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Soil Erosion and Sediment Analysis of Tawa Reservoir, District Narmadapuram M.P. using Remote Sensing and GIS

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Abstract

Soil erosion and sediment problem is becoming severe due to the effect of land degradation, soil fertility and agricultural production. It is one of the serious environmental problems. Thus, the investigation of soil erosion and sediment analysis risk is very crucial. The present study aims to estimate the potential soil erosion in Tawa Reservoir of Madhya Pradesh using Revised Universal Soil Loss Equation (RUSLE) model by integrating with Remote Sensing and GIS technology. The study area constitutes different types of soil like sandy_clay_loam, Loam & Clay and is embedded with the sandy-clay-loam. RUSLE model is used to calculate rainfall erosivity (R), Soil erodibilty (K), and topographic factor (LS), cover management(C) and support practice (P). The sediment analysis input are taken from NASA Power Data and processed in ArcGIS and ArcSWAT software. It is found that the values of above parameters are ranging from 5022.6 to 5798.73 (R), 0.1135 to 0.1403 (K), 0 to 385.033 (LS), 0.083 to 0.858 (C) and 0.20 to 0.89 (P) respectively and used for calculating soil erosion. The actual and potential soil erosion estimated in the Tawa Reservoir is 8, 28,505 (ty-) and 2, 31,283 (ty-). An updated LULC map of the study area is prepared using Sentinel-2 10 m resolution having features like water bodies, agricultural land, barren land, built up land and forest. The output of both the map i.e. actual and potential is classified into 5 categories. The effect of the drainage density has also shown the soil loss by overlaying the drainage density map on the soil erosion. After the calculation of discharge and sediment the graph is plotted between the year and rainfall, year and discharge, sediment and rainfall and finally in between the sediment and discharge.

Keywords: ArcSWAT; RUSLE model; Sediment erosion

Introduction

Soil erosion occurs as a result of changes in agricultural practices, agricultural intensification, land degradation and global climate change [1]. Soil erosion is the major problem for a river basin as it removes nutrient that is essential for the growth of the plants and increases sedimentation of the river channel and reservoirs [2]. The soil erosion process is modified by biophysical environment comprising soil, climate, terrain, ground cover and interactions between them. Important terrain characteristics influencing the mechanism of soil erosion are slope, length, aspect and shape. Substantial efforts have been spent on the development of soil erosion models [3]. Soil erosion and degradation of land resources are significant problems in a large number of countries [4, 5]. Often, a quantitative assessment [6] is needed to infer on the extent and magnitude of soil erosion problems so that sound management strategies can be developed on a regional basis with the help of field measurements. The main problem in relation to the erosion risk models is the validation, because of scarcely available data for comparing the estimates of the models with actual soil losses [7, 8]. Several soil erosion models exist with varying degrees of complexity. One of the most widely applied empirical models for assessing the sheet and rill erosion is the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith in 1965.

Study area

Tawa reservoir is a reservoir located on the Tawa River in central India. The study area lies in the Narmada

River valley. The Tawa River is the longest tributary of the Narmada, rising in the Satpura Range to the

South and flowing north to meet the Narmada at the village of Bandra Basin. The Tawa Reservoir lies in

The south-central region of the district. The Tawa Reservoir geographical coordinates are 77°40´ to 78°42´

Longitude to 21°47´ to 22°37´ latitude is shown in the (Figure 1).

Materials and Methodology

Data from satellite and global facilities were used for the study. Sources of data are listed in below.

Description of the data is provided in the forthcoming sections.

Satellite Data

Sentinel-2: The Sentinel-2 image is used for the identification and creation of LULC to generate a P factor map. The data is easily downloaded from the Copernicus. The Sentinel 2A and 2B systems are identical and represent one of five families being undertaken in support of Copernicus. All the bands of 10-m spatial resolution are being used except the 20-m and 30-m spatial resolution. Three tiles are used to cover the entire study area.

LISS-III: The LISSIII-image is used for the generation of the C-factor map. The LISS-III is a multispectral camera operating in four spectral bands, three in the visible and near infrared and one in

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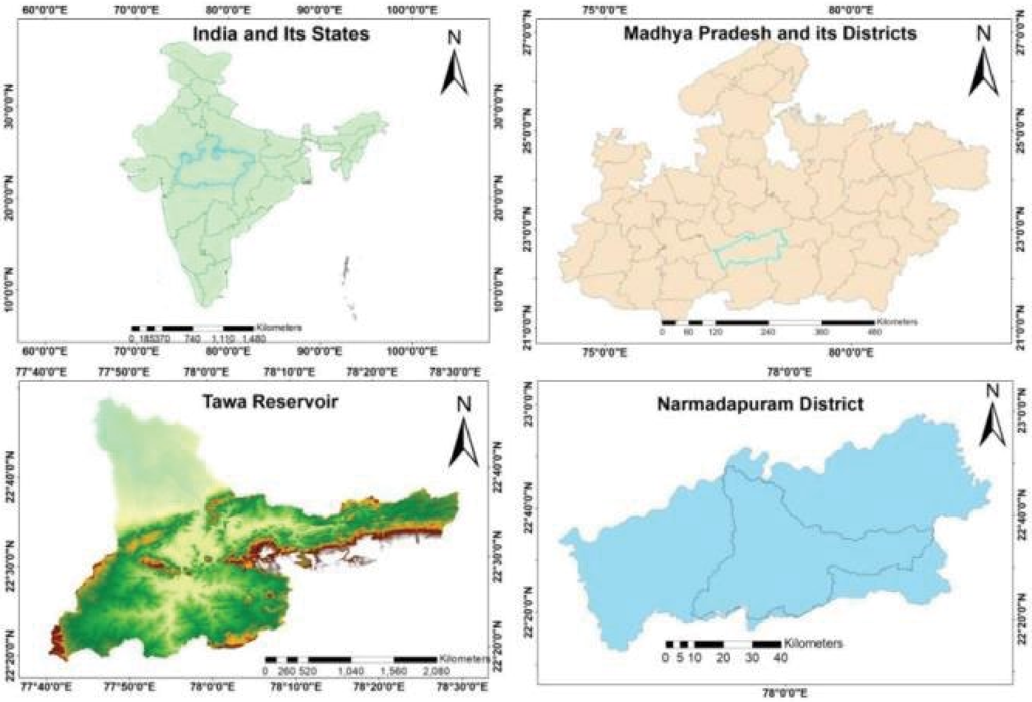

Figure 1: Location map of the study area.

the SWIR region, as in the case of IRS-1C/1D. The LISS-III camera is identical to the LISS-III flown in IRS-1C/1D spacecraft except that the spatial resolution of SWIR band (B5) is also 23.5 m (same as that of B2, B3, B4). LISS-III covers a swath of 141 Km in all the 4 bands. Seven tiles are being used to cover the entire study area. Seven tiles are being used to cover the entire study area. The image is easily downloaded from the BHUVAN NRSC portal.

STRM DEM: SRTM Digital Elevation Model is used in this study. The SRTM DEM is easily accessible from the USGS Earth Explorer. The National Aeronautics and Space Administration (NASA) and the

National Geospatial-Intelligence Agency (NGA) collaborated on an international project to collect radar data for the first near-global set of land elevations. Arc-Second SRTM 1 Global elevation data encompass the entire globe with void filled data at a resolution of 1 arc-second (30 meters) and allow for open sharing of this high resolution global data set.

Weather data: The temperature, precipitation, relative humidity, solar radiation and wind speed is taken from the NASA power data to make input for the SWAT Model.

Rainfall data: Annual rainfall data is collected from the Climatic Research Unit. This information is available in main gridded format which is one of the high resolution products and available free of cost in an easily usable format.

Soil data: Soil properties for the study area are acquired from the FAO Digital Soil Map of the World (DSMW).

Methodology

The main focus of the study is to integrate soil erosion factors (R, K, LS, C, and P) for getting the potential and actual soil erosion scenario over the Tawa Reservoir, i.e. Tawa Watershed. Overall methodological framework and data analysis are presented in (Figure 2).

Estimation of actual and potential soil erosion

Soil erosion estimation model

The revised universal soil loss equation (RUSLE) model was adopted to assess the soil erosion as reported by [9]. It is a statistical model developed to estimate the annual soil loss per unit area [10]. Hence, we have estimated the parameters of the RUSLE model based on the rainfall events; DEM, soil properties, and land cover data [11, 12, 13]. The map algebra functions were used to calculate erosion from each element in the raster data format through the following equation [14]:

A= R * K* LS*C*PWhere A = soil loss (t ha−1 year−1), R = rainfall erosivity factor (mm ha−1 year−1), K = soil erodibility factor (t ha−1 year−1), LS=slope-length and slope steepness factor (dimensionless), C=land management factor (dimensionless), and P=conservation practice factor (dimensionless). The multiplier of the initial three factors, i.e. R, K, and LS, leads to the potential soil erosion while all the parameters together (Eq. 5) resulted in actual soil erosion (Biswas and Pani 2015).

Preparation and computation of RUSLE parameter

Rainfall erosivity factor (R)

This rainfall erosion factor (R) indicates the potential erosivity of soil based on amount and intensity of

Precipitation at a particular location [15, 14]. It represents and quantifies the impacts of raindrop size, rainfall amount, rate of run of, and the ability of rainfall to trigger soil erosion development [16, 17, 14], which is expressed in mm ha−1 h−1 year−1. R is the long-term annual average rainfall event and represents the kinetic energy of raindrops which cause soil erosion [18]. In this study, daily rainfall data have been used to measure annual average rainfall using 10 years of data (2011–2021). The rainfall erosivity factor is calculated using.

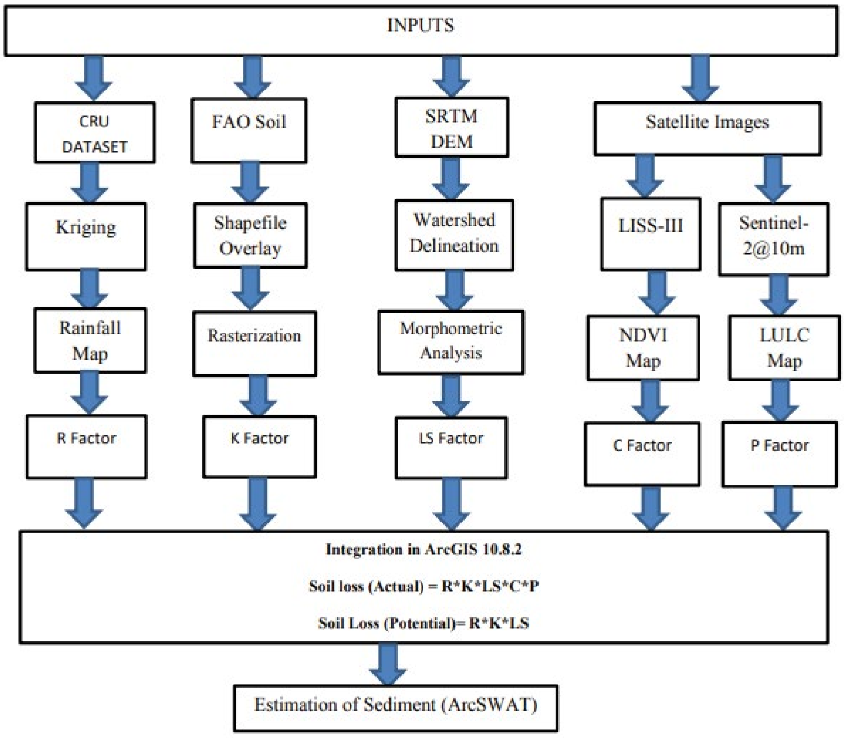

Figure 2: Flowchart of methodology adopted for the study.

$R=\sum_{i=1}^{12}1.735*10^{\left(1.5\log\frac{pi^2}{P}-0.8188\right)}$ Where p_i the monthly amounts of precipitation and pare is annual precipitation. . The annual summation $\frac{pi^2}{p}$ is called Fournier equation developed by (Wischmeier and Smith (1978) and modified by Arnoldus (1980).

Soil erodibility factor (K)

Soil erodibility factor (K) refers to the rate of soil susceptibility to detachment and transport of soil particles by amount and rate of rainfall and runoff [19, 14]. The K-factor is determined and influenced by the detachability of the soil, soil texture, structure, organic matter, the permeability of soil profile, infiltration, runoff, and the transportability of the sediment eroded from the soil [20, 21, 14]. It ranged on a scale from 0 to 1, where 0 indicates soil with resistive or least susceptibility to erosion, and 1 reflects the soil with high susceptibility to erosion by water [19]. Depending on the type of soil, erodibility of soil is an important index for evaluating susceptibility of soil to erosion by water. Since the type of soil is known the K factor is calculated as the product of the individual soil contributing to the erodibilty. The mathematical expression employed in calculating the K- factor is given by.

The expression for calculating the K- Factor is given below:

$$K_{RUSLE}=F_{csand}*F_{ci-si}*F_{orgc}*F_{hisand} \quad \text{(Equation 2.0)}$$

Where each component is evaluated is as follows:

$$F_{csand}=\left\{0.2+0.3exp\left[-0.256ms\left(1-\frac{m_{silt}}{100}\right)\right]\right\} \quad \text{(Equation 3.0)}$$

$$f_{ci-si}=\left(\frac{m_{silt}}{m_c+m_{silt}}\right)^{0.3} \quad \text{(Equation 4.0)}$$

$$F_{hisand}=\left\{1-\frac{0.7\left(1-\frac{m_s}{100}\right)}{\left(1-\frac{m_s}{100}\right)+\exp\left[-5.51+22.9\left(1-\frac{m_s}{100}\right)\right]}\right\} \quad \text{(Equation 5.0)}$$

$$F_{hisand}=\left\{1-\frac{0.7\left(1-\frac{m_s}{100}\right)}{\left(1-\frac{m_s}{100}\right)+\exp\left[-5.51+22.9\left(1-\frac{m_s}{100}\right)\right]}\right\} \quad \text{(Equation 6.0)}$$

Topographic factor (LS)

Slope length (L) and Slope steepness (S) are topographic factors which represent the influence of surface topography and slope gradient on erosion and considered as crucial parameters in soil erosion modeling. The slope (%) of the study area is derived from DEM. Sinks in the DEM were identified and a fill sink algorithm was employed for filling the sink. Therefore, filled DEM is used as input in the flow direction tool incorporated in the hydrology module, to determine the flow direction which was further used as an input to derive the flow accumulation. The LS factor is computed in raster calculator of ArcGIS 10.8.2 by using the equation LS= (Flow Accumulation*(Cell Size)/22.31) ^0.4*((Sin (slope))/0.0896) ^1.3.

Cover management factor (C)

The cover and management factor (C) reflects the combined effect of cropping and management practices on the runoff and soil erosion rate [19, 18]. C varies with plant growth and rainfall dynamics [14] and is considered the second major influencing factor controlling and affecting soil erosion after topography. The C- factor is calculated by the expression ((-NDVI.tif+1)/2) (Pavisorn Chuenchum et al., 2019).

Support practice factor (P)

The conservation and management practice factor (P) indicates the rate of soil loss according to agriculture practice or under specific management practices (Jahun et al. 2015; Thapa 2020). It describes the effects of surface management practices that are applied to reduce soil loss through the process of erosion [17]. P factor express the effect of practices such as contouring, strip cropping or terracing, slopes, sediment basins, silt fences, grass hedges, straw bales, and subsurface drainage [21]. For the generation of the P factor the LULC map with the help of the Sentinel-2 image is prepared. The prepared LULC map is also combined with the slope map so that effect of slope can also be accounted in the estimation. The respective prepared classes of the LULC are assigned a numerical value corresponding to P-factor which is as shown in the (Table 1).

Analysis and results

Spatial Distribution of Soil Erosion Factors over Tawa Reservoir the five factors R, K, LS, C, and P maps were created based on the different data inputs. The generation of a composite map of the estimated erosion or spatial distribution of the soil loss through the RUSLE model has been derived using, these raster maps. Thus, RUSLE layers were integrated within the raster calculator in the spatial analyst tool of the ArcGIS environment and potential soil erosion and severity/actual erosion maps were generated for Tawa Reservoir. The results obtained are shown in (Figure 3).

Rainfall erosivity factor (R): The long-term mean annual rainfall over the study area ranged between 1302.3 to 2122 mm. In the calculated R factor the rainfall erosivity factor value ranges between 5022.26 to 5798.73 mm ha−1 year−1. The distribution of rainfall erosivity is found to vary correspondingly with annual precipitation across the state as shown in (Figure 3a).

Soil erodibility factor (K): The K values in the study area ranged from 0.1135 to 0.1403 as shown in (Figure 3b). Lower K factor values are associated with soils with high permeability, low antecedent moisture content. Fine-loamy, coarse-loamy, fine and coarse-loamy texture having a higher value of K is more vulnerable to erosion. Soil with loose texture along with low organic matter is highly susceptible to erosion. Most part of the study area is covered with the sandy-clay-loam and clay due to which the probability of erodibilty factor is more prominent in the study area. The sandy Alfisol is susceptible to erosion by heavy rain if it is void of the natural surface litter.

Topographic factor (LS): The topographic factor indicates the influence of the length and gradient of the slopes on the erosion process. The analysis shows that the elevation value of the study area ranges from 277-m to 1129-m and LS factor ranges from the 0 to 385.033 as given in (Figure 3c). The high LS factors are mostly located towards the eastern, central, and southern ends of the Tawa Reservoir. To know the severity of the slope on the potential of the soil erosion the slope map is classified into following ways as shown in (Table 2). On the basis of the above table we can observe that the 76% of the area is contributing less amount of soil erosion while only 22.91% of the study area is contributing to high soil erosion.

Table 1: LULC classes and corresponding p-factor corresponding to each class.

S. No	Land Use Land Cover Classes	P Factor
1	Agricultural Land	0.55
2	Barren Land	0.6
3	Built up Land	0.85
4	Forest	1
5	Water Bodies	0.95

Cover management factor (C): The NDVI map with the help of the LISS-III is generated in the ArcGIS 10.8.2. The analysis of the LISS-III image shows that the NDVI values of the study area ranges from -0.72 to 0.83. The negative value in the NDVI is appearing because of the water bodies. The NDVI value is covering up to positive value 0.83 due to various features like built-up-area, forest, agricultural land and barren land. With the help of the NDVI map cover management factor (C) is developed. The C factor of the study area varies in between 0.083 to 0.858 as shown in the (Figure 3d).

Support practice factor (P): Support practice factor (P) ranges from the 0 to 0.9 for the entire study area as given in (Figure 3e). The highest P factor value is observed on the eastern part of the Tawa Reservoir. The highest P factor value also corresponds nearby to the reservoir. The lowest P factor value is observed in the uppermost part of the study area.

Estimates of soil erosion potential over Tawa reservoir

The potential soil erosion depicts the expected soil erosion and vulnerability of the landscape without taking into account C and P. It is associated with LS (slope), Soil, and Rainfall factor of the area [12, 17].

The soil erosion potential zones in the study area have been classified into five classes' viz., very slight (i.e. 0–5 tons per hectare), slight (i.e 5-10 tons per hectare), moderate (i.e. 10-15 tons per hectare), high

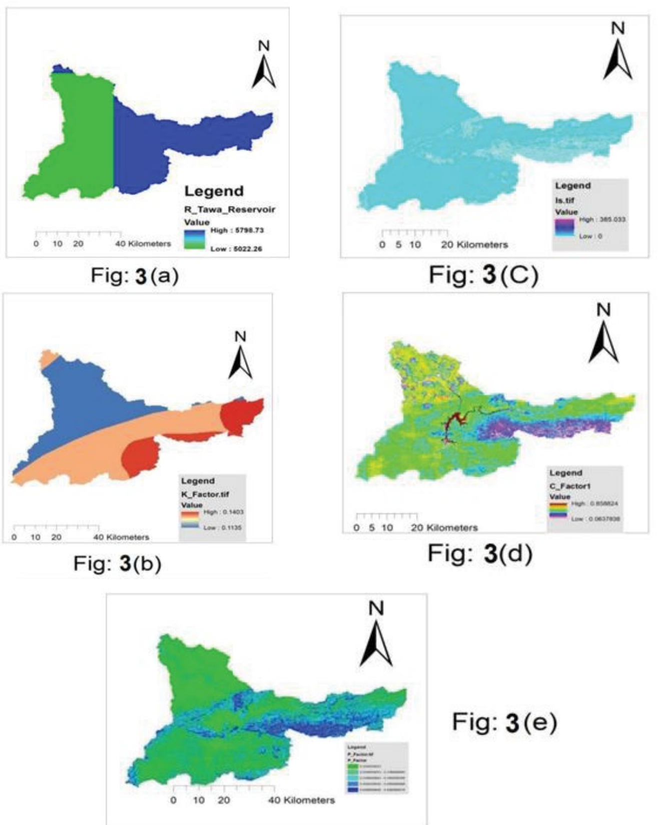

Figure 3: Soil erosion factors map; rainfall erosivity factor map (a), soil erodibility factor map (b), Topographic factor map (c), cover management factor map (d), and support practice factor map (e).

(i.e. 15-20 tons per hectare) and very high (i.e. >25 tons per hectare) as shown in (Figure 4) and (Table 3). It is observed that study area shows an annual soil loss of 231238 t of soil to be eroded annually in all the categories alarming the situation and severity of the soil loss.

Estimates of actual soil erosion in Tawa reservoir: The actual estimates of annual soil loss on a pixel-by-pixel basis have been produced spatially by multiplying R, K, LS, C, and P factors (Figure 4). The estimated soil erosion risk was classified in reference to the erosion rate as very slight (i.e. 0–5 tons per hectare), slight (i.e. 5–10 tons per hectare), moderate (10–15 tons per hectare), high (15 – 20 tons per hectare), very high (>25 tons per hectare), following [14] classification schema.

The result reveals that the minimum soil erosion is observed in the reservoir portion of the study area. The amount of the soil erosion is not uniform throughout the study area. Some of its part is undergoing low amount of the soil erosion while at the same time some its part is experiencing high soil erosion. One can also conclude that the major part of the study area is under low erosion rate (i.e. 0-5 ton per hectare) while the major part is also under the high erosion rate. Distribution of study area under different categories of actual soil erosion is shown in (Figure 5) and (Table 4).

Table 2: Classified slope map of the study area.

S. No	Slope Classes	Categories	Area (m2)	Percent
1	0 – 15 %	Gentle Slope	147165.8	76.2613
2	15 – 30 %	Slightly Undulating	1133.57	0.587
3	30 – 45 %	Moderate Steep	151.073	0.07
4	45 – 60%	Steep	297.967	0.15
5	>60 %	Very Steeper	44225.22	22.91

Table 3: Distribution of study area under different categories of potential soil erosion.

Class	Rate of Erosion (ton $ha^{-1}year^{-1}$)	Area (sq. Km)	Severity
1	0-5	72.441	Very Slight
2	05-Oct	0.072	Slight
3	Oct-15	0.041	Moderate
4	15-20	0.0818	High
5	>25	94.518	Very High

Comparison between potential soil erosion and actual soil erosion: With the help of all the inputs like rainfall data, soil data, satellites image and Digital Elevation Model all the factor for the calculation of RUSLE model i.e. R, K, LS, C & P is calculated. By the input parameter like R, K & LS potential soil loss is estimated and with all the input parameter the actual soil loss is calculated. It is observed that there is a major difference in Potential soil loss and Actual soil loss in the study area i.e. Tawa Reservoir. It has been also observed that the actual soil erosion is almost 3.57 times of the potential soil erosion estimated. One can also be sure to himself/herself only the multiplying with additional two factor i.e. C and P the actual soil erosion enhanced almost to 3.57 times. In the case of my study area constituting of Tawa Reservoir C and P factor is playing a crucial role. The summary of the comparison along with the soil loss efficiency is calculated in (Table 5).

Estimation of discharge and sediment of the Tawa reservoir: The study is not limited up to the soil loss estimation. It is further extended to determine the discharge and sediment for the reservoir. For the watershed delineation 4 sub basins and 1 outlet corresponding to that watershed is selected. The discharge and sediment corresponding to that watershed is also calculated in Arc SWAT as shown in (Figure 6).

The output of the entire process performed is shown in (Table 6). The above data is generated in the software with the help of the Arc SWAT. The data is employed for the period (2010-2021). The input for the data is downloaded from the NASA Power Data. The data obtained

Table 4: Distribution of study area under different categories of actual soil erosion.

Class	Rate of Erosion (ton $ha^{-1}year^{-1}$)	Area (sq. Km)	Severity
1	0-5	157.74	Very Slight
2	05-Oct	0.1	Slight
3	Oct-15	0.14	Moderate
4	15-20	0.16	High
5	>25	207.24	Very High

Table 5: Comparison of the soil loss and their efficiency.

S. No	Types of Loss	Loss Amount(tons)	Soil Loss Efficiency
1	Actual Soil Loss	8,25,505	72.35(%)
2	Potential Soil Loss	2,31,238	

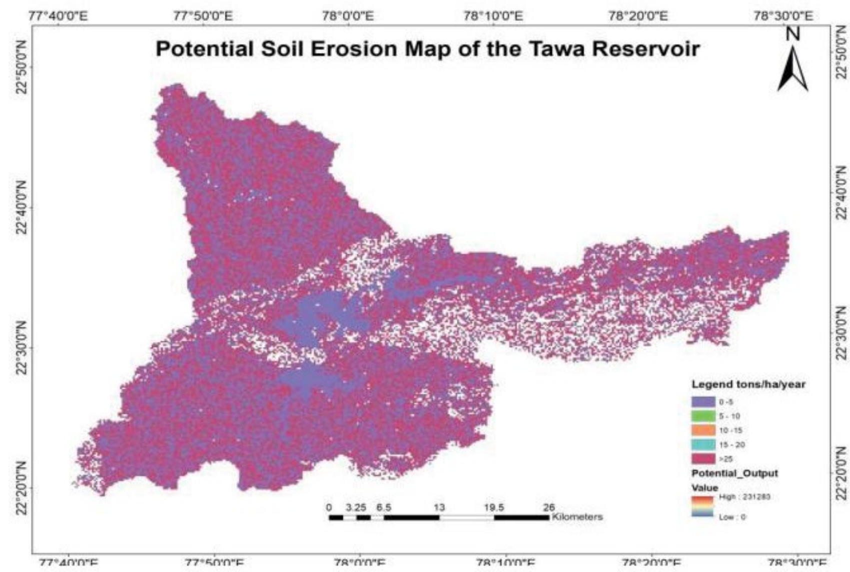

Figure 4: Potential soil loss map of the Tawa reservoir.

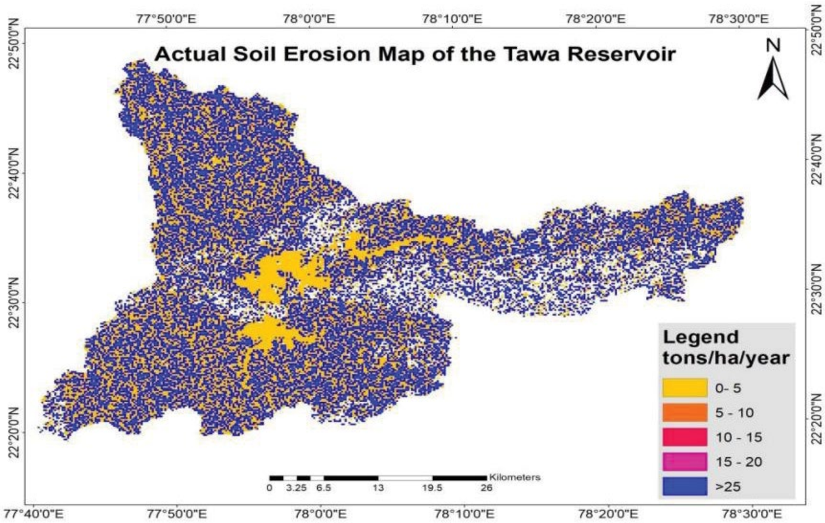

Figure 5: Actual soil erosion map of the Tawa reservoir.

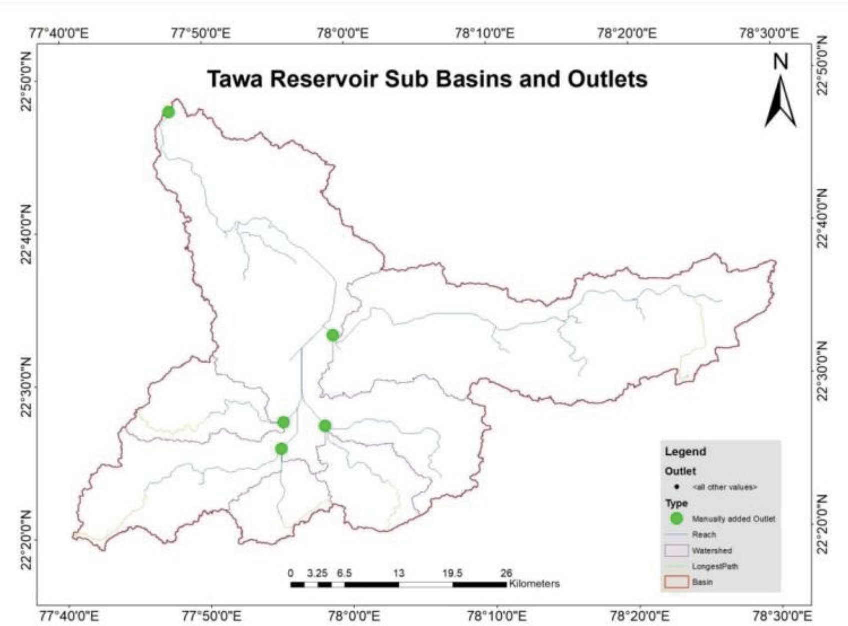

Figure 6: Sub basins and outlets of the Tawa reservoir.

Table 6: Hydrological data obtained for the period (2010 – 2021) in Arc SWAT.

S. No	Year	Rainfall(mm)	Discharge (cm3/s)	Sediment(tons)
1	2010	602	866.584686	10737471.58
2	2011	1,185	1215.01652	1176631.42
3	2012	1170	1102.883453	9469605.265
4	2013	1637.3	1522.399975	4322475.723
5	2014	1070.3	787.22105	4494678.422
6	2015	1212.6	1144.24812	5120877.85
7	2016	1270.9	1283.514211	7344175.268
8	2017	1015.4	641.903378	6975238.228
9	2018	1100	680.254808	4345926.218
10	2019	1668.8	1546.744802	12518073.14
11	2020	1254.5	1128.55825	5227145.574
12	2021	1012.6	888.42731	2343017.79

was in raw form and is prepared with the R- Software. The relationship between the above parameters listed in Table 6 is shown below with the help of (Figure 7a, b, c, d). After the graph is plotted the variation among them is shown in the (Table 7).

Discussion

The study demonstrated soil erosion in Haryana State using RUSLE model with the emphasis that an updated LULC is required. LULC is the most prominent and governing factor for soil erosion in numerous aspects and becomes exceedingly precious to efficient soil conservation and land resource management plan [19]. C-factor is primarily governed by NDVI of the study area. Most of the study area is dominated by agriculture due to plain topography, water availability and low elevation. The spatial distribution of the LS factor values is closely

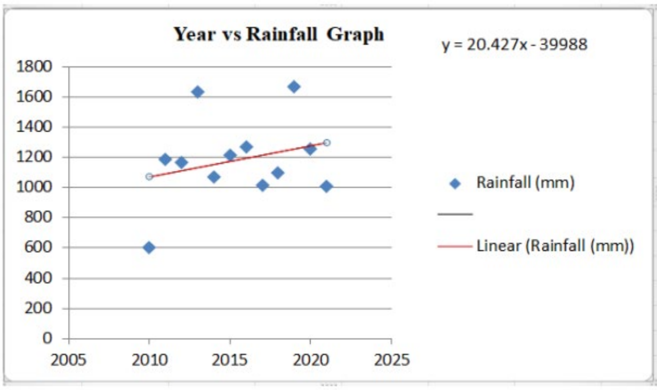

Figure 7(a): Graph plotted for showing the variation of rainfall with the year.

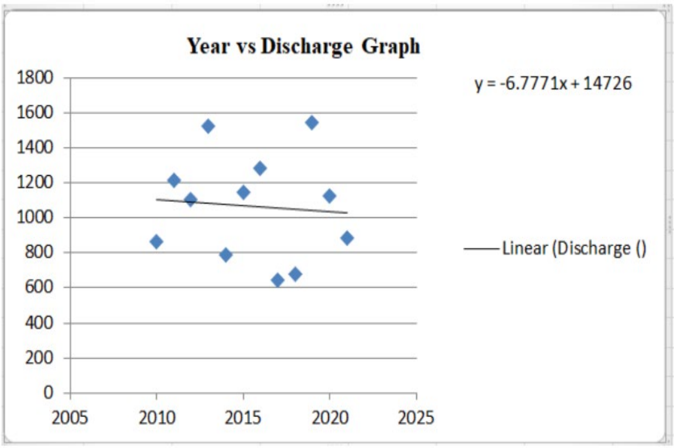

Figure 7(b): Graph plotted for showing the variation of discharge with the year.

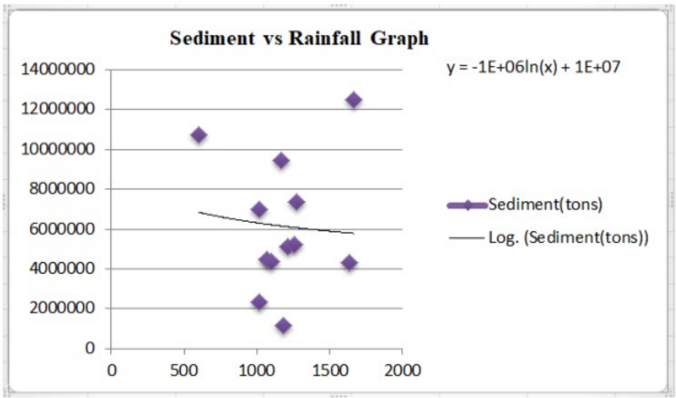

Figure 7(c): Graph plotted for showing the variation of rainfall with the sediment.

Table 7: Analysis, variation and nature of the data obtained from the Arc SWAT.

S. No	Graph Plotted Between	Equation	Nature of Graph
1	Year and Rainfall	Y=20.427x-39988	Linearly Increasing
2	Year and Discharge	Y=-6.7771x+14726	Linearly Decreasing
3	Sediment and Rainfall	Y=-1E+6ln(x)+1E+07	Logarithmic Decreasing
4	Discharge and Sediment	Y=9.1581-17648x+1E+07	Increasing with the Quadratic Nature

associated with the slope where the topographic factor represents the influence of slope steepness and length on erosion. The patterns of soil erosion have been similar in both the potential and actual soil erosion;

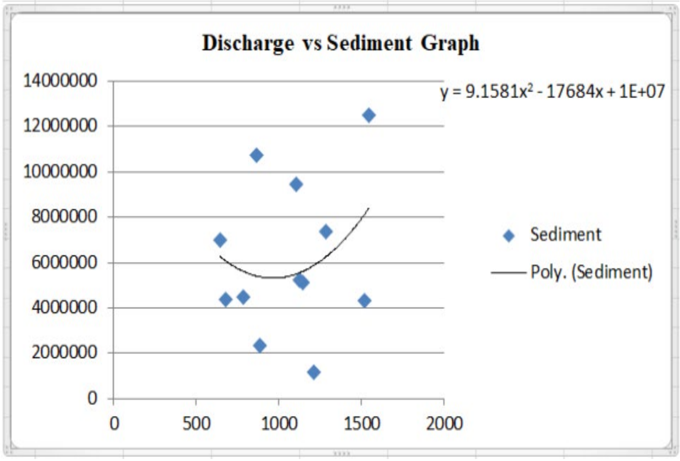

Figure 7(d): Graph plotted for showing the variation of sediment with the discharge.

however, the magnitude is relatively higher in potential soil erosion. 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. However, it is important to adequately track how man has changed the use of land through time, particularly for farming, deforestation, and other activities that encourage soil erosion [19, 17]. To create a cogent conservation and land management strategy with effective execution, this knowledge of soil erosion is very helpful.

Conclusion

The present study is undertaken with the purpose to emphasize the merit of Remote Sensing and GIS techniques in analyzing soil erosion and sediment analysis for the study area constituting Tawa Reservoir. To fulfil the objective the boundary of the study area and watershed delineation is done. The area of watershed is reported as 2, 02, 240 ha and of the perimeter 3, 59,158m. After that the RUSLE model is being used to estimate the soil erosion. For the applicability of the RUSEL model the various thematic maps like Rainfall Erosivity Factor(R), Soil Erodibilty Factor (K), Slope Length and steepness factor (LS), Crop Management Factor (C) and Support Practice Factor (P) is generated in the raster format. The empirical soil erosion model RUSLE integrated with GIS & RS technology is a very suitable and effective method in a simple, easy, and scientific way for the quantitative assessment of soil losses. It has applicability to spatially visualize and identify the erosion risk and Hazards zone on a local as well as regional scale which is crucial for watershed systems and administrative units. It provides a best management approach to formulate appropriate planning and policy for implementing optimal resource practices to sustain land resources, soil conservation, and avert environmental degradation. The outputs of the present study could be applied for immediate and efficient implementation of social moments like "Save Soil" and other government policies such as "Green corridors", and "Jal Shakti Abhiyan" for soil conservation in the State of Madhya Pradesh. The fndings of the paper can also use to make aware to local communities, protect natural resources, and prevent Ecosystem degradation required for sustainable development.

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