners and land managers in prioritization of critical soil erosion locations and in improving the soil and water conservation efforts.

For a more precise calculation the P factors will need to be more exact, since this project assumed P factor as the constant value of 1 over the target area. Although USLE model combined with GIS is effective tool for the estimation of soil loss, caution is needed when interpreting

the results considering the assumptions made to create each variable and errors of an empirical equation for the USLE model.

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