Geospatial Analysis of Soil Erosion Patterns in a river basin of Western Ghats

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Abstract
Loss of soil from river basins by water is a concerning issue for India which is an agricultural country. The particular distribution of quantitated soil erosion must be obtained to propose effective soil conservation practices. Revised Universal Soil Loss Equation (RUSLE) is a tool to estimate soil erosion distribution spatially. The properties of Vembanad lake that supports large biodiversity and ecosystem is altered by the sediments of Muvattupuzha River. The river, originating from the Western Ghats drains into Vembanad lake, has undergone many changes.

In this work, an attempt has been made to determine the soil erosion in the Muvattupuha River basin through the years. Annual sediment loss from the basin is obtained for three consecutive decades. Maps of soil yield, sediment delivery ratio and sediment transportation index of the basin for 2021 are also developed.

Keywords: Erosion, sediment, delivery, transportation, rainfall.

Introduction

Soil is an essential resource for India, an agricultural country with 58% of people depending on agriculture and allied sectors for their livelihoods[4]. Soil erosion degrades the nutritional value of soil making it unsuitable for agricultural activities and also causing reservoir sedimentation[7,20]. Soil from 45% of the total geographical area of India, i.e. almost 130 million hectares of land[13], is severely eroded. About 5.3 billion tons of soil are being removed annually[15]. Since 1950, every year, plant nutrients in the range of 5.37 to 8.4 Mt are lost due to soil erosion[1]. Soil conservation practices have to be undertaken to control the depletion of quality and quantity of available soil resources.

Regional-specific quantitative erosion assessment is needed to infer efficient erosion control and soil conservation strategies to prevent soil erosion and locate critical areas for its implementation. Conventional methods to determine quantitative soil erosion at a spatial scale are expensive and time-consuming[7]. Substantial efforts have been spent developing soil erosion models[5,17].

Physical based, conceptual and empirical erosion control models are available. The complexity of these models varies[5,6,19,25]. Among the empirical models, Universal Soil Loss Equation and its improvements ae used globally for modelling erosion among which Revised Universal Soil Loss Equation (RUSLE), developed by the U.S. Department of Agriculture is commonly used for assessing soil erosion. RUSLE uses a set of mathematical equations for estimating soil loss[20].

RUSLE model can be integrated with satellite images and a geographical information system (GIS). With lesser data requirement, flexibility[2] and execution in GIS, it forms the most commonly used erosion model globally[9,10,22]. As the RUSLE and GIS can be integrated, the soil loss spatial variation over large areas can be obtained with lesser cost and higher accuracy[12]. Cell-to-cell basis erosion potential can be predicted by the RUSLE model effectively identifying the spatial pattern of soil erosion within a large region[21].

Originating from Western Ghats, Muvattupuzha river flows through central Kerala discharge into Vembanad lake. Drastic changes in land use pattern[26] and the commissioning of the Idukki hydroelectric project[3] altered the flow characteristics of the river. Mining activities were also severe on its banks[1]. Malankara dam is constructed across Thodupuzha Ar as a part of Muvattupuzha Valley Irrigation Project.

All these have considerably altered the morphological characteristics and sediment dynamics of the river whose average sediment discharge and the erosion rate are 167408 MT and 0.042 mm/year respectively[16]. The sediments brought by Muvattupuzha river changed the shape and depth of the Vembanad estuary. The Vembanad lake in Kerala is India's longest and largest brackish-water lake.

The Vembanad lake system supports rich biological regions with a high degree of endemism, around 150 fish species and a bird population of more than 20,000 during winter[24]. 1.6 million people depend on this lake system for livelihood. Degradation of the health of the Vembanad lake system would have a wide range of ramifications and could negatively impact the services provided by this ecosystem. So, monitoring the Vembanad lake system and making necessary interventions continuously are imperative.

Hence, the present study was carried out to access the yearly soil erosion rate over three consecutive decades. The present erosion distribution scenario is obtained for the basin using GIS integrated RUSLE model. Sediment yield map, soil delivery ratio and sediment transport index of the basin are plotted.

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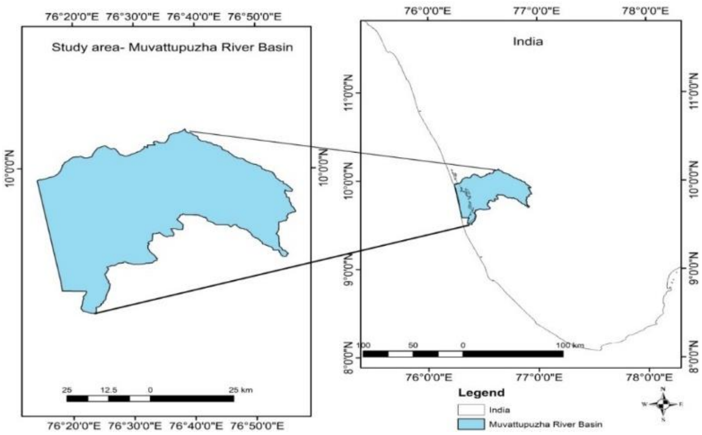

Figure 1: Muvattupuzha River Basin

Study Area

Originating from the Western Ghats, draining mainly through highly lateralized crystalline rocks and finally debouching into the Vembanad estuary near Vaikom, Muvattupuzha river is one of the major perennial rivers in Central Kerala. Muvattupuzha river basin lies between 9°45' to 10 0 05'N latitude and 76°22' to 76°50'N longitude. The basin receives good rainfall in the range 2779 mm to 4526 mm and the daily normal mean temperature varies from 25.9°C to 28.7°C throughout the year. The river flows through varied geological formations and laterite soil, hydromorphic soil and riverine alluvium form the major soil type.

Material and Methods

RUSLE model: To estimate the average annual erosion in a basin, RUSLE requires five input parameters[27]. Input parameters of RUSLE are rainfall erosivity factor which accounts the precipitation, soil readability factor that considers the soil composition, slope length and steepness factor that accomplish the effect of slope, cover management factor and conservation practice factor that account the effect of landuse, conservation practices and slope of area under consideration. Average annual soil erosion in t/ha.y is computed as:

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

where R is the rainfall erosivity factor in MJ.mm/ha.y, K is the soil erodibility factor in t/ha.MJ.mm, LS is topographic factor, C is cover management factor and P is conservation practice factor, the last three parameters being dimensionless.

Results and Discussion

Survey of India (SoI) toposheet on a 1:50,000 scale was used to delineate the river basin using ArcGIS 10.3 software. Using the base map, the study area was extracted from satellite image. The estimation of the various parameters and the data used are described below.

Rainfall erosivity factor: Rainfall erosivity is defined as the capacity of rain to cause erosion. The erosive force of rain is reported as rainfall erosivity factor. To determine the erosive force of rainfall, rainfall intensity in thirty minutes duration is required. But such data are often unavailable. So this factor is correlated to average annual precipitation (P in mm) and monthly rainfall (P_i in mm). The equation used in this study was proposed by Wischmeier and Smith in 1978[27]. This equation was modified by Arnold in 1980 as shown below

$$R = \sum_{1}^{12} 1.735 \times 10^{(1.5 \log_{10}(P_i/P) - 0.08188)}$$

where P is the annual rainfall in mm and Pi is the monthly rainfall in mm.

The monthly rainfall of different locations from 1991 to 2020 is obtained from NASA MERRA. The annual average rainfall is calculated for each year using the obtained monthly rainfall data. Using the above equation, the rainfall erosivity index is calculated at six locations in the basin for three decades. The obtained values are tabulated in table 1. At all stations, R value increased in 2000- 2010 from 1991-2000 and then decreased in 2011- 2020. R value completely depends on average annual precipitation value.

Slope Length Factor: It is the product of Slope length (L) and slope steepness (S) and is the ratio of soil loss from the site under consideration to and a site with a standard slope steepness and slope length of 9% and 22.6 m[7] respectively. The slope factor was obtained as follows:

$$LS = \left[\frac{QaM}{22.13}\right]^{y} \times (0.065) + \left(0.045 \times S_g\right) + (0.0065 \times S_g^2)$$

where Qa is flow accumulation grid, S_g is grid slope (%), M is grid or pixel size (x -y) and y is dimensionless support that assumes the value of 0.2–0.5[26].

The slope factor is obtained from Catostract DEM which is available in BHUVAN. The higher is the value, the greater is its susceptibility to erode. The slope varies from 7% at the north of the basin to 0% at the south. The slope length factor is in the range of 0 to 3.713. Slope Length factor of the basin in five different locations is tabulated in table 2. As the possibility of a change in slope with time is less, the soil erodibility value is assumed to be constant over the years.

Soil erodibility factor: This factor depended on the soil's permeability, particle size distribution and organic content. It is also affected by the physical, chemical, mineralogical and morphological properties of soil. It refers to the inherent vulnerability of the soil to erosion.

$$K = \left\{0.2 + 0.3\, exp\left[-0.0256 m_s\left(1 - \frac{m_{silt}}{100}\right)\right]\right\} \times \left[\frac{m_{silt}}{m_c + m_{silt}}\right]^{0.3} \times \left\{1 - \frac{0.25\, org\ C}{[org\ C + exp(3.72 - 2.95\, org\ C)]}\right\} \times \left\{1 - \frac{0.7\left(1 - \frac{m_s}{100}\right)}{\left\{\left(1 - \frac{m_s}{100}\right) + exp\left[-5.51 + 22.9\left(1 - \frac{m_s}{100}\right)\right]\right\}}\right\}$$

Table 3 depicts the variation of the soil erodibility factor. As the possibility of a change in slope with time is less, the soil erodibility value is assumed to be constant over the years.

Cover management factor: This factor depends on the land use and is the ratio of soil loss from cropped land to continuously tilled fallow on the same soil and slope[19]. The value varies from 0 to 1. LANDSAT 8 image is obtained from USGS. Using supervised classification, the land use of the basin is determined for the three different time duration. The cover management factor was obtained as in figure 5.

Conservation Practice Factor: It is the soil loss ratio from an area with a specific support practice to the corresponding soil loss with no support practice. The value varies from 0 to 1, with the value 1 assigned to an area with no conservation practices. Lowering the P value implies more effective conservation practices. The conservation practice factor is obtained from the land use map as in figure 6.

Table 1
Rainfall erosivity factor of Muvattupuzha River basin

Location		**Rainfall Erosivity Index (MJ/hr/h/yr)**		
Latitude	**Longitude**	**1991-2000**	**2000-2010**	**2011-2020**
9° 40”	76° 20”	959.176	1086.86	954.39
9° 45”	76° 30”	959.176	1086.86	954.39
9° 55”	76° 30”	959.176	1086.86	954.39
9° 55”	76° 45”	774.639	861.166	735.592
10° 00”	76° 30”	959.176	1086.86	954.392
10° 00”	76° 45”	774.639	861.166	735.592

Table 2
Slope Length factor of Muvattupuzha River basin

Location		**Slope Length Factor**
Latitude	**Longitude**	
9° 40”	76° 20”	0.029
9° 45”	76° 30”	0.029
9° 55”	76° 30”	0.029
9° 55”	76° 45”	0.029
10° 00”	76° 30”	0.029
10° 00”	76° 45”	0.029

Table 3
Soil erodibility factor of Muvattupuzha River basin

Location		**Soil erodibility factor (t/ha.MJ.mm)**
Latitude	**Longitude**	
9° 40”	76° 20”	0.917
9° 45”	76° 30”	0.1251
9° 55”	76° 30”	0.1251
9° 55”	76° 45”	0.1251
10° 00”	76° 30”	0.1251

Table 4
Cover management factor of Muvattupuzha River basin

Location		Cover management factor		
Latitude	**Longitude**	**1998**	**2008**	**2018**
9° 40”	76° 20”	0.014	0.014	0.004
9° 45”	76° 30”	0.1	0.1	0.004
9° 55”	76° 30”	0.1	0.1	0.1
9° 55”	76° 45”	0.1	0.1	0.004
10° 00”	76° 30”	0.1	0.1	0.004
10° 00”	76° 45”	0.1	0.014	0.004

Table 5
Conservation Practice factor of Muvattupuzha River basin

Location		Conservation Practice Factor		
Latitude	**Longitude**	**1998**	**2008**	**2018**
9° 40”	76° 20”	1	0.9	0.9
9° 45”	76° 30”	0.5	0.5	1
9° 55”	76° 30”	0.5	0.5	0.5
9° 55”	76° 45”	0.5	0.5	1
10° 00”	76° 30”	0.5	0.5	1
10° 00”	76° 45”	0.5	0.5	1

Table 6
Soil erosion of Muvattupuzha River basin

Location		Annual Soil Loss		
Latitude	**Longitude**	**1998**	**2008**	**2018**
9° 40”	76° 20”	0.321	0.364	0.091
9° 45”	76° 30”	0.174	0.197	0.014
9° 55”	76° 30”	0.174	0.197	0.173
9° 55”	76° 45”	0.141	0.156	0.011
10° 00”	76° 30”	0.174	0.197	0.014
10° 00”	76° 45”	0.141	0.022	0.011

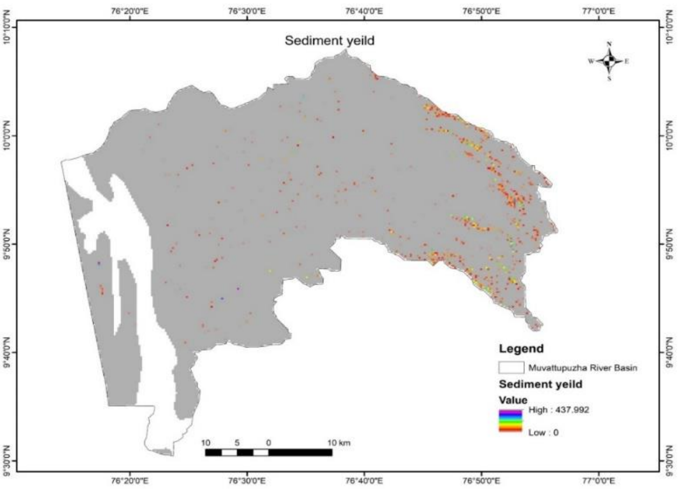

Figure 2: Sediment yield of Muvattupuzha River basin

Soil Erosion: The soil loss of that basin is the product of the factors mentioned above R, K, P, C and L.C. The average annual soil erosion of the Muvattupuzha river basin was obtained for six locations for 1998, 2008 and 2018. The western side of the basin is more eroded as compared to eastern side. This can be because, even though the slope is higher in the eastern side, the formation is rock which has more resistance to erosion. Precipitation and landuse are significantly effects soil loss from an area. To analyse the present erosion condition of the basin, sediment yield map, soil delivery ratio and sediment transport index of the basin were plotted for 2021 using RUSLE integrated with GIS.

Sediment yield: Quantity of sediment leaving the watershed or catchment is called sediment yield. Gross erosion is the total erosion occurring within the catchment. The value of sediment yield varied from 0 to 437.992 metric tons per kg per year as shown in figure 2.

Soil Delivery Ratio (SDR): It is the capacity of a catchment in move sediment from the eroded area to the point where the sediment yield is measured. It is obtained as the ratio of sediment yield at the watershed outlet to gross erosion in the entire watershed. Gross erosion includes sheet, rill, gully and channel erosions. The sediment delivery ratio of Muvattupuzha river basin is obtained in the range of 0 to 6.191.

Sediment transportation Index: The sediment transport index accounts for the effect of topography on erosion. It is obtained as $STI = (A / 22.13)^{0.6} \times \sin(\beta / 0.0896)^{1.3}$, where A is the area and β is slope angle. The sedimentation transportation index varied from 0 to 1609, as shown in figure 4.

Conclusion

The quantity of soil eroded from six different points of Muvattupuzha river basin was obtained. Changes in rainfall and landuse are significant and affect the soil erosion from the river basin. The maps of 2021 for sediment yield, sediment delivery ratio and sediment transportation index are obtained. On analysis, nearly ninety percent of the basin is eroded. Various measures for controlling erosion include control of tillage applications[28] intercropping[23], using crop cover[17], mulching[11,26], addition of organic matter[26], cultivation of grass[13,26,27].

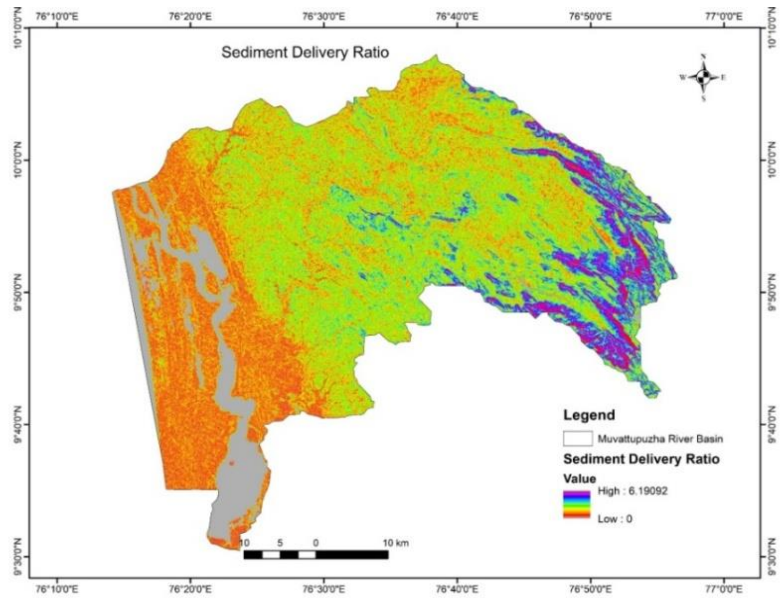

Figure 3: Soil delivery ratio of Muvattupuzha River basi

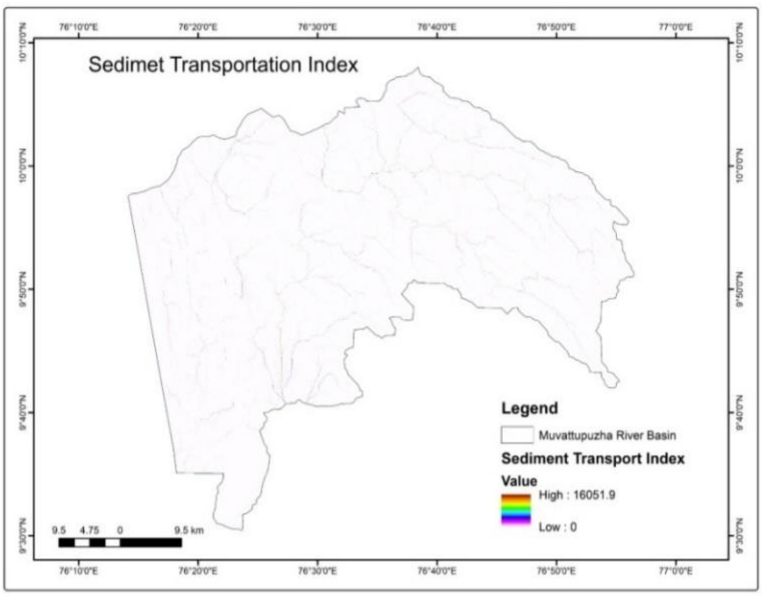

Figure 4: Sediment transportation Index of Muvattupuzha River basin

Department of Soil Survey and Soil Conservation of Kerala Government suggests various methods like construction of bunds, vegetative hedges, trenches, moisture conservation pits, check dams, coir geotextiles and percolation pits.

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