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RESEARCH PAPER

Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology

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Abstract A comprehensive methodology that integrates Revised Universal Soil Loss Equation (RUSLE) model and Geographic Information System (GIS) techniques was 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 17.73 t h^{-1} y^{-1} with a close relation to grass land areas, degraded forests and deciduous forests on the steep side-slopes (with high *LS*). 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.

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1. Introduction

Soil erosion and related degradation of land resources are highly significant spatio-temporal phenomena in many countries (Fistikoglu and Harmancioglu, 2002; Hoyos, 2005; Pandey et al., 2009). Soil erosion, generally associated with agricultural practices in tropical and semi-arid countries, leads to decline in soil fertility, brings on a series of negative impacts of environmental problems, and has become a threat to sustainable agricultural production and water quality in the region. It has been estimated that in India about 5334 m-tonnes of soil are being removed annually due to various reasons (Narayan and Babu, 1983; Pandey et al., 2007). In recent years, as part of environment and land degradation assessment policy for sustainable agriculture and development, soil erosion is increasingly being recognized as a hazard which is more serious in mountain areas (Millward and Mersey, 1999; Angima et al., 2003; Jasrotia and Singh, 2006; Dabral et al., 2008; Sharma, 2010). In many regions, unchecked soil erosion and associated land degradation have made vast areas economically unproductive. Often, a quantitative assessment is needed to infer the extent and magnitude of soil erosion problems so that effective management strategies can be resorted to. But, the complexity of the variables makes precise estimation or prediction of erosion difficult. The latest advances in spatial information technology have augmented the existing methods and have provided efficient methods of monitoring, analysis and management of earth resources. Digital elevation model (DEM) along with remote sensing data and GIS can be successfully used to enable rapid as well as detailed assessment of erosion hazards (Jain et al., 2001; Srinivas et al., 2002; Kouli et al., 2009).

Spatial and quantitative information on soil erosion on a sub-watershed scale contributes significantly to the planning for soil conservation, erosion control, and management of the watershed environment. The results of estimation of soil loss in the sub-watersheds were carried out on an experiment basis in many tropical regions using different prediction techniques (Shrestha, 1997; Douglas, 2006; Van De et al., 2008). However, soil erosion management strategies in the Western Ghats are constrained by dearth of such data, because actual measurements of soil loss from crop fields and mountainous regions are uncommon in the country. The area selected for the present study includes the most popular pilgrim centre in South India and millions of pilgrims visit the shrine especially during a short period. The gathering of very large crowd over a short period of time in an ecologically sensitive area has resulted in various environmental problems. Though most of the study area is covered with forest, the area has under gone changes in the forest/land use and causes environmental degradation. Since majority of pilgrims prefers the traditional forest route, lower order forests face degradation and destruction. Hence, the present study was carried out with an objective to assess the annual soil erosion rate and develop a soil erosion intensity map for a mountainous sub-watershed of river Pamba using RUSLE and GIS techniques, which in turn can be used as a scaleable model for various watersheds in the Western Ghats.

2. Study area

The small mountainous sub-watershed in Pamba river basin, Kerala, India, also called Pamba Ar, stretches from north latitudes 9°19′5″ to 9°28′39″ and east longitudes 77°04′06″ to 77°14′53″ and covers an area of 167.83 km^2 (Fig. 1). The region is highly undulating and exhibits the typical highland topography of Western Ghats, with a mean elevation of 1014 m above msl and a general northwest terrain slope. The study area receives an annual average rainfall of 3046 mm and exhibits a wet climatic condition with a mean minimum and maximum temperature of 22.6 °C and 32.7 °C, respectively. Almost 80% of the area is occupied by thick evergreen forests, followed by grasslands, forest plantations and degraded forests. Built-up can be found only at Sabarimala and Pamba reservoir areas. Almost all other parts of the catchment are highly inaccessible due to dense forest cover and rugged terrain. Geologically, the area falls in the Precambrian terrain and charnockite and gneiss are the major rock types with lateritic over burden. Geomorphologically, the sub-watershed is characterised by steep structural hills, denudational hills, narrow gorges, intermontane valleys and precipitous escarpments with thick vegetation. The soil texture is gravelly clay followed by gravelly clay loam, which is well drained with very low permeability.

3. Methodology

3.1. Annual soil loss estimation method

The emergence of soil erosion models has enabled the study of soil erosion, especially for conservation purposes, in effective and acceptable level of accuracy. To estimate soil erosion and to

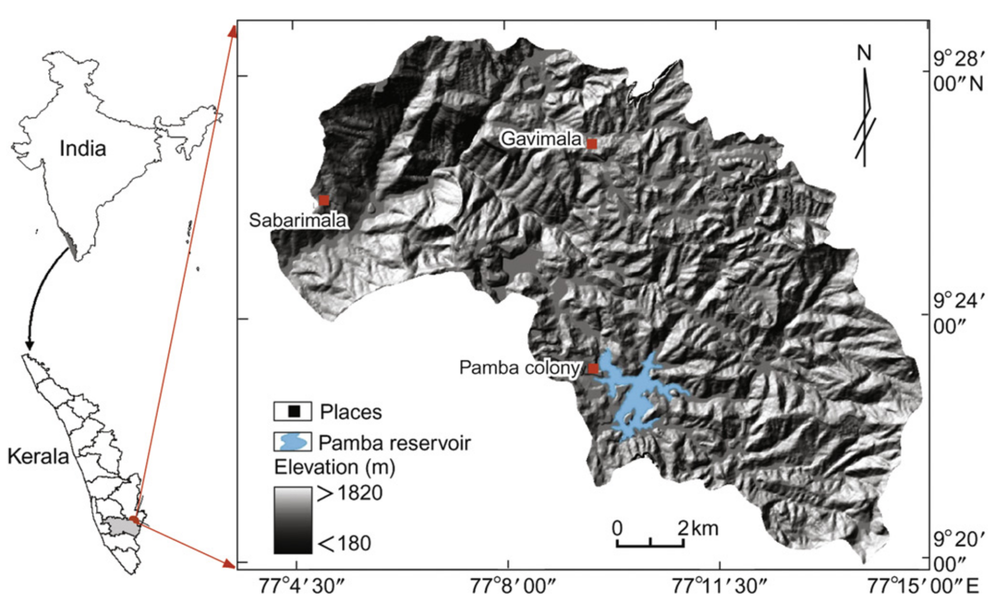

Figure 1 Study area location map.

develop optimal soil erosion management plans, many erosion models, such as Universal Soil Loss Equation/Revised Universal Soil Loss Equation (USLE/RUSLE), Water Erosion Prediction Project (WEPP), Soil Erosion Model for Mediterranean Regions (SEMMED), Areal Non-point Source Watershed Environment Response Simulation (ANSWERS), Limburg Soil Erosion Model (LISEM), European Soil Erosion Model (EUROSEM), Soil and Water Assessment Tool (SWAT), Simulator for Water Resources in Rural Basins (SWRRB), Agricultural Non-point Source pollution model (AGNPS), etc. were used in regional scale assessment. Each model has its own characteristics and application scopes (Boggs et al., 2001; Lu et al., 2004; Dabral et al., 2008; Tian et al., 2009). The dominant model applied worldwide to soil loss prediction is USLE/RUSLE, because of its convenience in application and compatibility with GIS (Millward and Mersey, 1999; Jain et al., 2001; Lu et al., 2004; Jasrotia and Singh, 2006; Dabral et al., 2008; Kouli et al., 2009; Pandey et al., 2009; Bonilla et al., 2010). Although it is an empirical model, it not only predicts erosion rates of ungauged watersheds using knowledge of the watershed characteristics and local hydroclimatic conditions, but also presents the spatial heterogeneity of soil erosion that is too feasible with reasonable costs and better accuracy in larger areas (Angima et al., 2003). The RUSLE has been widely used for both agricultural and forest watersheds to predict the average annual soil loss by introducing improved means of computing the soil erosion factors (Wischmeier and Smith, 1978; Renard et al., 1997). This equation is a function of five input factors in raster data format: rainfall erosivity; soil erodability; 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:

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

where A is the computed spatial average of soil loss over a period selected for R, usually on yearly basis (t ha^{-1} y^{-1}); R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1}); K is the soil erodability factor (t ha h ha^{-1} MJ^{-1} mm^{-1}); LS is the slope length–steepness factor (dimensionless); C is the cover management factor (dimensionless, ranging between 0 and 1.5); and P is the erosion control (conservation support) practices factor (dimensionless, ranging between 0 and 1).

3.2. Data processing and RUSLE factors generation

The RUSLE model has been widely used for both agricultural and forest watersheds to predict the average annual soil loss. It is a non data-demanding and less expensive erosion model; therefore it can be fed by data usually available in institutional databases, such as low or medium spatial resolution satellite images and limited rainfall data etc. The methodology used in the present work was the implementation of RUSLE equation in a raster GIS environment for the calculation of specific factors and annual soil loss of the area under investigation. The climatic and terrain factors which are used in the equation were derived from rainfall data collected from Indian Meteorological Department (IMD), satellite image, soil texture map of soil survey organization, Kerala and Survey of India (SOI) toposheets. IRS-P6 LISS-III digital data of the year 2008 with resolution of 23.5 m was used for assessment of vegetation parameters in the area. SOI toposheets were used to create the digital database for the boundary, drainage network and contour map (20 m intervals) of the sub-watershed. The cell size of all the data generated was kept in to 30 m × 30 m, in order to make uniform spatial analysis environment in the GIS.

3.2.1. Rainfall erosivity (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 (2004–2008) 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):

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

where R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1}), P_i is the monthly rainfall (mm), and P is the annual rainfall (mm). For the present analysis, R-factor for the Pamba sub-watershed was computed from available rain gauge data, because the watershed has no record of daily rainfall intensity. The spatial interpolation techniques available in the ArcGIS software were used along with rainfall data of far away rain gauge stations for assessing the spatial variability in the rainfall and rainfall erosivity in the study area. While assessing the R-factor, it was found that, the variation of R-factor among the rain gauge stations were in the limit of ±3. In order to make the R-factor value most reliable, the spatial distribution of R was calculated from the available rainfall data by considering that the area experiences relatively uniform rainfall, both in intensity and duration across the study area and the average R value was used for further calculation (Table 1). The rainfall erosivity factor (R) for the years 2004–2008 was found to be in the range of 784.96–2292.43 MJ mm ha^{-1} h^{-1} y^{-1}. The average R-factor was observed to be 1514.66 MJ mm ha^{-1} h^{-1} y^{-1}. The highest value (2292.43 MJ mm ha^{-1} h^{-1} y^{-1}) of R-factor was observed in 2004 and the lowest value (784.96 MJ mm ha^{-1} h^{-1} y^{-1}) was in 2008.

Table 1 Monthly rainfall data with annual average R-factor (MJ mm ha^{-1} h^{-1} y^{-1}).

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.	Average R
2004	14.1	12.5	123.3	159.6	723.6	549.8	270.6	274.3	257.5	373.6	169.2	4.0	2292.43
2005	20.0	0.9	77.3	358.8	278.5	651.8	670.2	154.9	421.3	219.9	404.7	90.9	1448.08
2006	16.3	0.0	148.3	135.6	488.7	452.0	476.0	271.3	320.9	480.4	253.7	0.0	1338.37
2007	0.0	10.0	24.5	261.6	156.8	632.8	755.2	325.6	444.1	456.2	176.5	8.1	1709.46
2008	0.0	65.3	157.7	198.4	61.5	287.0	644.1	346.1	368.2	345.9	142.9	40.7	784.96

3.2.2. Soil erodability factor (K)

Different soil types are naturally resistant and susceptible to more erosion than other soils and are function of grain size, drainage potential, structural integrity, organic content and cohesiveness. Erodability of soil is its resistance to both detachment and transport. Because of thick forested nature of the watershed, detailed field surveys of soils in the area were not possible. So a generalized soil texture map collected from the soil survey organization, Kerala, was used for the preparation of *K* factor map and the soil types are grouped into four major textural classes viz., gravelly loam, gravelly clay, clay loam and loam. The corresponding *K* values for the soil types were identified from the soil erodability nomograph (USDA 1978) by considering the particle size, organic matter content and permeability class. The estimated *K* values for the textural groups vary from 0.13 t ha h ha^{-1} MJ^{-1} mm^{-1} (gravelly loam), 0.14 t ha h ha^{-1} MJ^{-1} mm^{-1} for gravelly clay, 0.22 t ha h ha^{-1} MJ^{-1} mm^{-1} for clay and 0.30 t ha h ha^{-1} MJ^{-1} mm^{-1} for loam.

3.2.3. Slope length and steepness factor (LS)

Length and steepness of a slope affects the total sediment yield from the site and is accounted 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 slope steepness but, in contrast to the *L*-factor representing the effects of slope length, the RUSLE makes no differentiation between rill and inter-rill erosion in the *S*-factor that computes the effect of slope steepness on soil loss (Renard et al., 1997; Lu et al., 2004; Krishna Bahadur, 2009). The combined *LS*-factor was computed for the watershed by means of ArcInfo ArcGIS Spatial analyst extension using the DEM following the equation (eq. 3), 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.

$$LS = (\text{Flow accumulation} \times \text{Cell size}/22.13)^{0.4} \times (\sin \text{slope}/0.0896)^{1.3} \quad (3)$$

where flow accumulation denotes the accumulated upslope contributing area for a given cell, LS = combined slope length and slope steepness factor, cell size = size of grid cell (for this study 30 m) and sin slope = slope degree value in sin. The *LS*-factor value in the study area varies from 0 to 22.90, with mean and standard deviation of 2.04 and 1.95 respectively. Majority of the study area has *LS* value less than 5 and some specific areas only showing values higher than 10.

3.2.4. Cover management factor (C)

The *C*-factor represents the effect of soil-disturbing activities, plants, crop sequence and productivity level, soil cover and subsurface bio-mass 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 (eq. 4) to generate the *C*-factor value image for the study area (Zhou et al., 2008; Kouli et al., 2009).

$$C = \exp\left[-\alpha \frac{\text{NDVI}}{(\beta - \text{NDVI})}\right] \quad (4)$$

where α and β are unitless parameters that determine the shape of the curve relating to NDVI and the *C*-factor. Van der Knijff et al. (2000) found that this scaling approach gave better results than assuming a linear relationship and the values of 2 and 1 were selected for the parameters α and β, respectively. This equation was successfully applied for assessing the *C*-factor of areas with similar terrain and climatic conditions (Prasannakumar et al., 2011a,b). The *C*-factor in the present case ranges between 0.3 and 1.5.

3.2.5. 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 down slope 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

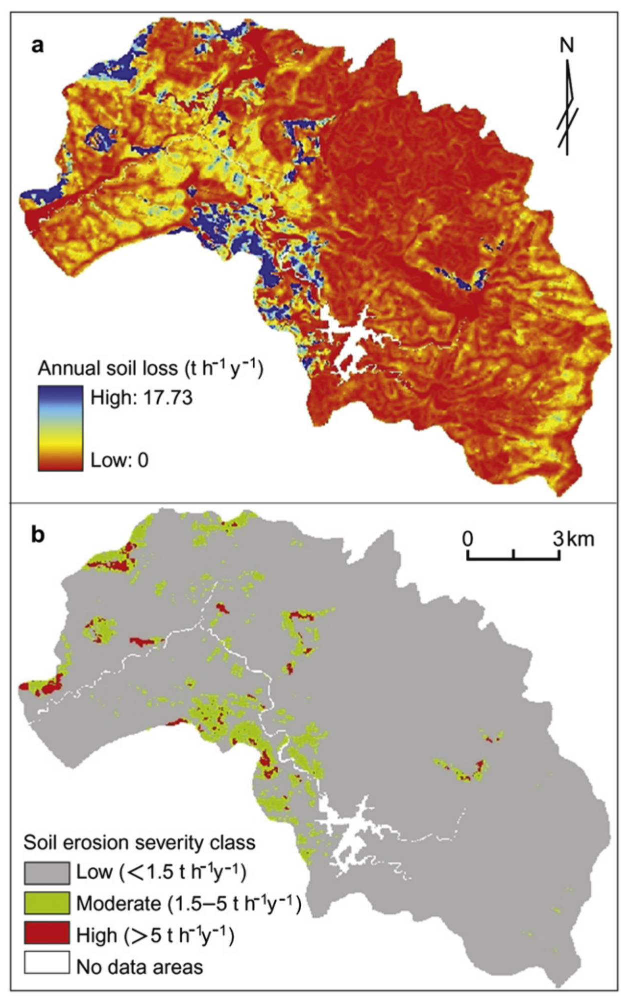

Figure 2 Spatial distribution of (a) predicted annual soil loss (t h^{-1} y^{-1}), (b) classified soil erosion risk zones.

Table 2 Soil erosion severity zones with erosion rate and area covered.

Soil erosion classes	Rate of soil loss (t h^{-1} y^{-1})	Area (km^2)	Area (%)
Nil (no data areas)	0	3.34	1.98
Low	0–1.5	155.34	92.55
Moderate	1.5–5	7.37	4.419
High	>5	1.79	1.06

built-up-land and plantation area with strip and contour cropping. The lower the *P* value, the more effective the conservation practices.

4. Results and discussion

RUSLE is a straightforward and empirically based model that has the ability to predict long term average annual rate of soil erosion on slopes using data on rainfall pattern, soil type, topography, crop system and management practices. In the present research, annual soil erosion rate map was generated for Pamba sub-watershed, a mountainous area, which represents most of the terrain characteristics of Western Ghats. 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 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 17.73 t h^{-1} y^{-1} with a standard deviation of 0.975 t h^{-1} y^{-1} (Fig. 2a). The results were correlated with similar studies carried out in different parts of the Western Ghats (CWRDM, 1997; Matsuura, 2000; Prasannakumar et al., 2011a,b) for validating and to ensure the applicability of the proposed method in the study area. Soil erosion rate calculated in these studies are found to be appropriate and matching. The results were also compared with the studies carried out in areas having similar geo-environmental and rainfall characteristics (Bacchi et al., 2000; Mati, 2000; Shiono et al., 2002; Angima et al., 2003; Lee and Lee, 2006; Yuksel et al., 2008; Adediji et al., 2010) and were found to be comparable with an annual average soil erosion rate of 10–45 t h^{-1} y^{-1}. The assessed average annual soil loss of Pamba sub-watershed was grouped into different classes based on the minimum and maximum values and the spatial distribution of each class is presented in Fig. 2b. The grouping of different soil erosion severity zones was carried out by considering the field conditions. The results presented in Table 2 show that about 92% of the study area is classified as low potential erosion risk (<1.5 t h^{-1} y^{-1}), while rest of the area is under moderate to high erosion risk. In terms of actual soil erosion risk, the study area has 4% moderate (1.5–5 t h^{-1} y^{-1}), and 1.06% high (>5 t h^{-1} y^{-1}) erosion risk levels. The spatial pattern of classified soil erosion risk zones indicates that the areas with high and severe erosion risk are located in the west, northwest and southern regions of the study area, while the areas with low erosion risk are in the eastern and central parts of the study area.

In order to assess the role of human intervention in the soil erosion risk in the sub-watershed, land use/land cover map (Fig. 3)

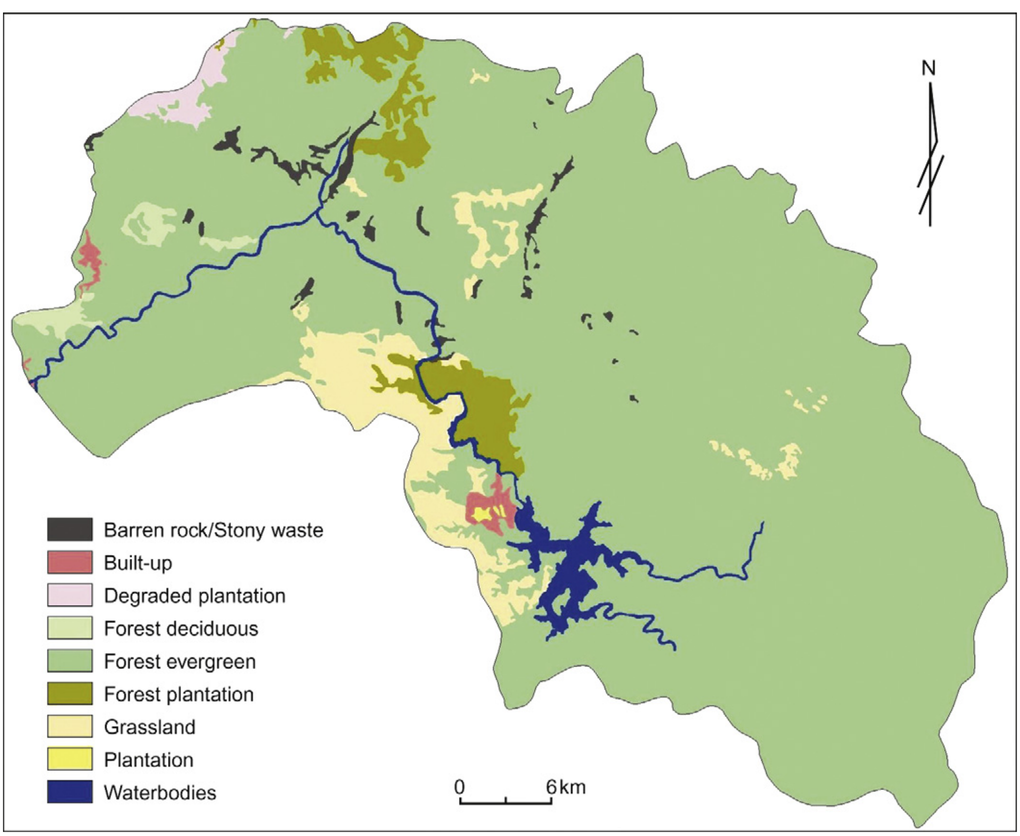

Figure 3 Land use/land cover types in the study area.

Table 3 Land use/land cover in the Pamba sub-watershed with *P* values and soil erosion statistics.

Land use/land cover class	Area (km^2)	*P* value	Soil erosion ($t\ h^{-1}\ y^{-1}$) (mean)
Built-up-land	0.88	0	2.07
Grass land	8.25	1.0	6.56
Wasteland	1.76	1.0	0.16
Plantation	0.10	0.5	1.79
Degraded plantation	1.23	0.8	10.09
Forest plantations	5.57	0.7	3.18
Forest deciduous	1.32	1.0	11.65
Forest evergreen	146.04	0.1	0.92
Water bodies	2.689	0	0

of the area was overlaid with classified soil erosion risk zone map. With the spatial pattern, the severe and high levels of soil erosion risk zones are distributed on the grassland, degraded plantation, and deciduous forest areas (Table 3). The area with the larger gradient is mostly covered by high fraction vegetation, and is on lower level of soil erosion risk than that with little gradient. At the same time the spatial pattern of annual average soil erosion risk map shows high spatial correlation with *LS*-factor map, and it indicates the role played by topography in controlling soil movement in a watershed. Therefore, the areas with high *LS*-factor and degraded/deciduous forest/grasslands need immediate attention in soil conservation point of view.

5. Conclusion

A quantitative assessment of average annual soil loss for Pamba sub-watershed is made with GIS based well-known RUSLE equation considering rainfall, soil, land use and topographic datasets. In the sub-watershed the land use pattern in areas prone to soil erosion indicates that areas with natural forest cover in the head water regions have minimum rate of soil erosion while areas with human intervention have high rate of soil erosion ($>5\ t\ h^{-1}\ y^{-1}$). Terrain alterations along with high *LS*-factor and rainfall prompt these areas to be more susceptible to soil erosion. 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 mapping 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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