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Prioritization of Watershed using Sediment Yield Index Method: A Case study of Semi-Arid Ecosystem of South India

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Abstract

Soil erosion is a severe problem in arid and semi-arid environments, especially on grazing land, where extreme rainfall intensities of short duration, soil vulnerability to erosion, and human land mismanagement have increased soil degradation by erosion leading to sedimentation downstream. For the better agricultural sustainable development, estimation of soil sedimentation is critical for watershed planning, prioritization and development. A sediment yield index (SYI) model describing the relative yield of sediments from various sub-watersheds works out the preferences for soil and water conservation interventions in a watershed. The study recognizes the extent of soil loss and recommends a method for prioritization of sub-watershed in the Sarabhanga watershed of Tamil Nadu state by integrating the topography, soil, rainfall erosivity and land use/land cover parameters under 17 sub-watersheds with a Geo-informatics approach. Of the 17 sub-watersheds, five sub-watersheds (SB-6, SB-3, SB-14, SB-12 and SB-5) came into the extremely high priority category, with a higher SYI value (>170) and covering 584.3 sq. km, about 49.7% of the Sarabhanga watershed due to high rainfall and high slope value imply that these sub-watersheds have a high potential for erosion and sedimentation. Six sub-watersheds (SB-1, SB-11, SB-2, SB-13, SB-4 and SB-15) were classified under a low priority class covering an area of 233.4 sq.km (19.9%) and these sub-watersheds have low amounts of precipitation and less than 70 SYI values. The study comments on conservation techniques that can be adopted in the Sarabhanga watershed to the increase agro pastoral efficiency.

1. Introduction

Globally, soil erosion by water is one of the main causes of land degradation and a critical environmental hazard of modern times (Ganasri and Ramesh, 2016; Thomas *et al*., 2018; Gianinetto *et al*., 2019). The negative impacts of soil erosion include a reduction in the root zone's efficient root depth, nutrient and water imbalance, and the resulting deterioration in soil quality leads to loss of fertile topsoil cover and consequently a decrease in agricultural production (Pradeep *et al*., 2015; Noori *et al*., 2016). Human interference, however, can accelerate soil erosion rate through land use transformation, deforestation, agricultural practices, and construction activities (Jinren and Yingkui, 2003; Srinivasarao *et al*., 2013). The average rate of soil erosion in cropland is around 30 t ha^{-1} yr^{-1} globally, varying from 0.5 to 400 t ha^{-1} yr^{-1} (Pimentel *et al*., 1987). According to the reports, about 85% of soil attenuation in the world is due to soil erosion, which decreases crop production by about 17%, initially impacting soil fertility and long-term soil desertion (Singh and Panda, 2017). Globally, the total land area affected by water erosion is 1094 million hectares (Mha); of which 751 Mha deteriorate significantly (Lal, 2003). In India, out of 329 Mha of the country's total land area, 69 Mha of land is critically degraded and 106 Mha land is severely eroded at an average rate of 16.4 t ha^{-1} yr^{-1} soil detachment (Singh, 2000). Soil erosion in India is, therefore, one of the nation's main concerns as agriculture is adversely affected. Erosion results either the loss of topsoil or the terrain deformation or both are the most common type of deterioration and occur widely in all agro-climatic zones of India (Reddy *et al*., 2016). In India, almost 10% of the total soil detached and it is accumulated in surface reservoirs annually and resulting in a loss of about 1 to 2% of storage capacity (Mandal and Sharda, 2011).

Scholars are focused on developing the soil erosion prediction models by utilizing the advances of remote sensing technologies and geographic information systems (GIS) in different parts of the world (Mitasova *et al*., 2013;

Igwe *et al*., 2017; Wijesundara *et al*., 2018). It also helps in the identification of erosion-prone areas and provides data inputs to many of the soil erosion models (Rawat *et al*., 2014). In addition to the above, robust spatial processing capability of GIS and its connectivity with remote sensing data have rendered soil erosion modelling approaches more systematic and comprehensive (Saha *et al*., 1992; Shrestha, 1997). They have devoted particular attention to the evaluation of soil erosion modelling based on empirical conceptual and physical models (Eisazadeh *et al*., 2012; Udayakumara *et al*., 2010; Singh and Panda, 2017). The sediment yield index (SYI) and revised universal soil loss equation (RUSLE) are two commonly used models to quantify the soil erosion and to prioritize watersheds for their management among several methods. The All India Soil and Land Use Survey (AISLUS) has introduced the SYI model (AISLUS, 1991), provides comparative catchment erodibility criteria (low, moderate, high, etc.) and providing absolute silt yield, mainly because it is easy to use and needs less data. Variables such as climate, type of soil, vegetation cover, terrain and anthropogenic activities influence soil erosion and sediment distribution at watersheds (Ochoa *et al*., 2016).

Watershed planning, restoration and management are essential to the soil with the purpose of preventing more erosion damage (Meshram *et al*., 2019), so any effort to evaluate the erosion danger and prioritization of watersheds for treatment would aid to plan better against the menace. However, prioritization is very helpful in understanding the actions of each sub-watershed system and in providing more reliable information to minimize floods efficiently and avoid soil erosion over a watershed (Vittala *et al*., 2008; Lakkad *et al*., 2017). Prioritizing and formulating effective watershed management strategies for sustainable development needs knowledge on the yield of sediment from watersheds (Pandey *et al*., 2007). Chakraborti (1991) used the SYI method to predict sediment yields using remote sensing data to prioritize watersheds. Ayadi *et al*. (2010) used principal component analysis (PCA) and complementary multidimensional statistical methods to measure and estimate the sedimentation intensity for 26 hillside dam reservoirs in central Tunisia. Naqvi *et al*. (2015) describes the amount of soil loss and suggests a strategy measures for micro-watershed prioritization in a sub-tropical climate. Nanda *et al*. (2015) employed the SYI model to prioritize a Himalayan watershed based on erosion intensity mapping units (EIMU). Sub-watersheds are ideal units for assessing the sediment yield, prioritizing sediment degradation and supplying decision-makers with knowledge (Food and Agriculture Organization (FAO), 1985). Beyond this, it is important to identify the soil erosion hotspots for priority conservation in order to implement the rigid watershed mitigation strategy (Saha *et al*., 2018; Nikolic *et al*., 2018). Soils of arid and semi-arid environments are highly susceptible to erosion (Lopes *et al*., 2019), mainly due to the limited vegetation density, poor organic matter and weak tolerance to erosion forces. Arid and semi-arid areas have been considered a fragile area where vegetation cover is limited and degradation processes occur very rapidly and seriously after rainfall. Precipitation is typically defined as torrential events in these areas, occurring within a short period of time with high rainfall intensities (Wei *et al*., 2007; Filho *et al*., 2017). The present research was thus taken up with the objective of developing a prioritization measures for Sarabhanga watershed of southern India using remote sensing and GIS, bearing in mind the evolving planning pattern in which a natural boundary like a watershed is considered the basic unit for growth. The study mainly aimed (i) to examine the land use/land cover pattern of Sarabhanga watershed and (ii) to estimate the SYI for each sub-watershed and prioritization for soil and water conservation measures at the sub-watershed level.

2. Materials and Methods

2.1. Study area

The Sarabhanga watershed is located in the Salem district of Tamil Nadu state and covers five tehsils (sub-divisions) namely Omalur, Mettur, Edappadi, Yercaud and Sankari and its geographical location extends between 11° 29' 27.72" to 11° 56' 5.15" in northern latitudes and 77° 44' 9.73"to 78° 13' 39.2" in eastern longitudes with an area of 1175.3 sq. km (Fig. 1). The watershed is drained by Sarabhanga river, main tributary of river Cauvery which originates at the foothills of Yercaud near Danishpet and flows through Omalur, Tharamangalam, Edappadi and Thevur before joining the Cauvery river north of the town of Bhavani. This is formed by the union of two streams, viz Omalur east river and the Omalur west river. The elevation of the watershed varies from 154 to 1641 m from mean sea level (MSL). The study area receives maximum amount of rainfall during south west monsoon season and the annual rainfall varies from 800 mm to 1600 mm, near Sankari receives minimum rainfall (800 mm) in the southwest portion of the study area and it rises steadily towards the north, northeast and east and reaches maximum in the northern part of Yercaud (1594.3 mm) (Arulmozhi and Arulraj, 2017). The landscape of the watershed includes plain, uplands, lower valley, upper valley and dissected/degraded hills. The quaternary alluvium occurs all along the course of the Sarabhanga river in the central part. Major agriculture crops in the study area includes paddy, groundnut, fodder, sugarcane etc.

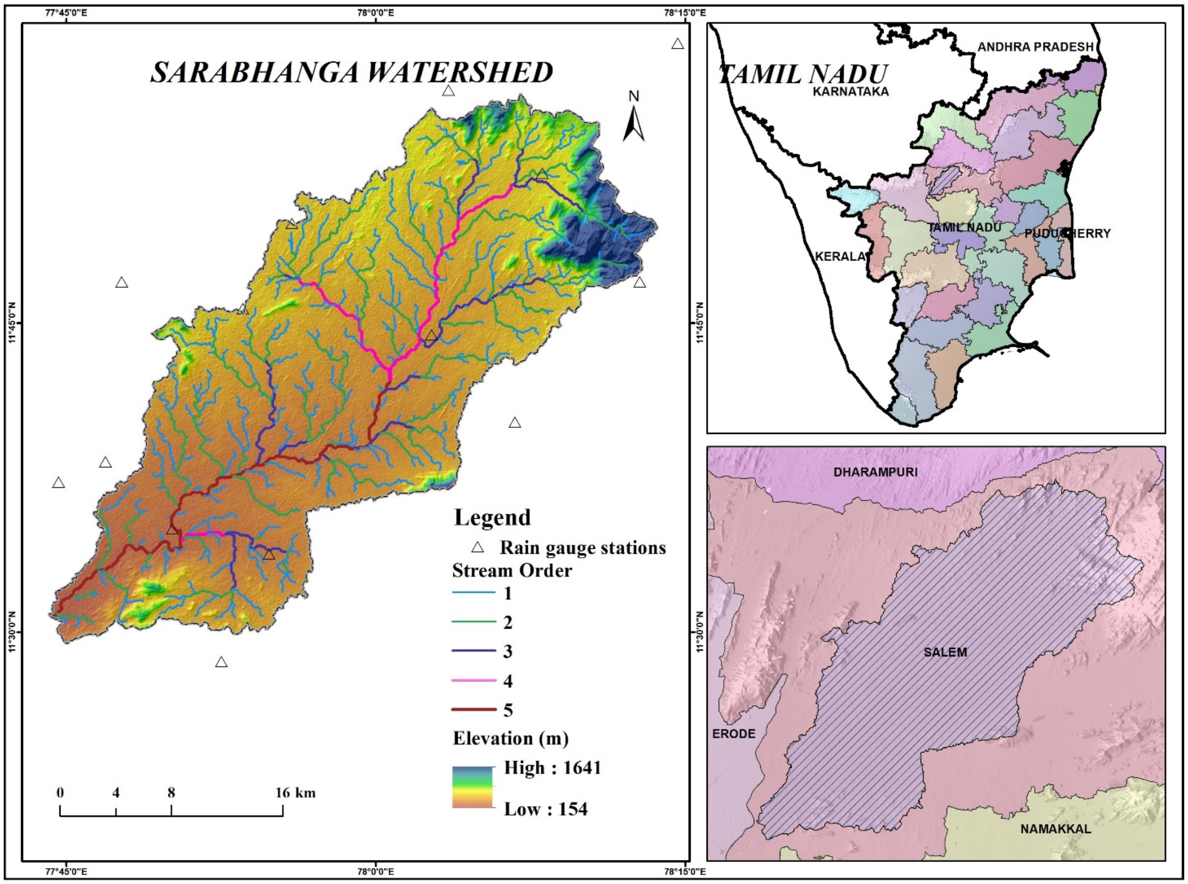

Fig. 1: Location of study area shown with SRTM DEM (30 m) and rain gauge stations.

2.2. Database

Landsat-8 multispectral satellite image of 3rd March 2018 and Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) for the study area with a spatial resolution of 30m were downloaded from United States Geological Survey website (https://earthexplorer.usgs.gov). The rainfall data of 30 years (1989 to 2018), acquired from the State Surface and Groundwater Resources Data Centre (SSGRDC), Chennai for fourteen rain gauge stations. The soil characteristics data for the watershed was collected from the Tamil Nadu Agricultural University (TNAU) with scale 1: 50000. Table 1 shows the data sets used in the study.

2.3. Watershed and sub-watershed delineation using Arc Hydro

Arc Hydro is a model designed to develop hydrological information systems to synthesize data from geospatial to support hydrological modelling and analysis. The model is developed as an add-on tool to ArcGIS software. The first phase is that pre-processing of terrain using SRTM DEM to define the pattern of surface drainage. The purpose of the sinks of fill is to eliminate the problem as if a cell is surrounded by higher elevation cells and the water is immovable in that cell that can't flow. The flow direction method generates a direction of flow grid from each pixel to its steepest downslope neighbour. The next step was to define the flow accumulation; in this process, for each cell in the input grid, the flow accumulation grid including the accumulated number of cells upstream of a cell is calculated.

Table 1 Datasets used in the study.

Sl. No	Data set	Variable	Temporal coverage	Spatial resolution	Source
1	Landsat-8	LU/LC	16 day	30 m	USGS Earth Explorer
2	SRTM DEM	Slope		30 m	USGS Earth Explorer
3	Rain gauge data	Erosivity	1989 to 2018	-	State Surface and Groundwater Resources data centre
4	Soil texture	Sandy loam, Loamy sand	-	1:50000	Tamil Nadu Agricultural University (TNAU)

The stream definition method evaluates a stream grid based on a flow accumulation grid with a 10% threshold value of the drainage area. Stream segmentation generates a stream segment grid with a specific identification code, and the link grid was used as a next step to develop a value-based catchment grid. The next step is the delineation of the catchment system; in this process, a grid is generated in which each cell bears a value (grid code) indicating that it belongs to which catchment. The catchment polygon processing function converts a catchment grid into a catchment polygon feature class and the drainage line processing function converts the stream link grid into a polyline feature class.

2.4. Preparation of thematic layers

The major parameters used in the study include land use/land cover (LU/LC), slope, soil texture and rainfall erosivity. The thematic layers were created and stored in a geodatabase, and all the thematic layers were converted from vector to raster format with 30 m × 30 m grid cell for further integration analysis for SYI model. Using supervised classification technique, the LU/LC for the study area was extracted from Landsat-8 multispectral data with nine classes relevant for this study. Drainage density was calculated with the total length streams divided by the total area of the watershed which is delineated from the SRTM topographic data using the raster calculator in ArcGIS. The slope map of the study area was generated from SRTM data by spatial analyst tool box in ArcGIS. The soil characteristics data were collected from Tamil Nadu Agricultural University (TNAU) with a scale of 1:50,000 for the Sarabanga watershed. The rainfall erosivity factor (R factor) of the study area was prepared by acquiring data on 30 years of rainfall (1989 to 2018) from the State Surface and Groundwater Resources Data Centre (SSGRDC), Chennai for 14 rain gauge stations by using the Eq. below (1) developed by Wischmeier and Smith (1978).

$$R = \sum_{1}^{14} 1{:}735 \times 10^{(1.5\, log_{10}(P_1/P) - 0.08188)} \quad (1)$$

where, R is a rainfall erosivity factor (MJ mm ha^{-1} $h^{-1}yr^{-1}$); Pi is monthly rainfall (mm); P is an annual rainfall (mm).

2.5. Sediment Yield Index (SYI)

The SYI method is highly useful for prioritization of sub-watersheds according to erosion impact (AISLUS, 1991). All the thematic layers were prepared for each parameter and used for assigning weighted values to calculate the SYI in t km^2yr^1 according to the following Eq. (2):

$$SYI = \sum(A_i \times W_i \times D_i) \times 100/A_w \quad (2)$$

where, Ai = area of i^{th} unit; W_i = weighted value of i^{th} mapping unit; D_i = delivery ratio; A_w = total area of watershed.

The amount of soil sedimentation for each sub-watershed was determined and then classified according to the SYI values in four priority rating classes (very high, high, medium and low). First, the weighted values were assigned for each factor based on their level of risk, and then input into the SYI model. Fig. 2 describes the comprehensive methodology flow chart used in the study.

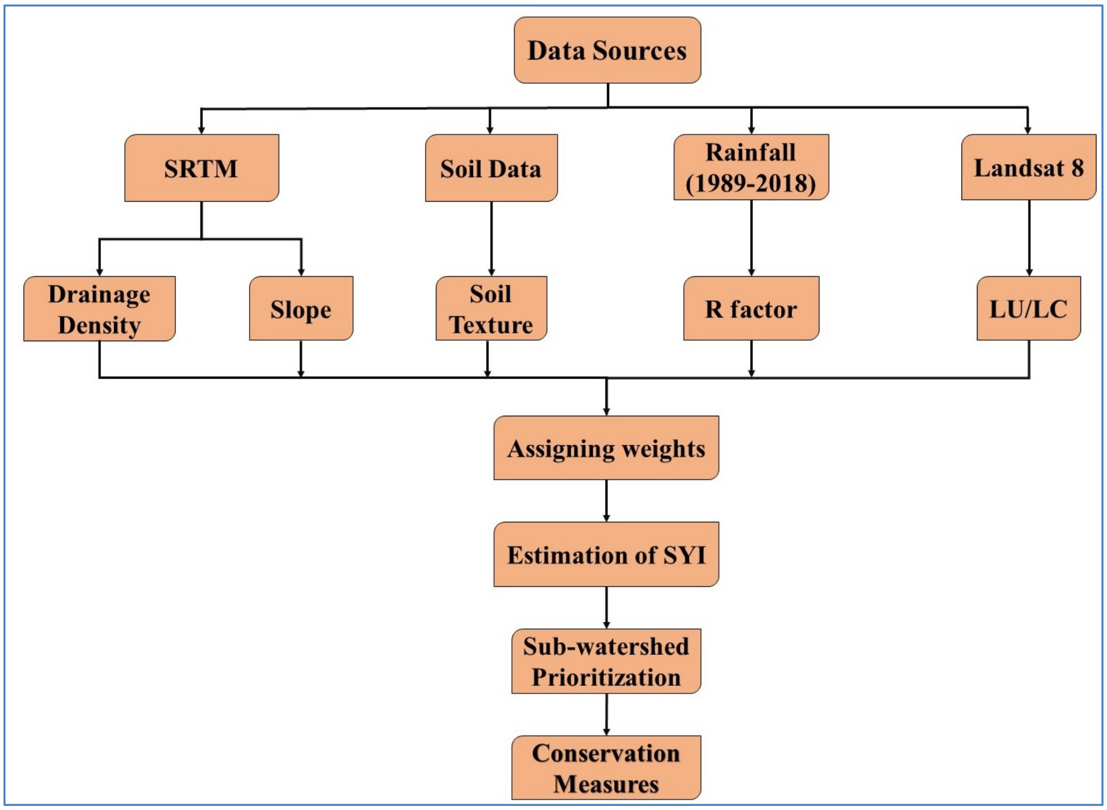

Fig. 2: Comprehensive methodology flow chart for sub-waetershed prioritization.

3. Results

3.1 Land use/land cover (LU/LC) analysis

The land use/land cover is an important criterion for prioritizing a watershed in the semi-arid environment since the hydrological response of the watershed is affected by the land use/cover change and rainfall of a particular watershed (Ibrahim *et al*., 2019). LU/LC pattern of the study area was prepared using Landsat-8 OLI satellite image and nine major LU/LC classes were identified, namely built-up land, single crop, double-crop, current fallow land, degraded forest, forest land, scrubland, waste lands and water bodies. The single crop is predominantly covered with 410.8 sq.km which is about 35% of the total area of the watershed, while forest land covered approximately 147.9 sq. km, account for about 12.6% of the total area of the watershed. Detailed information about the area under different land use/land cover classes is shown in Fig. 3 and Table 2. In SYI model, mainly two LU/LC classes are under consideration which include forest land and single crop.

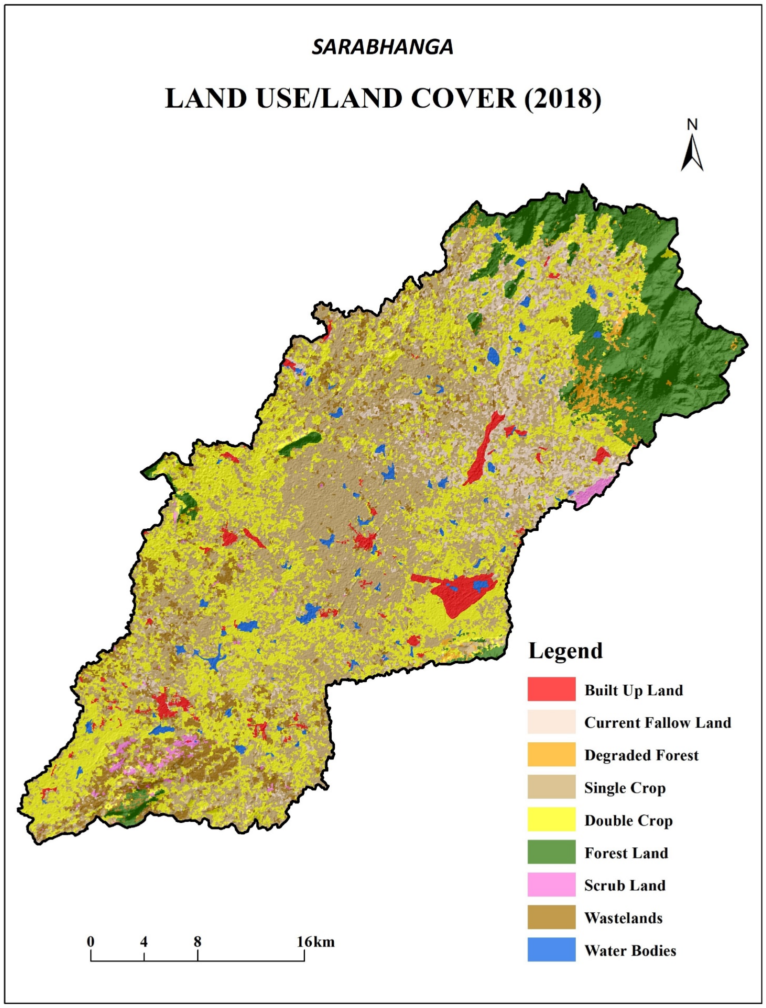

Fig. 3: Land use/land cover map of the Sarabhanga watershed.

Table 2 LU/LC classes of area under different classes.

LU/LC Class	Area (sq. km)	Area (%)
Built Up Land	27.9	2.4
Single Crop	410.8	35.0
Double Crop	386.5	32.9
Current Fallow Land	77.9	6.6
Degraded Forest	13.4	1.1
Forest Land	147.9	12.6
Scrub Land	9.6	0.8
Wastelands	83.1	7.1
Water Bodies	18.2	1.5
Total	**1175.3**	**100.0**

3.2. Delivery ratio

The concept of the delivery ratio is an important factor in the transport of sediments through drainages (Slattery *et al*., 2002; Kinnell, 2004; Beven *et al*., 2005). It is the ratio of the total length of all streams in a watershed divided by the total area of the watershed and it calculates how well or how poorly stream flows drain a watershed. The drainage density depends on both the watershed's climate and physical characteristics, and the delivery ratio values were assigned according to the stream length. Most of the sub-watersheds were assigned 0.6 and 0.8 weight from the delivery ratio according to the drainage density of the Sarabhanga watershed. The average length of the stream in this study is about 1.6 km (Fig. 4a).

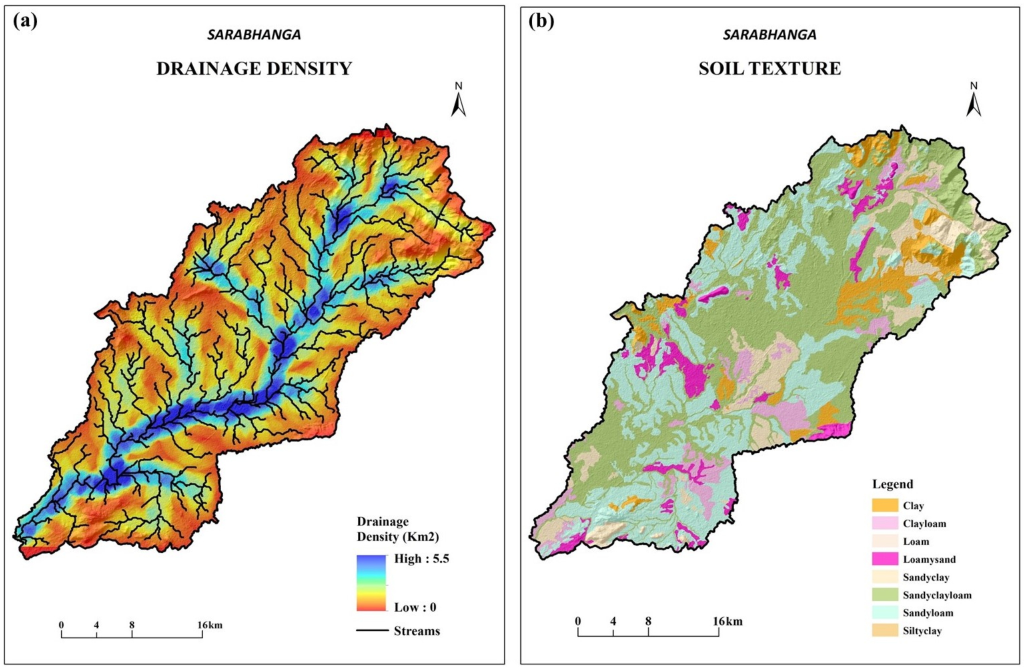

Fig. 4a-4b: Drainage density (a) and Soil texture (b) map.

3.3. Soil texture

The texture of the soil refers to the proportions of sand, silt and clay content which contains in a particular soil and it is considered as an important soil property that affects water holding capacity and base saturation related to agricultural production (Greve *et al*., 2012). The texture is based on less than 2 mm (fine earth) relative particle size. Soil texture map (Fig. 4b) was prepared to explain soil erodibility characteristics in the study area, which plays a significant role in soil erosion impacts. Sandy clay loam soils are the dominant soil class in the watershed, covering with an area of 448.4 sq.km or around 38.1%. Sandy loam and sandy clay soil classes were covered with a watershed area of 315.5 (26.8%) and 117.6 (10%) sq.km. For sandy loam soils, higher weighted values have been assigned because these can be easily eroded compared with other types of soil texture in the study area.

3.4. Rainfall erosivity factor (R)

The rainfall erosivity factor can be described by the interaction of rainfall kinetic energy with the soil surface (Kayet *et al*., 2018). It measures the erosive force caused by the runoff of a given region. If such data are available, the rainfall erosivity factor is often estimated from the intensity of the rainfall. The R factor was associated with precipitation pattern among the region if the soil particles were preserved by rainfall from the eroded region by an area having nearly slope terrain with low erosivity and water ponding (Farhan and Nawaiseh, 2015). The rainfall data collected from fourteen rain gauge stations in and around the study area and prepared a spatial distribution map using an inverse distance weighted (IDW) interpolation method and categorized into classes, with higher weighted values assigned to regions receiving high rainfall (Fig. 5a). The erosivity factor varies from 176.3 to 593.1 MJ mm $ha^{-1}h^{-1}yr^{-1}$. The areas under high rainfall region were assigned higher weightage values.

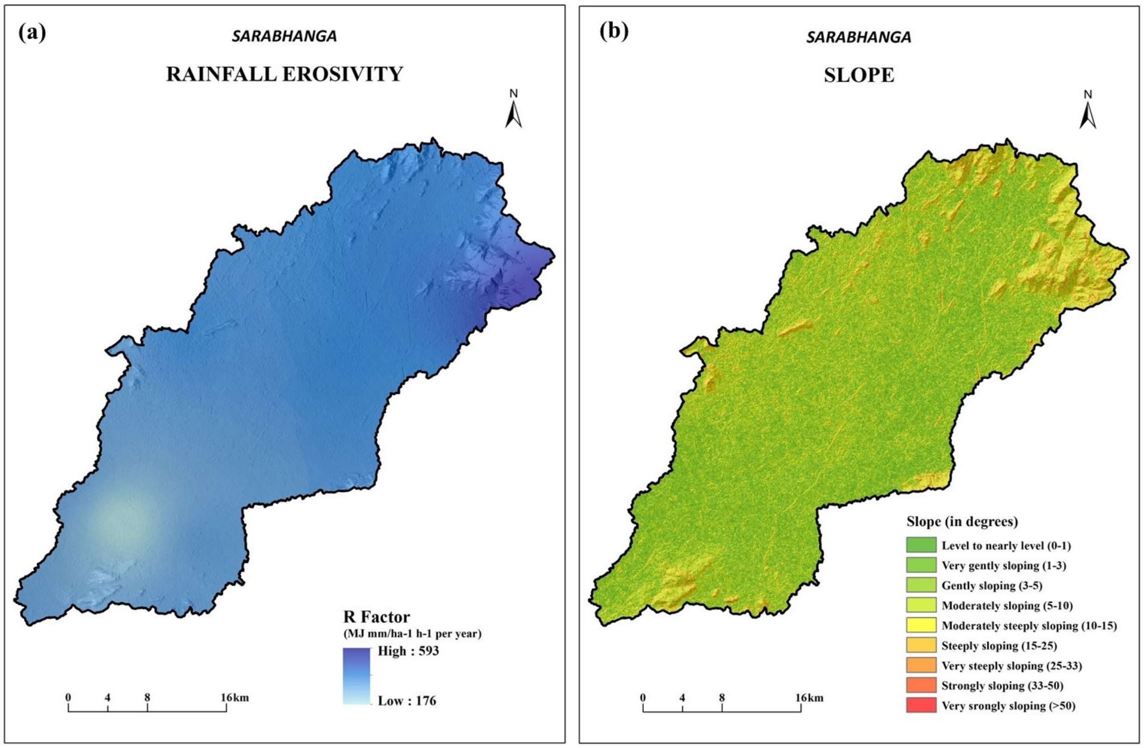

Fig. 5a-5b: Rainfall erosivity (a) and Slope (b) map.

3.5. Slope

The degree of the surface slope has long been considered one of the major factors regulating the volume of run-off and soil erosion in the watershed and thus affects the potential for land utilization. As the slope rises, the type of erosion varies, chiselling the ground into different shapes and thus raising the surface area and thus the number of pores that can absorb water, at least in the initial phase. The steeper the slope, the higher the water flow and the more energy the material will have to move. The slope map (Fig. 5b) was generated from the SRTM DEM and classified by ArcGIS 10.1 software. Lower weighted values were allocated to areas with high altitude areas.

3.6. Estimation of SYI in Sarabhanga watershed

Priority scores were given after the sediment yield indices for each sub-watershed (SBW) were determined (Table 3). A total of 17 sub-watersheds were categorized into low, medium, high and very high priority (critical) classes based on the calculated SYI values (Table 4). The SYI values and associated priority categories are shown in Fig. 6. Out of 17 sub-watersheds, five sub-watersheds (SB-6, SB-3, SB-14, SB-12 and SB-5) were included in the very high priority group, with a higher SYI value (>170) and occupy 584.3 sq.km (49.7%), with limited forest cover, and the barren surfaces having very little colluviums accumulation. The high rainfall and high slope gradient value indicate that these sub-watersheds have a high potential for erosion and sedimentation and deserve immediate attention in order to control further rate of erosion. Through implementing appropriate land management methods, such as contour bunding, vegetative contour barriers, field bunding, gully reclamation, etc., so as to improve soil fertility and increasing soil quality to achieve sustainable agricultural growth.

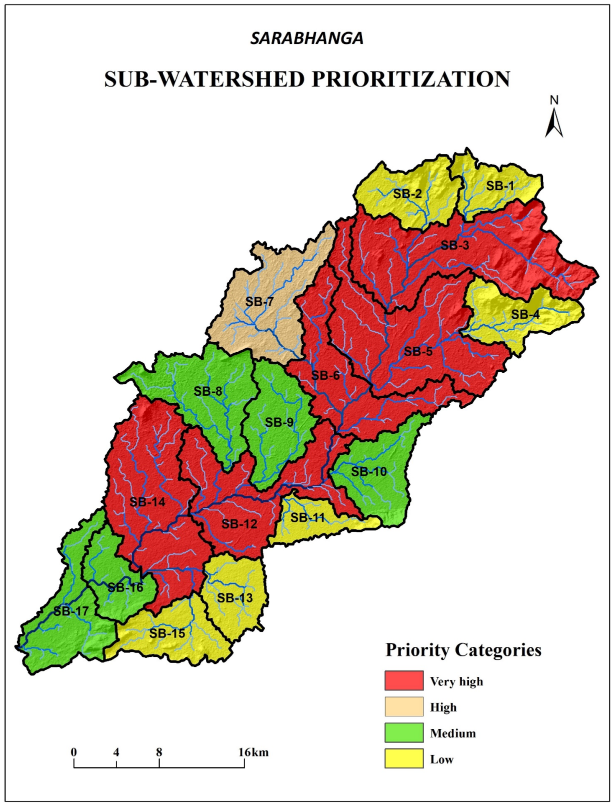

Fig. 6: Sub-watershed prioritization map of Sarabhanga using SYI.

Sub-watershed (SB-7) is in the high priority group with SYI scores between 120 and 170 and spanning the Sarabhanga watershed area by 79.9 sq. km (6.8%). This sub-watershed is located in the eastern part of the Sarabhanga watershed. Approximately half of the sub-watershed area covers the single crop (45.9%) with a sandy loam soil texture (48.9%) of gently sloping wetlands in Sarabhanga. Geomorphologically, this sub-watershed has a medium drainage density and a poorer forest cover so that this unit's erosivity rate is high implying that this watershed faces slightly to the moderate sheet erosion and moderate to severe gully erosion. Because of these adverse conditions, this watershed needs higher priority management and suitable for soil and water conservation measures as well.

Five sub-watersheds (SB-16, SB-10, SB-9, SB-17 and SB-8) fall under the category of medium priority covering 277.7 sq. km and 23.6% of the study area. Such sub-watersheds are well distributed across 17 sub-watersheds. Low slopes were noticed in these sub-watersheds. Due to the low delivery ratio, the SYI values are comparatively less within the range of 70 to 120 and these watersheds more or less free from severe soil erosion, therefore don't need to take any immediate attention towards these sub-watersheds in priority. Six sub-watersheds (SB-1, SB-11, SB-2, SB-13, SB-4 and SB-15) have been placed under low priority category covering an area of 233.4 sq. km (19.9%) of the Sarabhanga watershed area. These sub-watersheds have poor runoff concentration and less than 70 sediment erosivity values. The topography of these sub-watersheds are dominated by flat gentle slope plains.

However, as compared to other sub-watersheds SB-4 is recorded as high SYI values since this region occupied by degraded forest land. This sub-watershed group has comparatively good vegetation cover so that no imminent action is required on soil and water conservation measures

Table 3 SYI Values of sub-watersheds of Sarabhanga with priority classes.

SBW Code	Area (sq.km)	Weightage	DR	SYI	Priority class
SB-1	31.8	11	1.0	29.8	Low
SB-2	45.9	12	1.0	46.8	Low
SB-3	140.3	13	1.4	217.2	Very high
SB-4	45.2	12	1.1	50.8	Low
SB-5	132.8	15	1.4	237.3	Very high
SB-6	85.8	16	1.6	186.8	Very high
SB-7	79.9	16	1.2	130.6	High
SB-8	74.5	14	1.1	97.6	Medium
SB-9	54.0	17	1.2	93.7	Medium
SB-10	51.0	15	1.2	78.1	Medium
SB-11	26.2	14	1.1	34.4	Low
SB-12	100.2	13	2.0	221.7	Very high
SB-13	38.1	14	1.1	49.9	Low
SB-14	125.2	13	1.6	221.6	Very high
SB-15	46.2	15	0.9	53.1	Low
SB-16	36.3	13	1.9	76.4	Medium
SB-17	61.9	12	1.5	94.8	Medium

Table 4 Sub-watersheds under different priority classes.

Priority class	**SYI class**	**SBW code**	**Area (sq.km)**	**Area (%)**
Very high	> 170	SB-6, SB-3, SB-14, SB-12, SB-5	584.3	49.7
High	120-170	SB-7	79.9	6.8
Medium	70-120	SB-16, SB-10, SB-9, SB-17, SB-8	277.7	23.6
Low	< 70	SB-1, SB-11, SB-2, SB-13, SB-4, SB-15	233.4	19.9
			1175.3	**100.0**

3.7. Proposed soil conservation measures for Sarabhanga watershed

There are several factors that can be related to the soil loss experienced in Sarabhanga watershed, including traditional farming methods, human encroachment on vegetated lands, increased population density and lack of awareness. These practices degrade the soil quality in this region and result in increased vulnerability to erosion.

i. The enclosed gabion boxes and stone walls should be built by the SBWs with high SYI values.

ii. Simple, cost-effective conservation interventions such as contour farming, crop covering, conservation farming, check dams, trying to channel terraces, grass strips, social forestry, etc. can contribute significantly to mitigate the soil erosion and soil sedimentation.
iii. To reduce the impacts especially on high slopes of corrosive rainstorms and soil erosion, current fallow and wastelands should be covered with fodder grasses and other cover crops. Better training among farmers will improve the acceptance of conservation programs with the ultimate increase in crop production.
iv. At the same period, policymakers can adopt strict legislation and execute awareness campaigns on unauthorized interference in regions with natural vegetation.

4. Conclusions

In this study, the intensity of soil loss is identified and a method for prioritizing the sub-watershed in Sarabhanga watershed of Tamil Nadu state by integrating topography, vegetation, rainfall erosivity and land use parameters under 17 sub-watersheds is proposed. Of the 17 sub-watersheds, five sub-watersheds (SB-6, SB-3, SB-14, SB-12 and SB-5) came into the extremely high priority category, with a higher SYI value (>170) and covering 584.3 sq. km, about 49.7% of the Sarabhanga watershed due to high rainfall and high slope value imply that these sub-watersheds have a high potential for erosion and sedimentation. Six sub-watersheds (SB-1, SB-11, SB-2, SB-13, SB-4 and SB-15) were classified under a low priority class covering an area of 233.4 sq. km (19.9%) and these sub-watersheds have low amounts of precipitation and less than 70 SYI values. The study reports on strategies which can be introduced for protection. This work may be also extended for other watersheds, where there is severe soil erosion. One of the major causes of erosion in the study area is the development of higher reaching buildings near the Danish pet hills, and the encroachment of farming into vegetated regions. This SYI map is essential as a preliminary study that allows explorers, decision-makers and managers to prioritize the Sarabhanga watershed using the cost-effective conservation interventions such as contour farming, crop covering, conservation farming, check dams, farm ponds, trying to channel terraces, grass strips and social forestry for the better agricultural sustainable development.

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