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# Prioritization of Sub-Watershed Based on Soil Loss Estimation Using RUSLE Model:
## A Case Study of Digaru Watershed, Assam, India

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## ABSTRACT

Soil erosion is one of the most crucial land degradation problems and is considered the most critical environmental hazard worldwide. The present study uses remote sensing data integrated with the geographical information system (GIS) technique and the revised universal soil loss equation (RUSLE) model for assessing the annual average soil loss of the Digaru watershed of India for 1999 and 2020. The estimated mean gross yearly soil loss from the entire watershed was 102716 t yr-1 in 1999 and 178931.6 t yr-1 in 2020. The overall average soil loss rate increased significantly between 1999 and 2020, rising from 4.73 t—ha-1yr-1 to 8.43 t—ha-1yr-1. The sub-watersheds are prioritized as high (≥ 40 t ha−1yr−1), moderate (20–40 t ha−1yr−1), and low (<20 t ha−1yr−1) based on the spatial distribution of soil erosion. Seven sub-watersheds have been grouped under low priority, followed by seven under moderate priority and one under high priority. This study demands instant attention for soil and water conservation efforts in highly eroded watershed areas.

## KEYWORDS

Digaru Watershed, GIS, Land Degradation, RUSLE, Soil Erosion, Sub-Watershed Prioritization

## INTRODUCTION

One of the most serious environmental challenges facing the world today is land degradation, which is threatening many areas across the globe at an alarming rate (Devatha et al., 2015; Olorunfemi et al., 2020). Land degradation happens when natural and anthropogenic processes reduce the land's capacity to sustain crops, livestock, and organisms (Bhan, 2013). Approximately 6 billion hectares of land have been impacted by various forms of land degradation worldwide, including soil erosion, sealing, pollution, salinization, and acidification (Mohammed et al., 2020; Wessels et al., 2007; Kertesz, 2009; Inbar & Zgaier, 2016; Ganasri & Ramesh, 2016, Djoukbala et al., 2018). Soil

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erosion is accelerated by uncontrolled deforestation, poor land use and land management practices, over-grazing, incorrect tillage, and unscientific agricultural practices adopted in the upland areas of watersheds (Arekhi et al., 2012). The most common effects of land degradation are a raised risk of flooding, eutrophication, turbidity, lowered topsoil nutrients, decreased agricultural output, decreased vegetation growth, excessive sedimentation, and other effects (Hlaing et al., 2008; Pradeep et al., 2015; Eniyew et al., 2021, Kebede et al., 2021).

Therefore, throughout the past three decades, watershed-level research has become the subject of both societal concern and hydrological exploration (Wang et al., 2016). Despite being a global problem, soil erosion is more prominent in the tropics and sub-tropics. In India, the sustainability of the human population is seriously threatened by soil erosion, which also jeopardizes the productivity of all other natural ecosystems, including wetlands, grazing, and agriculture. In addition, soil erosion induces aquatic imbalances, harm to drainage systems, declining water bodies and reservoir water quality, and environmental and infrastructural problems (Kumar & Sahu, 2020). The projected overall land degradation in India is estimated at 147 million hectares, of which around 94 million hectares have been degraded by acidity and the rest by flooding, wind erosion, salt, or a combination of these processes (Bhattacharyya et al., 2015).

The north-eastern region of India is endowed with distinct physical characteristics including mountainous topography and torrential downpours with broad spatial fluctuations. Thus, this region is vulnerable to significant soil erosion due to unsustainable and improper land-use practices along the steep hill slopes (Choudhury et al., 2022). To implement successful management techniques, it is necessary to conduct a quantitative and detailed assessment using a scientific database to determine the intensity and severity of soil erosion issues. This will further aid in identifying the probable sites for soil erosion. By implementing necessary strategies and measures, improved planning for soil conservation and agricultural activities could be accomplished (Tiwari et al., 2018). Soil loss estimation at the watershed level and its management through sub-watershed prioritization have been found to be authentic and satisfactory (Naqvi et al., 2012). Various empirical models have been developed to estimate soil loss, followed by watershed prioritization.

The most popular empirical model is the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith in 1965 and refined in 1978 (Wischmeier & Smith, 1978). Furthermore, numerous scholars have employed the new model, the Revised Universal Soil Loss Equation (RUSLE) developed by Renard et al. (1997), in subsequent studies to investigate soil loss estimation. When Geographical Information System (GIS) is combined with remote sensing, the RUSLE can effectively show the regional variance of long-term average soil loss on both a large and small scale (López-Vicente & Navas, 2009; Onori et al., 2006). In the RUSLE model, six important factors are considered: rainfall erosivity (R), soil erodibility factor (K), slope length (L), slope steepness factor (S), cover management factor (C) and conservation practice (P) factor. The model is widely utilized because of its ease of use and simple input parameter calculation compared to other models.

There are several studies conducted globally on soil loss estimation employing USLE and RUSLE models at international level. Hao et al. (2017) conducted a study on the karst basin of Guizhou Province, China to quantify the distribution of soil erosion using the RUSLE model. Their findings emphasised that the average annual soil loss rate of the simulation was 30.24 Mg ha–1 yr–1. Compared with the previous observation result, the RUSLE model performed effectively with the selected sub-models for all the factors. Al-Mamari et al. (2023), focusing on Oman, realized that the RUSLE method has shown potential for predicting soil loss in wadi systems using a GIS environment and satellite remote sensing data. They have estimated a total soil loss of 196,599 ton/ha yr− 1. Mohammed et al. (2020) studied the spatial distribution of soil erosion in the southern part of Syria using a RUSLE-integrating geoinformatics approach, concluding that the integration of GIS and remote sensing technology played a key role in estimating the soil erosion risk in a simple, easy, and scientific way. Further, they have quantified that the potential soil erosion ranged from 1.26 to 350.5 tons' ha− 1 yr− 1, where 5% of the study area showed extreme erosion risk.

Additionally, many similar studies have been carried out in Morocco, Ethiopia, Romania, Sri Lanka, Tunisia, Switzerland, Iran, Nigeria, and more to quantify the soil erosion and their spatial distribution at watershed level (Aouichaty et al., 2022; Eniyew et al., 2021; Kebede et al., 2021; Patriche, 2023; Guduru & Jilo, 2023; Bircher et al., 2019; Olika et al., 2023; Fang et al., 2019; Cheikha et al., 2023; Getu et al., 2022; Ostovari et al., 2017; Joshi et al., 2023; Balabathina et al., 2020). These studies revealed that a massive amount of productive soil is being lost annually, creating risk to food security, livelihoods, and environmental sustainability. A few more studies on soil loss estimation realized that the RUSLE model, in combination with remote sensing and GIS technology, can be effectively used to estimate the priority-based risk-prone areas for further implementation of conservation strategies (Fayas et al., 2019; Avand et al., 2023; Godif & Manjunatha, 2022; Getnet & Mulu, 2021; Paroissien et al., 2015). These studies emphasized the validity of the model and its predictions at ground level, which is generally felt to be complicated. Many Indian studies have also investigated soil loss estimation and their prediction at various scales using the USLE and RUSLE models (Masroor et al., 2022; Mhaske et al., 2021; Sathiyamurthi et al., 2023; Prasannakumar et al., 2012; Achu & Thomas, 2023; Abdul Rahaman et al., 2015; Kumar et al., 2022; Biswas & Pani, 2015). They revealed that advancement in geospatial technologies has enabled effective soil erosion modelling and helped estimate the distribution of soil loss.

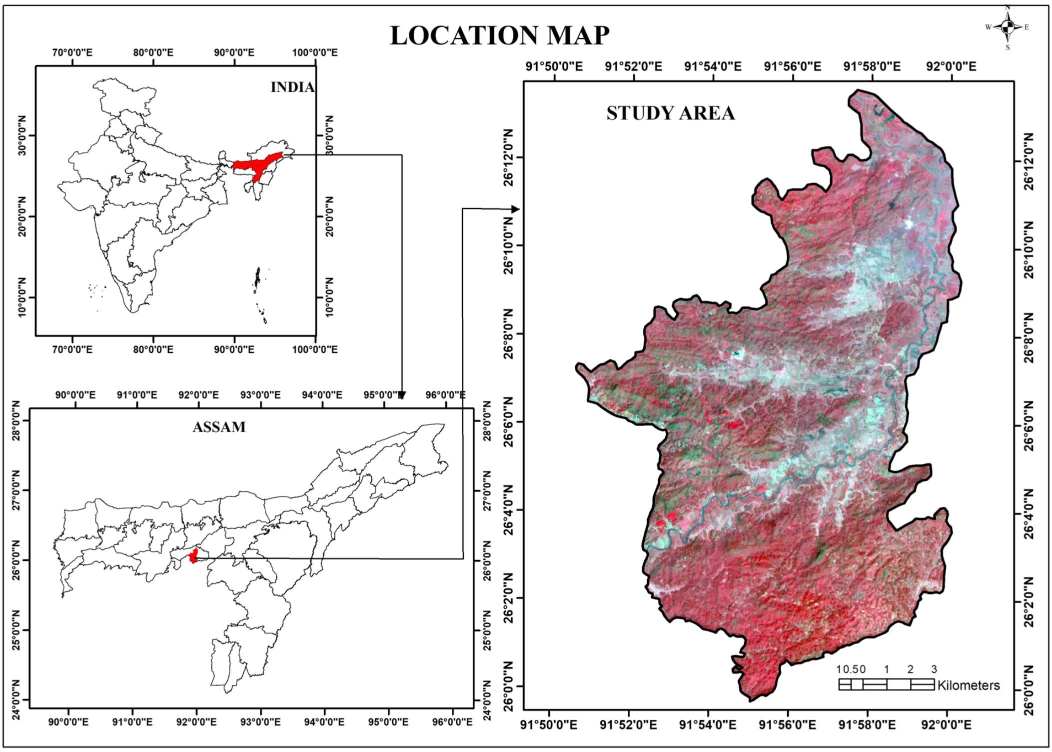
Moreover, some attempts have been made to project soil erosion estimation in a local context such as Assam. Sarma and Dutta (2021) reported that the mean annual soil loss rate in the Palashbari area of Assam was 42 t ha−1yr−1. Sarma and Dutta also revealed that the soil erosion rate in the study area is closely related to the land cover types. Das et al. (2020) found that the average annual soil loss in the Sadiya region of Assam is 5.45 t ha−1yr−1. Their study revealed that the quantity of soil loss is higher in the riverine areas and areas of higher elevation with more gradient. Borgohain et al. (2019) emphasized the importance of the LS factor on soil loss in the Jiadhal river basin of North East India. In her study on the lower Kulsi River basin of Assam, Thakuriah (2023) revealed that high-intensity rainfall, soil characteristics, and cover management are equally important contributing factors to soil erosion.

Several other authors have also investigated the impact of various individual parameters such as LULC, soil, and precipitation on soil loss estimation and prediction (Ran et al., 2012; Wei et al., 2024; Senanayake et al., 2024). However, a detailed analysis of soil loss estimation incorporating all the parameters and further risk-based prioritization for management is yet to be conducted, especially in the north-eastern region of India. Therefore, this research aims to delineate the soil erosion-prone areas and estimate the soil loss at different temporal scales using the RUSLE model in the Digaru watershed of Assam, which is highly vulnerable to soil erosion. Further, this study also incorporates the prioritization of sub-watersheds based on risk for meaningful future planning and management. The study incorporates all the significant factors: *R, K, LS, C,* and *P*. It will provide a significant database for developing soil erosion strategies that would be useful to policy makers, soil scientists, and planners in effectively managing soil erosion in the study area.

## LOCATION

The study was conducted within the lower Digaru watershed, located in the Northeastern region of India. It lies between 25° 30’ 15” N to 26° 14’ 18” N latitude and 91° 34’ 15” E to 92° 0’15” E longitude (see Figure 1), covering a surface area of 217.5 km2. Digaru is a sub-tributary stream of the mighty river Brahmaputra. It rises at an elevation of 1167 meters near a village called Raitong, located in the Khasi hills of Meghalaya. It flows mostly over a geologically controlled rugged terrain and finally debouches into plain areas near Byrnihat, located in the bordering areas of Assam and Meghalaya. The watershed has an altitude range of 200 to 600 meters above mean sea level. The mean minimum and maximum annual temperature ranges from 11°C to 35°C. The annual average rainfall is about 1180 mm per year. The study area incorporates 62 rural villages with an indigenous

Figure 1. Location Map of the Study Area




population whose main occupation is agriculture. Though the study area has four reserve forests, ever-increasing human encroachment in combination with unscientific agricultural development pushes the entire area to a worse situation in terms of land degradation.

## MATERIALS AND METHODS

The present study is based on both primary and secondary data. The datasets used in this study were topographical sheets, DEM, soil, temporal satellite imageries, and rainfall. The watershed has been delineated using the DEM of spatial resolution 10 X 10 m, which was downloaded from Advanced Land Observation Satellite (ALOS) PALSAR (Alaska Satellite Facility, *n.d.*). The delineated watershed was further modified using the Survey of India (SOI) topographical map (78 N/16, 78 O/9) at 1:50000 scale. The present study is a kind of longitudinal study which involves a variety of data collected for different temporal periods. Monthly rainfall data for the period 1990-1999 and 2000-2020 from six rain gauge stations, located within and outside the study area, were collected from various government offices and other government of India undertaking agencies. These rainfall data have been used later to prepare the rainfall maps in the GIS environment. The soil texture map was collected from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Government of India, and accordingly the study area has been clipped from the collected map. The satellite data, namely Landsat TM 5 for the year 1999 and Landsat OLI 8 for the year 2020, have been acquired from *EarthExplorer* (United States Geological Survey, *n.d.*). The spatial resolution of the acquired satellite imageries is 30 meters. The land use/ land cover polygons, as seen in the satellite data of the study area, have been delineated on screen using the NRSA standard classification system, and a preliminary thematic map has been prepared (Deka & Kumar, 2023). Before initial interpretation, all the imageries of different years have been rectified, and various image enhancement techniques, namely contrast enhancement and histogram equalization, have been adopted for a better view of the land use/land cover patches (Abdulaziz, 2009). The already prepared preliminary LU/LC maps have been modified and finalised after the field visit.

### Revised Universal Soil Loss Equation (RUSLE)

The RUSLE is an empirical model widely employed in estimating soil erosion in India (Saha et al., 2022; Thomas et al., 2018a; Rajbanshi & Bhattacharyya, 2020; Thomas et al., 2018b). The USLE determines soil loss at any particular location, which considers the energy and intensity of rainfall, soil erodibility, slope length, slope gradient, soil cover, and conservation measures (Wischmeier & Smith, 1978). Although the RUSLE is essentially the same as the USLE, it incorporates additional complex calculations for soil cover and conservation techniques and updates to the slope length and slope gradient calculations (Renard et al., 1997). The model's requirement for clear and simple computational inputs compared to other models has made it widely employed. The soil loss rate from an area strongly depends upon its soil, vegetation, and topographic and climatic characteristics. These factors usually vary significantly within a watershed's various parts (Das, 2017). RUSLE provides an improved means of computing all these factors and is used in Equation 1 (Guduru & Jilo, 2023):

$$A=R*K*LS*C*P, \tag{1}$$

where $A$ is the amount of soil loss in tons' ha−1 yr−1, $R$ is the rainfall erosivity factor, $K$ is the soil erodibility factor, $LS$ is the slope length and steepness factor, $C$ is cropping and land-cover, and $P$ is the conservation practice factor. The input factors for the RUSLE model in this study were adapted to Indian conditions.

After quantifying the soil loss of the Digaru watershed for different years, the watershed has been further subdivided into 15 micro-watersheds based on the drainage network delineated from the DEM and topographical sheet. Further, the prioritization of sub-watersheds has been accomplished based on the mean soil loss value calculation of each sub-watershed. The following flow chart depicts the entire methodology, from data preparation to soil loss estimation and prioritization of micro watershed using the RUSLE model (Figure 2).

## DATA PREPARATION

### Rainfall Erosivity (*R*) Factor

Rainfall erosivity is the prime factor and is defined as the aggressiveness of rain to cause erosion (Wu et al., 2018). The data indicates that when factors other than rainfall are held constant, soil losses from cultivated fields are directly proportional to a rainstorm parameter. Many scholars have attempted to estimate rainfall erosivity using rainfall data with long-term time intervals for various parts of the planet (Parveen & Kumar, 2012; Shamshad et al., 2008). The rainfall erosivity factor ($R$) was calculated based on ten years' and twenty years' annual average rainfall data during different periods, namely 1990-1999 and 2000-2020, here in this research. Six rainfall stations exist in and near the study area: Morigaon, Digaru, Umtru, Nongpoh, Nongkyrnih, and Barapani (Table 1). The rainfall data was interpolated using the inverse weighted distance (IWD) method in Arc GIS software with a cell size of 30 meters. In this study, the final $R$ factor map has been prepared using the formula suggested by the Central Soil and Water Conservation Research Training Institute (1981):

$$R= 79+0.363*R_{N,} \tag{2}$$

where $R_N$ is the average annual rainfall in mm.

**Figure 2. Flow Chart Showing Steps for Soil Loss Estimation and Sub-Watershed Prioritization**

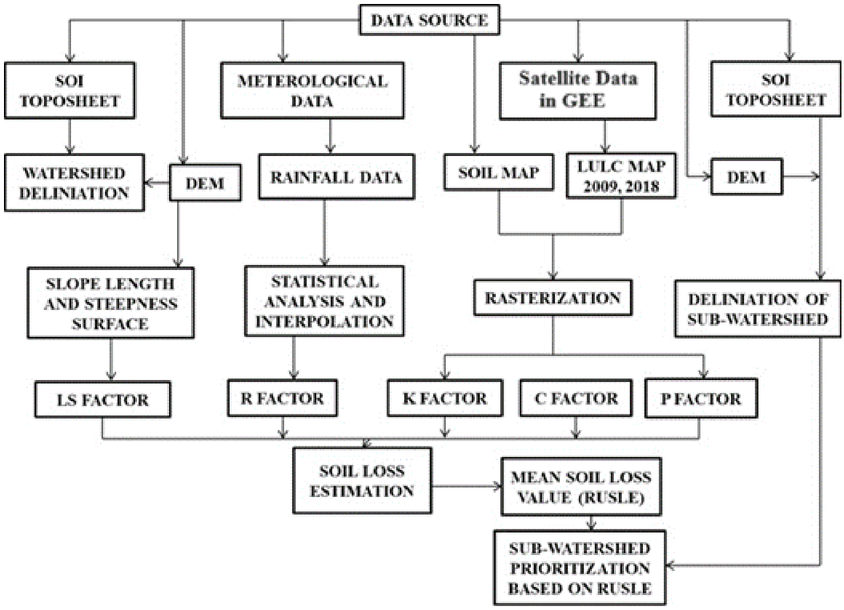



**Table 1. Station Wise Rainfall in Different Station for 1990-1999 and 2000-2020**

| Name of the Station | Coordinates | Annual Average (1990-1999) | Annual Average (2000-2020) |
|---|---|---|---|
| | (Latitudes and Longitudes) | rainfall in mm | Rainfall in mm |
| Digaru | 26°14’0.35”N & 91°56’25.17”E | 1240 | 1180 |
| Umtru | 26°0’42.21”N & 91°49’13.57”E | 2434 | 2116 |
| Nongpu | 25°52’11.69”N & 91°50’1.40”E | 2194 | 2063 |
| Borapani | 25°40’36.50”N & 91°55’37.29”E | 2662.8 | 2331 |
| Morigaon | 26°15’10.38”N & 92°20’13.04”E | 1357 | 1263 |
| Nongkyrnih | 25°34’17.49”N & 91°53’49.27”E | 2175 | 2016 |

*Source: Office of the* Indian Council of Agricultural Research, Shillong and Guwahati

## Soil Erodibility (*K*) Factor

Soil erodibility factor (*K*) is one of the essential variables influencing soil erosion, which is often defined as the rate of soil loss per erosion index unit and expresses how susceptible a particular type of soil is to erosion (Wischmeier & Smith, 1978; Balabathina et al., 2020). The influential determining factors of soil erodibility include soil texture, structure, depth, drainage ability, and organic matter level (Eniyew et al., 2021). The soil texture map published by the National Bureau of Soil Survey and Land Use Planning (NBSSLUP) was used to prepare the *K* factor map. The USDA 1978 soil erodibility nomograph was used to get the equivalent *K* values for each type of soil by considering the permeability class, organic matter content, and particle size (United States Department of Agriculture, 1978).

### Slope Length and Steepness (*LS*) Factor

*LS* is the standardized plot's ratio to observed soil loss (Endalamaw et al., 2021; Bircher et al., 2019; El Jazouli et al., 2017). It combines slope steepness (*S*) and slope length (*L*) factors. The rate of soil erosion is determined by the slope's length and steepness, where a higher rate of soil erosion develops on the longer and steeper slope (Sinshaw et al., 2021). In this study, the *LS* factor was calculated using the following formula (equation 3) suggested by Wischmeier and Smith (1978):

$$LS = ((\text{Flow accumulation} * \text{resolution of the pixel}/22.1)\ \hat{}\ *(0.065+0.045*\text{slope}+0.065*(\text{slope})^2), \tag{3}$$

where ^ =Slope Category Value as per percentage

ALOS Palsar DEM of 12.5-meter resolution was employed to calculate flow accumulation and slope using spatial analysis tools in Arc GIS software. Further, a raster calculator in Arc GIS was used to calculate the *LS* value, and the map was produced accordingly.

### Cover Management (*C*) Factor

The vegetation cover is one of the most influential factors controlling soil erosion (Chen et al., 2021). The *C* factor is defined as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier & Smith, 1978). The value of *C* mainly depends on the vegetation cover percentage and growth stage. It indicates the soil protection level under a specific category of land use/land cover (Olika et al., 2023). The *C* factor ranges between 0–1, where the value 0 corresponds to high plant cover with complete resistant to soil erosion, and the value close to 1 denotes high susceptibility to soil erosion with no forest canopy protection (Renard et al., 1997; Panditharathne et al., 2019). In this study, the values of the *C* factor have been assigned according to the LU/LC category, which has already been delineated using satellite data for two different years.

### Support Practice (P) Factor

The support practice (*P*) factor refers to the ratio of soil erosion with a particular land management practice to its equivalent soil loss along the slope (Wischmeier & Smith, 1978; Renard et al., 1997). These practices primarily alter erosion by lowering the quantity and velocity of runoff and altering the flow pattern, slope, or direction of surface runoff (Renard et al., 1997; Panagos et al., 2015). Human knowledge in the form of field data is essential to understanding soil erosion control (Naqvi et al., 2013). If unavailable, the *P* factor could be determined from the slope and LU/LC type without field data (Wischmeier & Smith, 1978). Since there is no well-documented data about the type of management or support practice undertaken in the Digaru watershed, the *P* factor value has been introduced in this study based on the USDA handbook. For assigning the *P* value, LULC of Digaru watershed was categorized into cropland and non-cropland. The values of the *P* factor are assigned between 0–1, in which the value near 1 is assigned to areas with no cropland regardless of slope consideration. In contrast, a value near 0 corresponds to cropland areas.

### Results and Discussion

The spatial distribution of soil erosion was evaluated and quantified by cell-by-cell raster calculation using all the RUSLE model parameters layers, namely rainfall erosivity, soil erodibility, topographic (LS) factor, cover management, and support practice factors in the GIS environment.

### Rainfall Erosivity *(R)* Factor

The rainfall stations in and within the study area considered for this research show significant variations. The rainfall stations, namely Barapani, Nongpu, Umtru, and Nongkyrnih, located in the foothills and uphills of Meghalaya, receive the maximum average annual rainfall, whereas the stations in Digaru and Marigaon, located in the floodplains, received less rainfall than the other four stations during the study periods (Table 1). In the study area, the *R* factor ranges between 529 MJ mm ha-1h-1y-1 and 888 MJ mm ha-1h-1y-1 during 1991-1999 and between 507 MJ mm ha-1h-1y-1 and 795 MJ mm ha-1h-1y-1 during 2000-2020. The *R* factor maps depict that the southern part of the Digaru watershed has relatively higher *R* values than the rest of the area of the watershed (Figure 3). More than 71.25% of the total rainfall in all the stations occurs during monsoon season, which is from May to September. Such a massive volume of rainfall within a few months largely contributes to high surface runoff, resulting in more soil erosion.

## Soil Erodibility *(K)* Factor

The soil texture of the Digaru watershed has been grouped into four categories, namely alluvial soil (coarse loamy and silty), alluvial soil (fine loamy), hill soil (fine loamy and skeletal) and hill soil (fine loamy and clayey). The *K* factor equation used in this study allows the variability of derived *K* factor value from 0.09 t h MJ−1 mm−1 in fine loamy texture to 0.87 t h MJ−1 mm−1 in coarse loamy and silty texture (Figure 4). The soil texture fine loamy and skeletal and fine loamy and clayey corresponds to moderate *K* factor value. A higher *K* value corresponds to more susceptibility to erosion (Adornado et al., 2009).

## Slope Length and Steepness Factor (*LS*)

The *LS* factor is the most significant factor when the watershed lies in the hilly terrains. The Digaru watershed is characterized by a high topographic nature where more than 70% of the total area of the watershed falls within the average slope category of 5o to 15o. This kind of slope generally aggravates

**Figure 3. R Factor Map 1990-1999 and 2000-2020**

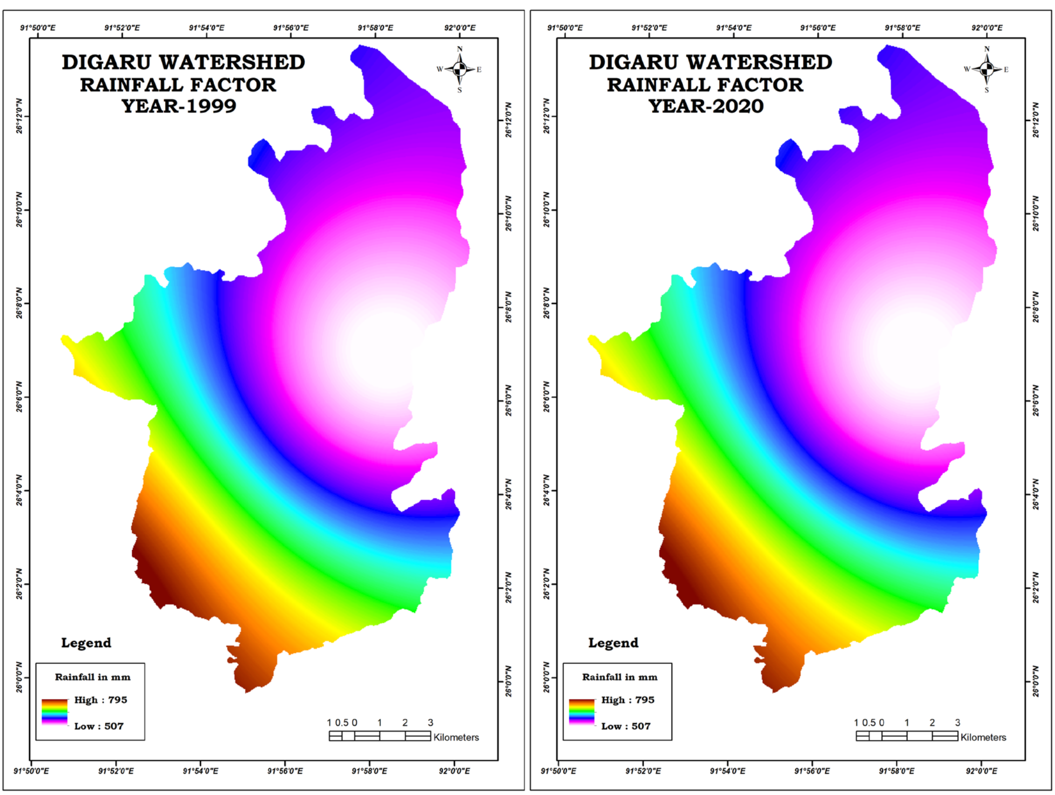
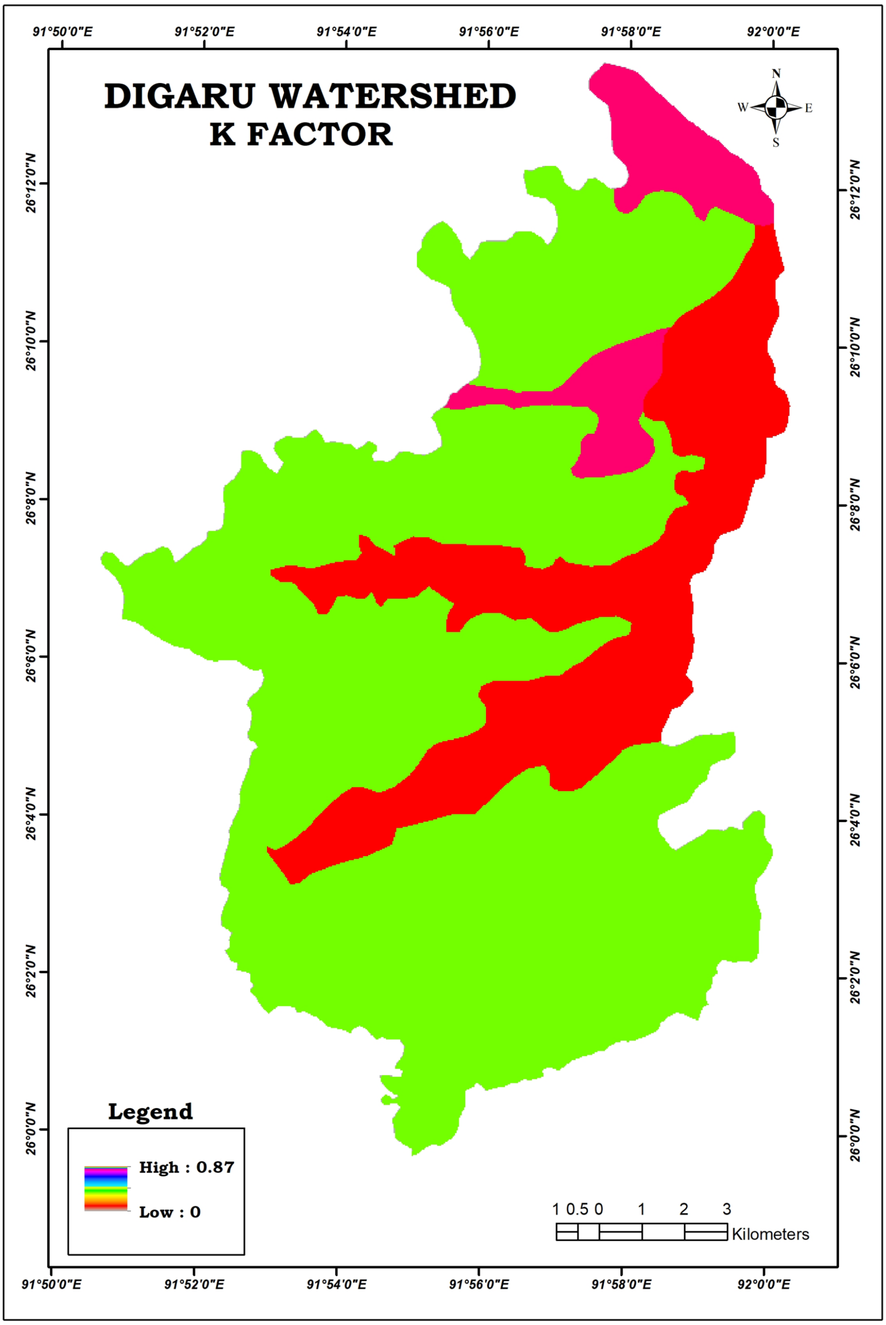
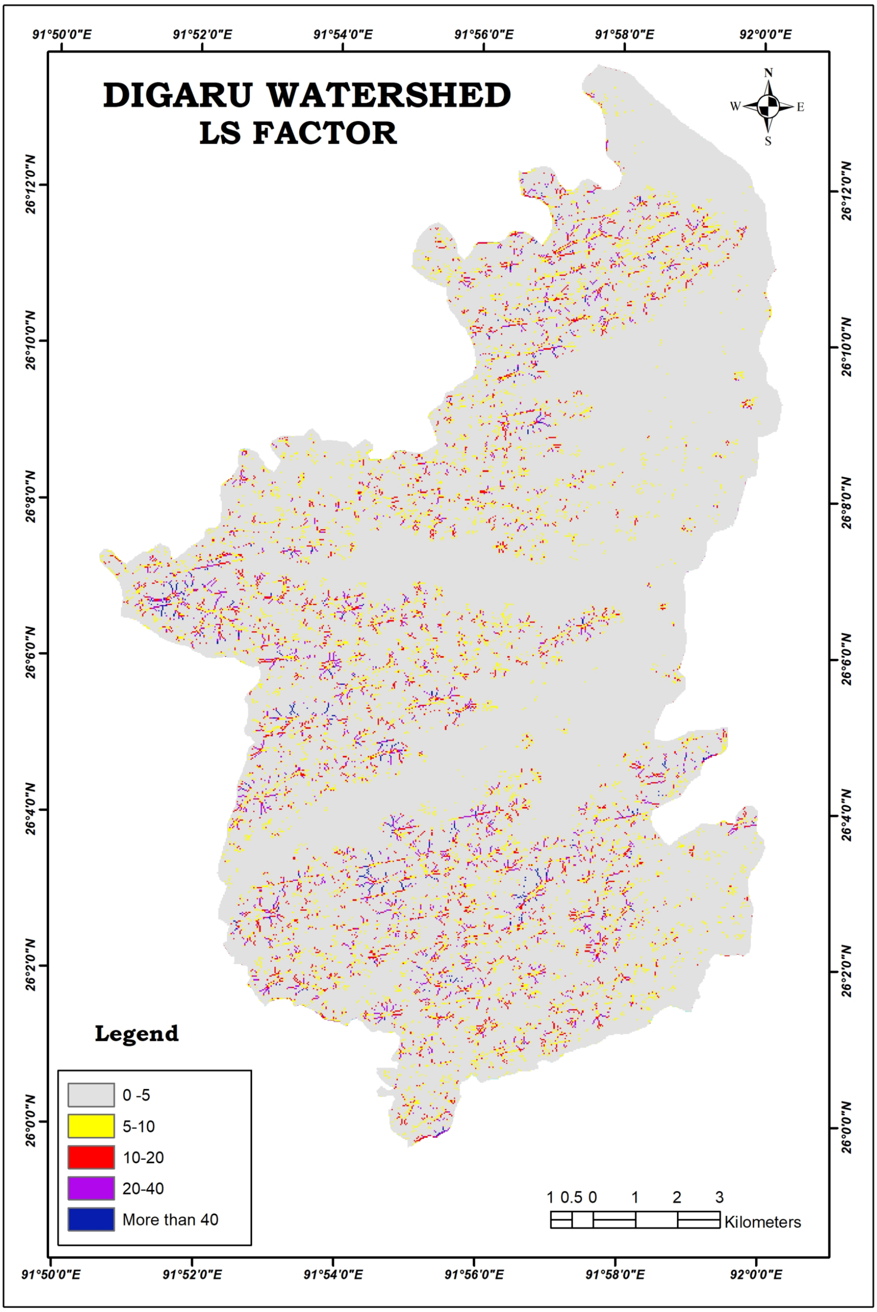


**Figure 4. K Factor Map, 2018**




rainfall-driven rills and inter-rill soil erosion (Getu et al., 2022). The *LS* factor in the study area ranged from near 0 to 50 (Figure 5). It has been clearly observed that the *LS* factor increases with increasing slope steepness and flow accumulation. When the slope length increases, the opportunity for accumulation and concentration of runoff water increases; slope steepness also accelerates the runoff velocity (Brady & Weil, 2003; Wischmeier & Smith, 1978).

**Figure 5. LS Factor Map**




## Cover Management (*C*) Factor

The classification of satellite imagery for assessing the pattern of LU/LC in the Digaru watershed has been undertaken employing the visual interpretation technique. Multi-temporal satellite data, namely Landsat 5 TM for 1999 and Landsat 8 OLI for 2020, have been used during the preparation of LU/LC maps. Based on the knowledge gathered during the field visit, the selected imageries have been classified into nine LU/LC categories: dense forest, open forest cropland, fallow land, barren land, scrub forest, dense scrub, mixed built-up land, and waterbody (Figure 6). The LU/LC statistics revealed that the forest cover has significantly decreased in 2020 (16.59%) compared to 60.13% in 1999.

In contrast, scrub forest has been increased manifold from 0.96% in 1999 to 25.02% in 2020. Similarly, the barren land category has also grown from 0.002% in 1999 to 6.62% in 2020. The overall coverage of the cropland category has fallen from 5.1% in 1999 to 2.2% in 2020. The LU/LC statistics reveal an eye-catching alteration in various categories observed in the study area during the research period. The field visit also demonstrates a similar situation. Though the study area comprised parts of five reserve forests in the hills, continuous human encroachment alters the forest area of the reserve forest into scrub and barren land, favouring soil erosion (Sharma et al., 2011; Deka & Sharma, 2012).

Moreover, the establishment of 15 brick industries during the last two decades converted the agricultural lands to barren land in the recent past and also enhanced the soil erosion near the Digaru River (Deka & Kumar, 2023). Based on the LU/LC category, the C factor values were assigned to each category, and accordingly, *C* factor maps were generated for the years 1999 and 2020 (Figure 7). The *C* factor values in this study range from near 0 to 1, where near 0 indicates bare surface cover, which has a more significant contribution to reducing detachment and overland flow as well as soil erosion rate (Ma et al., 2021).

## Support Practice *(P)* Factor

The *P* factor values, like the *C* factor, have been incorporated in the LULC maps for different years. After putting the values from the available literature, the *P* factor maps for both years were generated

**Figure 6. LULC Map of the Study Area, 1999 and 2020**

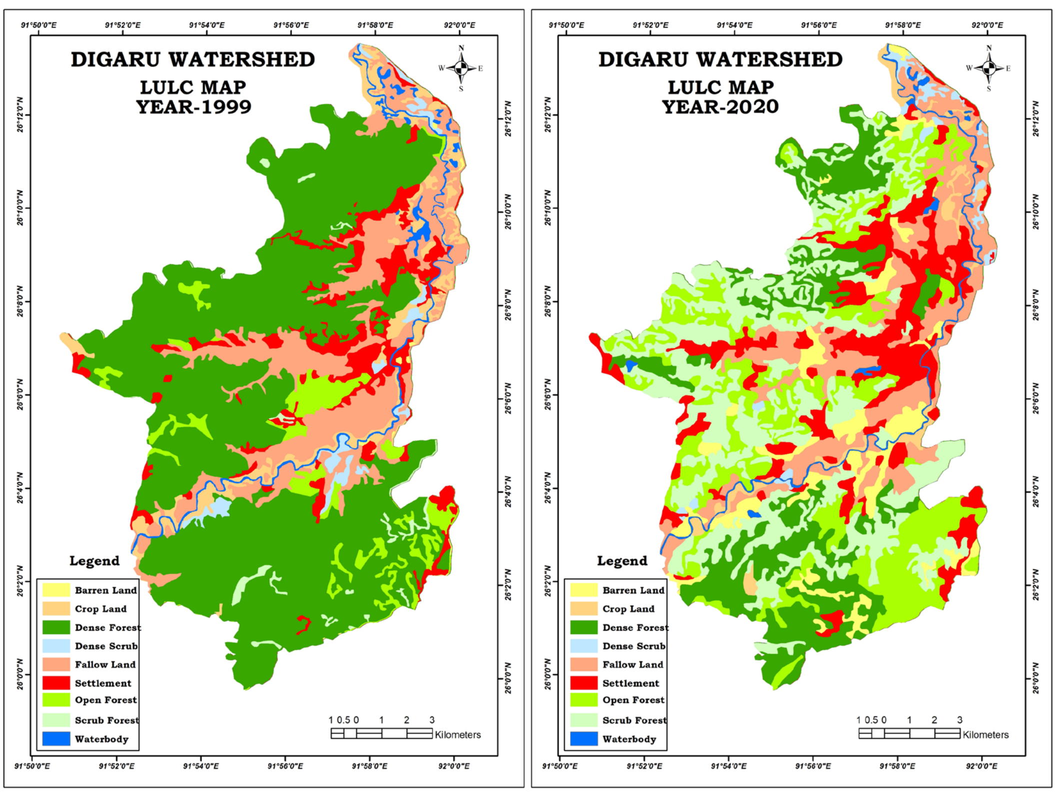
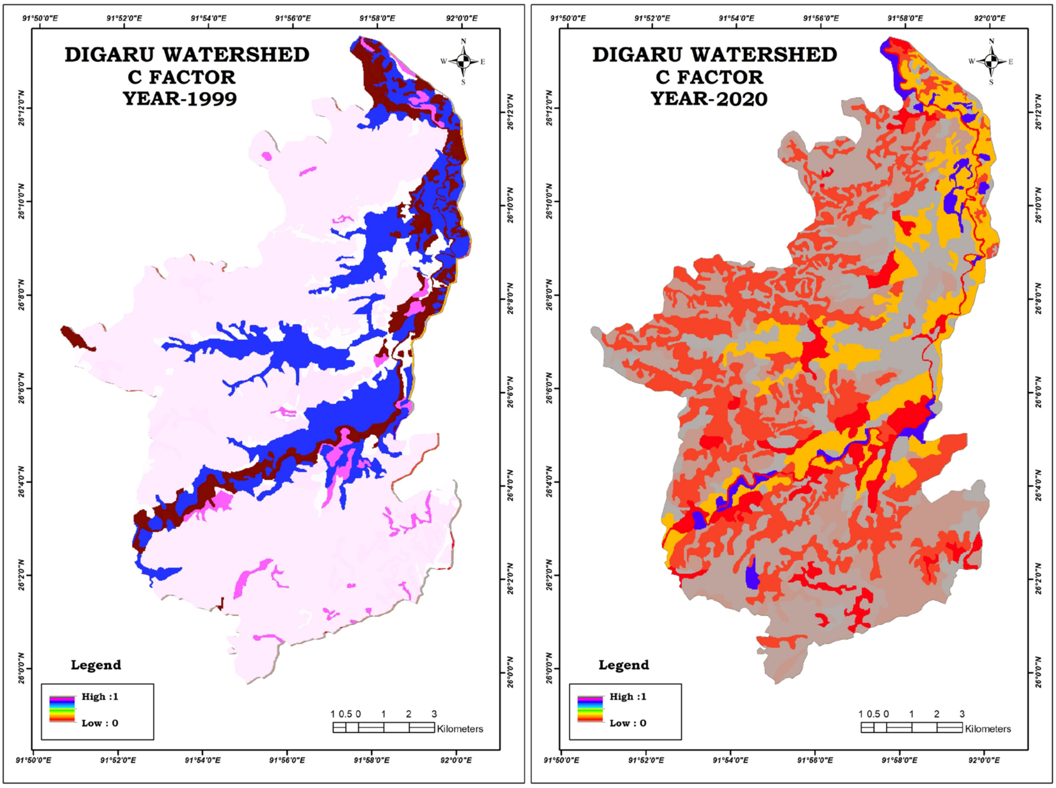


Figure 7. C Factor Map, 1999 and 2020

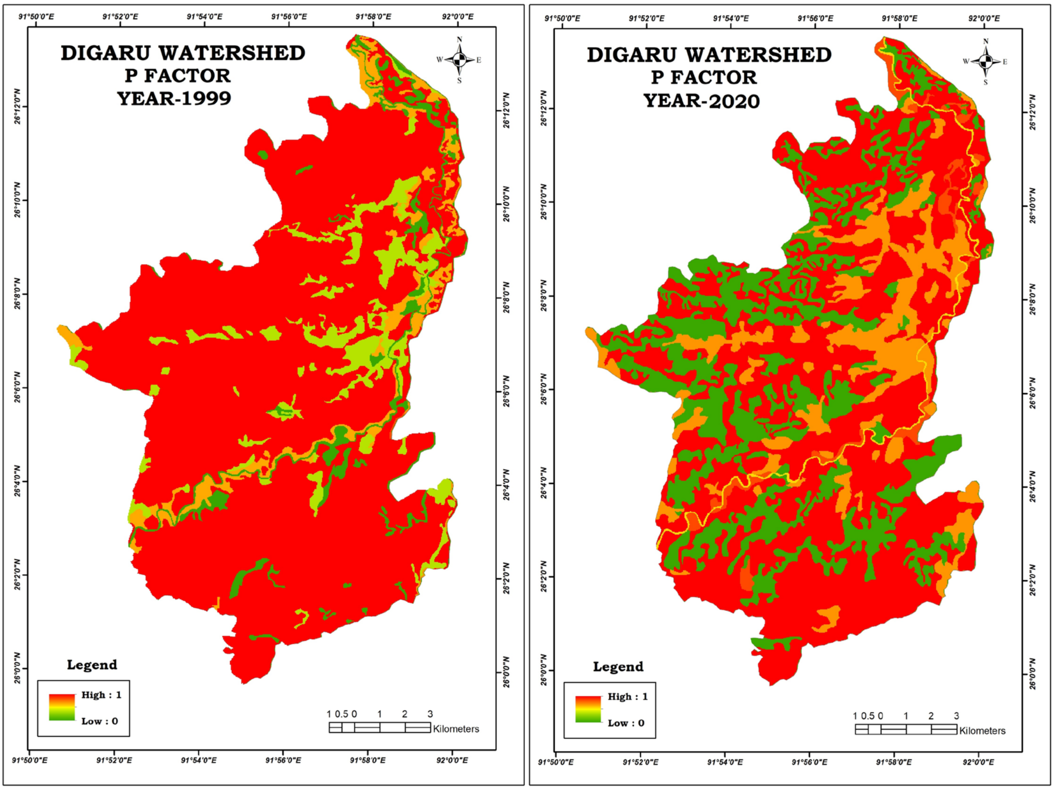



in raster format. Spatial variation of *P* values has been observed throughout the watershed in both 1999 and 2020. *P* values range between near 0 and 1, while closeness to 1 indicates the absence of conservation practice and vice versa (Figure 8).

## SOIL LOSS ESTIMATION

The total soil loss of the Digaru watershed for 2020 was 178931.6 t—yr-1 with a mean soil erosion rate of 8.24 t ha−1yr−1. Similarly, for 1999, the estimated soil loss was 102711.6 t—yr-1 with a mean soil erosion rate of 4.73 t ha−1yr−1. The results were correlated with similar studies carried out in different parts of the world. Similar results were obtained in the Wadi El-Ham watershed by Djoukbala et al. (2018), who reported an estimated 3 to 5.7 t ha−1yr−1 of annual soil loss; in the Languedoc watershed in Peyne, France, Paroissien et al. (2015) estimated an average soil loss of 4.2 t ha−1yr−1. Furthermore, according to Fang et al. (2019), the average soil loss in China's Yangtze river basin was 3.89 t ha− 1y− 1, and Thomas et al. (2018b), in the Muthirapuzha river basin of India, estimated the average soil erosion as 3.60 t ha−1yr−1. Masroor et al. (2022) estimated the soil loss as 9.88 t ha−1yr−1 in the Godavari middle sub basin, India, and Fayas et al. (2019) estimated the mean soil loss as 10.88 t ha−1yr−1 in the Kelani River basin of Sri Lanka. At the local level, similar results have been obtained, as Das et al. (2020) estimated the mean soil loss as 5.45 t ha−1yr−1 in the Sadiya region of Assam, and Jaiswal et al. (2014) estimated the average soil loss as 2.08 t ha−1yr−1in the Pachnoi River basin of Assam. However, as compared to the above-mentioned studies, the results of the present study revealed that the rate of soil loss has significantly increased over 21 years. Erosion of soil

Figure 8. P Factor Map, 1999 and 2020




above 1 t ha−1y−1 is deemed irreversible (Khosrokhani & Pradhan, 2014). Though rainfall was found to be lower during 2000-2020 than 1990-1999, other parameters significantly contribute to the total soil loss estimated in the Digaru watershed.

In order to understand the variation of the severity of soil loss, the study area is classified into five categories: slight (≤ 2 t ha−1yr−1), low (2-5 t ha−1yr−1), moderate (5-10 t ha−1yr−1), high (10-25 t ha−1yr−1), and very high (≥ 25 t ha−1yr−1) (Figure 9). This classification was adopted based on slight modification of different soil erosion intensities in Indian conditions, as suggested by Singh et al. (1992). The results revealed that during 1999, nearly 84% of the total area of the watershed was prone to slight erosion (≤ 2 t ha−1yr−1), whereas 3.79% of the area experienced a very high rate of soil erosion (≥ 25 t ha−1yr−1). Similarly, during 2020, the estimated value revealed that 82.67% of the total area experienced slight erosion (≤ 2 t ha−1yr−1), and only 3.86% falls in the category of very high (≥ 25 t ha−1yr−1) rate of soil erosion (Table 2). The various categories of soil loss in both years are irregularly distributed across the watershed and correspond to various parameters considered for the study. The bare exposed surface areas with high *LS* and *R* factor values exhibit severe erosion. The results are verified by multiple field visits. It is observed that the parts of four reserved forests located within the watershed are severely prone to deforestation and agricultural activities. Additionally, 15 brick and 18 coke industries have been established during the last 30 years, expanding their territory to 77 hectares of land. The brick industries are located along the Digaru River, and the coke industries are mostly located in the adjoining areas of Assam and Meghalaya.

Figure 9. Average Soil Loss Map, 1999 and 2020

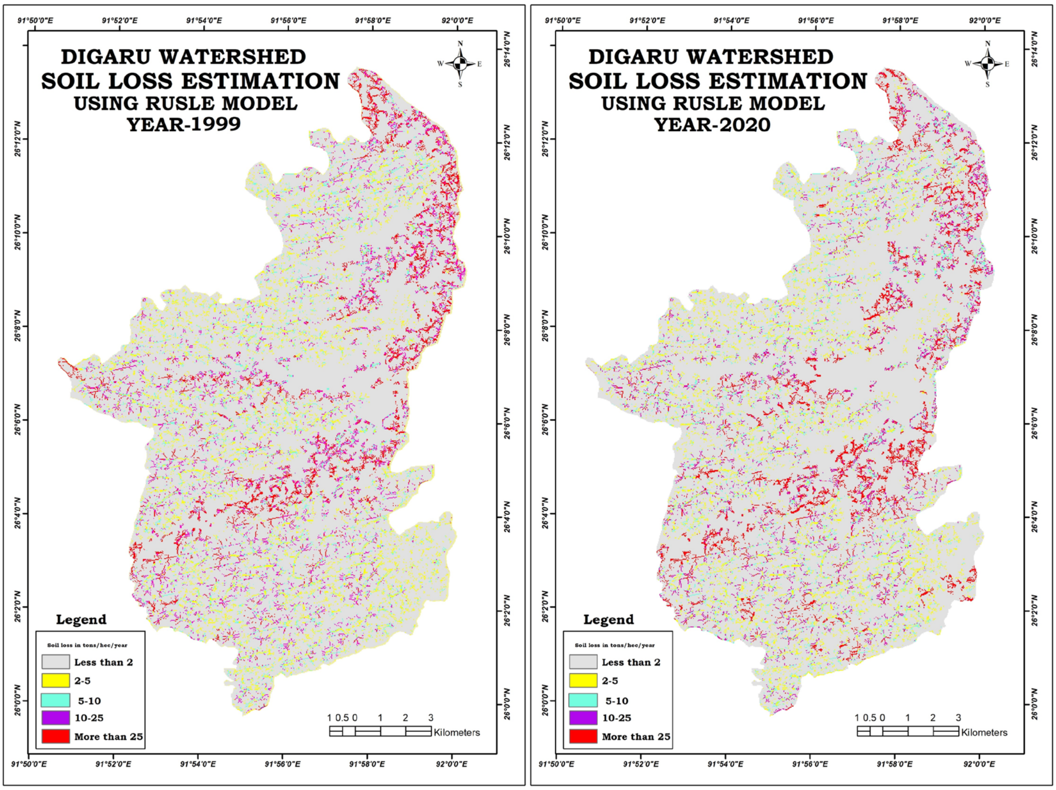



Table 2. Percentage-Wise Area Covered by Different Soil Loss Category for 1999 and 2020

| Soil Loss in t $ha^{-1}yr^{-1}$ | Area (Hectare) | | % of the Total Area of the Watershed | |
|---|---|---|---|---|
| | Year (1990) | Year (2020) | Year (1990) | Year (2020) |
| $\leq 2$ | 18297 | 17943 | 84.30 | 82.67 |
| 2-5 | 1010 | 1091 | 4.65 | 5.02 |
| 5-10 | 795 | 908 | 3.66 | 4.18 |
| 10-25 | 777 | 923 | 3.58 | 4.25 |
| $\geq 25$ | 824 | 838 | 3.79 | 3.86 |

*Source:* Calculated from the average soil loss map.

## PRIORITIZATION OF SUB WATERSHED

Due to variations in the input parameters like rainfall, topography, soil, LULC, and management, uniform soil loss and severity cannot be revealed (Bekele & Gemi, 2021). Spatial variation in soil erosion is prevalent, and prioritization is necessary for conservational measures (Avand et al., 2023; Godif & Manjunatha, 2022). Hence, the identification of soil erosion hotspots and prioritization of sub-watersheds has been evaluated based on soil loss estimation for 2020. Digaru is a 5th-order stream with a good drainage network. Based on DEM and the available drainage network identified from the topographical sheet, the Digaru watershed has been divided into 15 numbers of sub-watersheds (Figures 10 and 11).

The sub-watersheds have been assigned priority values ranging from high, moderate, and low based on the mean value of soil loss for each sub-watershed. The mean estimated value has been calculated after individually clipping the soil loss map as per the sub-watershed boundary

**Figure 10. Digital Elevation Model**

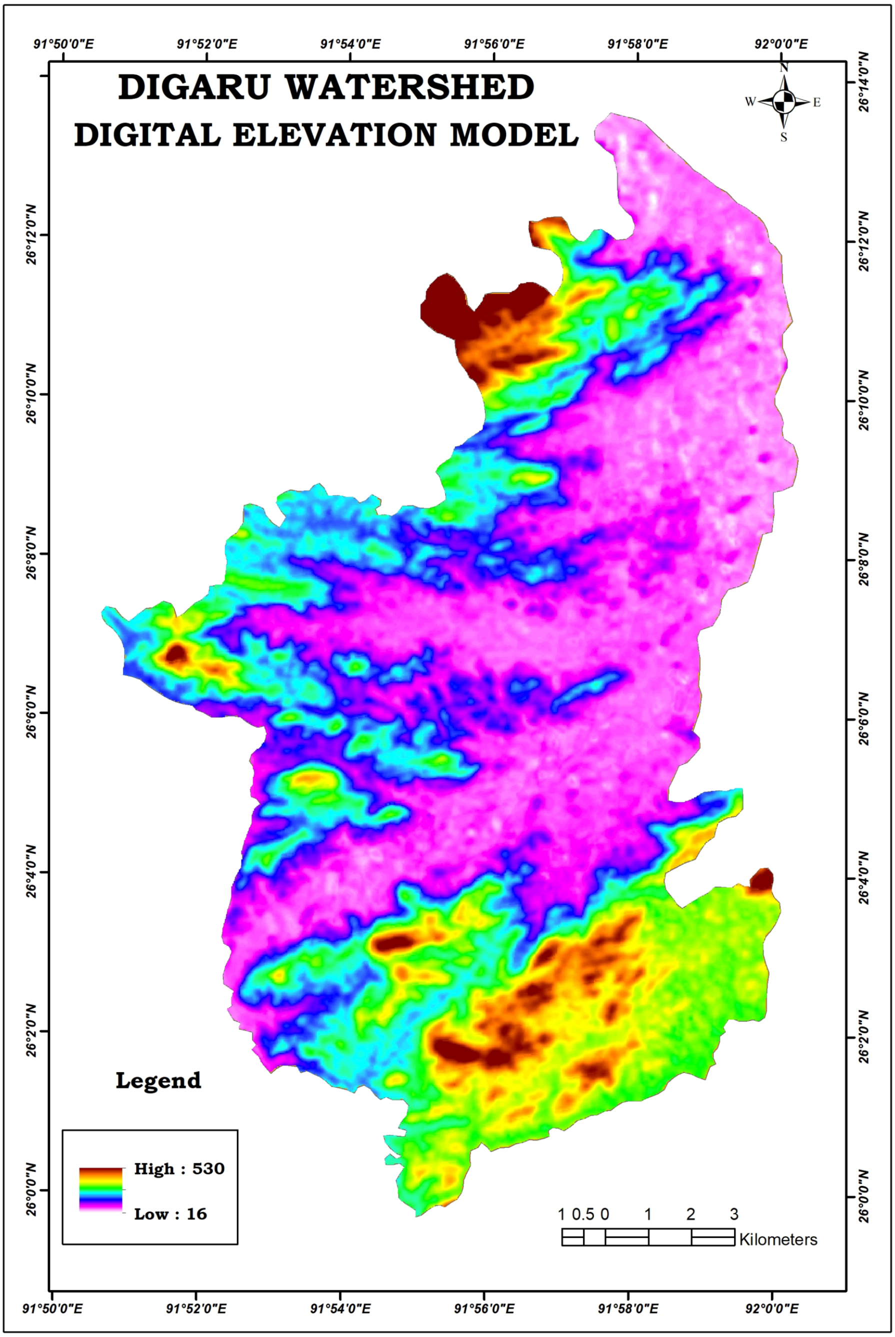
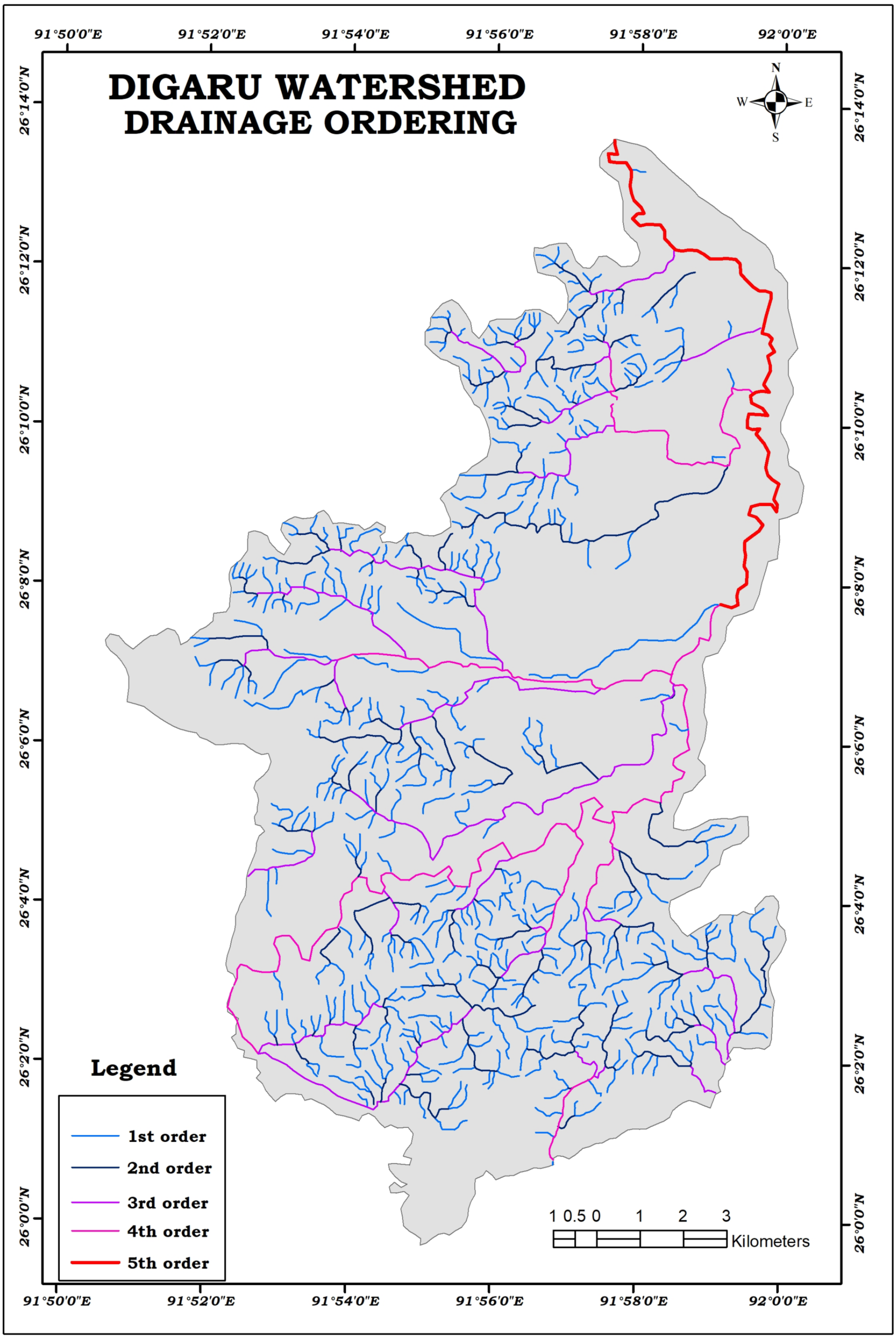
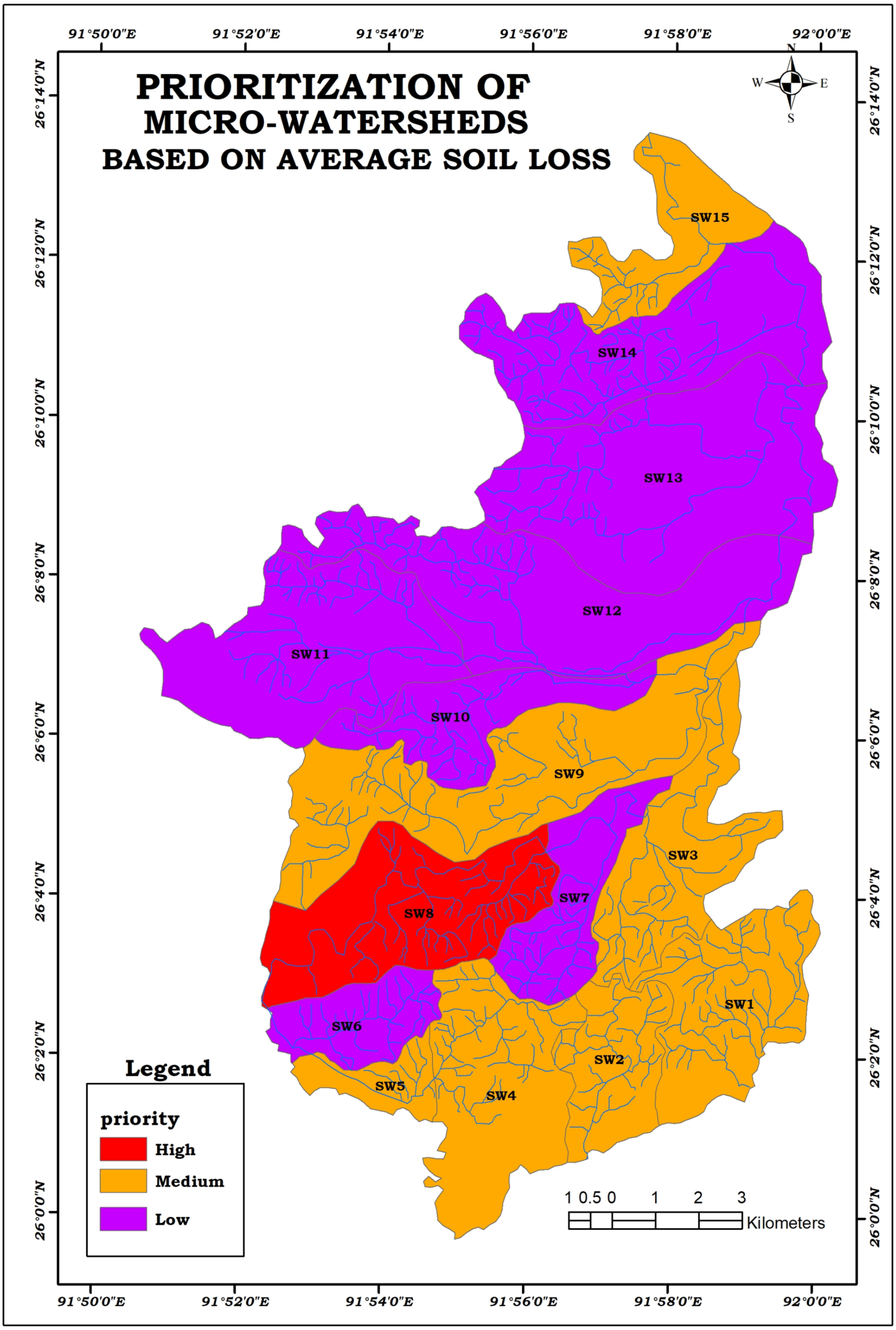


**Figure 11. Drainage Network**




(Figure 12). It has been observed that out of a total of 15 micro-watersheds, the highest average soil loss (49.8 t ha−1yr−1) was found in SW 8 followed by SW 2 (35.12 t ha−1yr−1), SW4 (30.56 t ha−1yr−1), SW 3 (29.17 t ha−1yr−1), and SW 5 (29.11t ha−1yr−1), respectively. The

Figure 12. Prioritization of Sub-Watersheds




lowest average soil loss has been observed in SW 11 (5.45 t ha−1yr−1), followed by SW 12 (6.43 t ha−1yr−1) and SW 13 (12.14 t ha−1yr−1). Based on the field observation and the local context, three priority classes, namely high (≥ 40 t ha−1yr−1), moderate (20-40 t ha−1yr−1), and low

(<20 t ha−1yr−1), have been assigned according to their average soil loss. It is estimated that out of the total 15 sub-watersheds, seven sub-watersheds covering 114.95 km2 have been included in the low priority category, the other seven sub-watersheds covering 75.78 $km^2$ have fallen in the moderate category, and the rest, that is SW 8, having the area of 16.98 $km^2$, has been given the highest priority based on highest mean soil loss (Table 3).

**Table 3. Prioritization of Sub-Watershed on the Basis of Mean Soil Loss**

| Sl. No | Sub-Watershed Code | Mean Value of Soil Loss (t $ha^{-1}yr^{-1}$) | Priority Rank | Area in (Km2 |
|---|---|---|---|---|
| 1 | SW13 | 12.14 | 3 | 27.99 |
| 2 | SW14 | 14.03 | 3 | 19.92 |
| 3 | SW15 | 28.96 | 2 | 8.56 |
| 4 | SW11 | 5.45 | 3 | 20.33 |
| 5 | SW12 | 6.43 | 3 | 22.94 |
| 6 | SW9 | 23.79 | 2 | 23.87 |
| 7 | SW10 | 13.48 | 3 | 9.23 |
| 8 | SW7 | 17.63 | 3 | 8.34 |
| 9 | SW8 | 49.8 | 1 | 16.98 |
| 10 | SW4 | 30.56 | 2 | 15.51 |
| 11 | SW1 | 29.11 | 2 | 13.20 |
| 12 | SW6 | 15.25 | 3 | 6.20 |
| 13 | SW5 | 29.11 | 2 | 3.45 |
| 14 | SW2 | 35.12 | 2 | 8.05 |
| 15 | SW3 | 29.17 | 2 | 12.89 |

## CONCLUSION

This study primarily estimates the average annual soil erosion in the Digaru watershed using GIS integrated RUSLE model. It demonstrates that the GIS systems combined with the RUSLE model is a practical and relevant method for assessing spatial variability of soil erosion. The present study reveals that soil erosion in the study area is primarily induced by deforestation in the reserve forests and mere negligence in conservation practices. The estimated annual gross soil loss from the entire watershed for the years 1999 and 2020 was 102711.6 t—yr-1 and 178931.6 t—yr-1, respectively. There was a significant increase in the overall average soil loss rate from 4.73 t—ha-1yr-1 in 1999 to 8.43 t—ha-1yr-1 in 2020. The mean soil loss at the sub-watershed level varies between 5.45 t ha−1yr−1 to 49.8 t ha−1yr−1. Marked spatial variation in the soil loss has been recorded within the study area. Based on the spatial distribution of soil erosion, the sub watersheds are prioritized as high (≥ 40 t ha−1yr−1), moderate (20-40 t ha−1yr−1), and low (<20 t ha−1yr−1) where seven sub-watersheds have been grouped under low priority followed by seven under moderate priority and one sub-watershed under high priority. The areas more prone to severe soil loss correspond to uncontrolled human encroachment, especially in the reserve forests in the study area's hills and the brick kilns near the Digaru River. High population pressure, overgrazing and over-cultivation in the reserve forests, the establishment of industries near the river and foothills, and poor conservation practices are the prime drivers for land degradation in the Digaru watershed. Strict rules and regulations must be implemented urgently to protect the reserve forests and croplands from human encroachment, including expanding industrial territory. Conservation tillage, buffer strips, and minimum cultivation and soil terracing in the high priority risk areas should be introduced immediately for effective management. For further studies, experimental plots should be conducted to validate the RUSLE model. Micro level study using a village cadastral map may be adopted for precise understanding of the cause-effect relationship of soil degradation in the study area.

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