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Application of GIS for Soil Erosion Modeling in Bina River Basin

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Soil erosion is a major environmental problem that threatens the sustainability and productivity of agricultural areas. Universal Soil Loss Equation (USLE), originally developed by the USDA for agricultural lands and then used throughout the world. With the advance of Remote Sensing technique it becomes possible to measure hydrologic parameters on spatial scales while Geographic Information System integrates the spatial analytical functionality for spatially distributed data. This study was performed in the Bina River Basin having outlet at dam side. USLE model and ILWIS 3.0 GIS has been used for determining the quantity of soil erosion. ILWIS 3.0 GIS package has been used as the core of the spatial database and analysis. Results obtained from USLE model has been compared with existing empirical equation namely Joglekar's Curve developed for Central India and Khosla's method. It is observed that the mean annual soil loss estimated by using USLE method has been found to be 12.63 tons ha^{-1} year^{-1} for the Bina river watershed.

Key words: USLE, GIS, ILWIS, Soil Erosion, Bina river.

Soil is one of the important components of the lithosphere and biosphere system. It is a vital natural resource on which the supporting life systems and socio-economic development depends. Soil erosion is one of the most imperative environmental problems in the world causing land degradation is mainly related to increasing population pressure. Hydrologists estimated that one-fourth of the soil lost through erosion in a watershed actually makes it way to the ocean as sediment (FAO/UNEP, 1994). In an overview of global erosion and sedimentation, (Pimental, 1995) stated that more than 50% of the world's pastureland and about 80% of agricultural land suffer from significant erosion. In India about 5334 million tonnes of soil is eroded every year and about 29 per cent of it is lost permanently to seas (Singh *et al*., 2008). Soil erosion in watershed area and the deposition in rivers, lakes and reservoirs are of great concern for two reasons firstly, rich fertile soil is eroded from the watershed area and secondly, there is a reduction in reservoir capacity as well as degradation of downstream water quality. For this reason, prevention of soil erosion is of prime importance in the management and conservation of natural resources (Morgan, 1995; Sadeghi *et al*., 2007). Thus the integration of GIS and remote sensing in mapping soil erosion status can identify areas that are at potential risk of extensive soil erosion. Remote sensing provides multi-spectral and multi-temporal synoptic coverage for any area of environmental interest. On the other hand GIS provides the facility to integrate multi-disciplinary data for the dedicated interpretation in an easy and logical way (Songara *et al*. 2010) The Universal Soil Loss Equation (Wischmeier and Smith, 1978) and its revised versions (RUSLE) is widely accepted tool to predict soil loss and to plan soil conservation works (Renard *et al*., 1991, Sadeghi *et al*., 2004, Yang *et al*., 2005).

Several studies for soil erosion loss estimation and the various models have been

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developed (Nearing *et al.*, 1989, Shen *et al*., 2003). The Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) and its revised forms (RUSLE, Renard *et al*., 1997; Foster, 2004) are the most frequently applied worldwide for estimating the annual soil loss from rainfall erosivity, topography and land-use. However, application of such models to provide annual or long-term erosion hazard assessment for a site depends on knowledge of number of factors such as climate, vegetation, soil topography and land management (Amore *et al*.,2004) and are limited to predictions of erosion only. The USLE is a statistically-based water erosion prediction model sensitive to changes in all the six erosional factors (Wischmeier and Smith, 1978). Keeping the above references in mind, an attempt has been made to estimate the average soil loss (tons/hectare) per year by combining the USLE method and geographic information system tools ILWIS 3.0

MATERIALS AND METHODS

Study Area

The study was conducted in Bina river watershed upto Rahatgarh G&D site in Sagar district of Madhya Pradesh having area of 1145.5 Km^2. Bina River is one of the important tributary of Betwa River in Yamuna Basin. Bina river basin traverses through the fertile plains of Madhya Pradesh covering the Rahatgarh, Begumganj, Gairatgunj and Jaisingnagar towns and Geographically situated between 24° 09' N to 24° 42' N latitudes and 78°09' E to 78°23' E longitudes and at an average elevation of 412 m above mean sea level (Nayak, 2013). The average annual rainfall of study area is about 1196 mm. The rainfall in the area is due to southwest monsoon which starts from the middle of June and ends in last of September. The climate condition of the study area in December and January are severely cold, whereas summer month of May and June are intensely hot. The mean monthly minimum air temperature during the winter is around 11.5 °C while the maximum mean air temperature in the hottest month (May and June) is around 40.7 °C. The relative humidity is low in April to June and high in July to September. The major part of the area is covered by black cotton soil. However clay soil and clay loam soil falls in the southern and northern part. Main crop grown in the Kharif season is soybean and in Rabi season is wheat and other major crops are jowar, urad, paddy, gram etc. The study area has been given at Fig. 2.1.

Methodology

A well known USLE was used for this study because it is one of the most appropriate model-based approaches that could be applied to the authoritatively available data in Bina river basin. Mathematically the equation is denoted as:

$$A = R \times K \times L \times S \times C \times P \qquad ...(2.1)$$

Where

A = Annual soil loss ($t\ ha^{-1}\ y^{-1}$)

R = Rainfall and runoff erosivity index

K = Soil-erodibility factor

L = Length of slope factor

S = Degree of slope factor

C = Cropping-management factor

P = Conservation practice factor

All the factor of the USLE is geographic in nature. Therefore these factors are easily and efficiently computed using GIS with various data layers representing slope, soils, rainfall distribution, land use and management practices.

R-factor

Soil loss is closely related to rainfall partly through the detaching power of rain drops striking the soil surface and also the contribution of rain to the surface runoff. The impact of rainfall and its related parameters is best described as erosivity, which is determined by the raindrop size, rainfall intensity, amount and frequency of the rain as well as runoff amount and velocity (Lal, 2001). Due to the difficulties to measure these highly varying characteristics an equation on the general relationship between kinetic energy and rainfall intensity was developed by Wischmeier and Smith (1958):

$$KE = 0.0119 + 0.8793 \log 10l$$

Where, I is the rainfall intensity (mm/h) and KE is the kinetic energy (MJ/ha/mm). In India, simple relationship between erosivity index (R) and annual or seasonal rainfall (X) has been developed by (Singh *et al*, 1981) after analyzing the data collected from 45 stations distributed in different rainfall zones throughout the country. The relationship can be expressed by the following equations.

$$Ra = 79 + 0.363 \times Xa \quad ...(2.3)$$
$$Ra = 50 + 0.389 \times Xs \quad ...(2.4)$$

Where,
R_a / R_s = annual / seasonal erosivity index, and
X_a / X_s = average annual / seasonal rainfall (mm)

The coefficient of correlation was found to be 0.83 for annual and 0.88 for seasonal regression equations. The Eq. 2.3 and Eq. 2.4 have been used to estimate annual and seasonal Rainfall factor for soil loss estimation. In ILWIS 3.0, a rainfall distribution map was created using the interpolation technique. Map calculation was done by applying above equation to get rain erosivity map. The final R-factor map for the study area is shown in Fig. 2.2(a)

K-factor

The soil erodibility defines the resistance of the soil to both detachment and transport. Erodibility varies with soil texture, aggregate stability, shear strength, infiltration capacity and organic and chemical content (Morgan, 1986).The Soil database from National Bureau of Soil Survey and Land use Planning (NBSS&LUP), Government of India was referred to map K values of the study area. A vector coverage that had polygons of soil classes was digitized and soil units which enclosed the combinations of texture and erosion were assigned to different classes of K and rate of runoff, as measured under standard plot conditions Using the soil map the properties of different soil type such as sand-silt-clay contents, soil texture, organic matter content and permeability class, In present study the K factor map was prepared by attributing K factor values(Table 2.1) to the digitized soil map shown in Fig. 2.2 (b).

LS- Factor

The equation used for estimating the slope length and slope gradient factor for slope gradient till 9 % was:

$$LS = \left(\frac{\lambda}{22.13}\right)^{0.5} * [0.065 + 0.045(G) + 0.0065(G)^2]$$

Equation used for slope gradient of 9 % or more (Gaudasasmita, 1987) was:

$$LS = \left(\frac{\lambda}{22.13}\right)^{0.7} * [6.432 * \sin(\theta^{0.79}) * \cos\theta]$$

Where, LS is the slope length and slope gradient factor, is the slope length (m) and G is defined as the slope gradient in percent. The slope map was generated from the DEM Fig 2.2 (c) in ILWIS environment by applying the digital gradient filters dfdx and dfdy (i.e. called x-gradient and y-gradient maps). The relationship between the slope steepness in percentage (S) and slope length in meter (L) for the study area was estimated as;

$$L = 0.4 \times S + 40$$

From the slope map, using the above equation (2.7) in map calculation function, slop length map was created. By combining the slope length map and slope steepness map, LS-factor map Fig. 2.2(d) was created.

C-factor

Crop cover and management factor is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss. The importance of mapping landuse classes and monitoring their changes with time has been widely recognized in the scientific community (Songara at al. 2010) and the remote sensing (RS) and geographical information systems (GIS) are important tools for studying land-use patterns and their dynamics. The land use map of the Bina watershed was prepared by satellite data LISS-III images. Onscreen visual interpretation technique was followed to prepare the land use map of the Bina watershed using remote sensing data. The land use map was used for analyzing the C-factor. The C-factor values (Table 2.2) were assigned to each land use classes using attribute operation in ILWIS. A map of USLE C-factor was generated through attributed class of each land-use/land-cover type into its corresponding C-factor values as given in Fig. 2.2(e).

P-factor

By definition, factor P in the USLE method is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope culture. Improved tillage practices, sod-based rotations, fertility treatments and greater quantities of crop residues left on the field contribute materially to erosion control and frequently provide the major control in a farmer's field (Wischmeier and Smith, 1978). The 'P' factor is considered only for cultivatable lands; therefore the agricultural lands (good crop and poor crop area) were masked out from the land use map of Bina basin. 'P' value also depends on slope percent thus the slope map was classified as per the slope class using Slicing operation applied to the raster map 'slope'. A table was created showing the values of 'P' factor and similar slope gradient in the ILWIS 3.0. Then the classified map was attributed to the column P-factor to create a raster map of 'P' factor value a. The agriculture and non-agricultural lands (agriculture forest, scrub/bushes and barren/ grazing land/water body) were assigned value 1.0 for 'P' factor the output map thus generated as 'P_factor' map which is shown in Fig 2.2 (e).

RESULTS AND DISCUSSION

After completing data input procedure and preparation of R, K, LS, C and P factor maps as data layers, the maps were multiplied in the GIS environment to provide erosion risk map (Fig. 3.1) which shown spatial distribution of soil loss with degree of the soil loss (Table 3.1) in the study area. Approximately 37.49% of the total watershed area was estimated to have soil loss between 0 tons/ ha/year to 5 tons/ha/year. The soil loss ranges between 5 tons/ha/year to 10 tons/ha/year was estimated to be 23.69% , the soil loss ranges from 10 tons/ha/year to 20 tons/ha/year was estimated to be 22.23% , the soil loss ranges from 20 tons/ha/ year to 40 tons/ha/year was estimated to be 10.23% and the soil loss ranges between 40 tons/ha/year to 80 tons/ha/year was estimated to be 5.2% of the total watershed area. Severe rate soil loss (greater than 80 tons/ha/year) was obtained approximately in 1.13% of the total soil loss prediction at agro climatic zone (V) of Madhya Pradesh. The mean annual soil loss of the working area found to be 12.63 tons/ha/year with the existing vegetative cover and the conservation practices adopted in the agricultural fields of the study area.

Table 1. Soil class Distribution with K factor values

Soil Class	Area (sq. km.)	'K' Factor
Loamy sand	196.95	0.04
Coarse sandy *loam*	205.91	0.07
Sandy clay *loam*	97.54	0.20
Heavy clay	101.01	0.17
Clay	542.39	0.22
Silty clay	1.70	0.26

Table 2. P- Factor for Different Slope Gradient

S. No	Slope %	'P' value	Max. Slope Length
1	1.0-2.0	0.6	131.2
2	2.0-5.0	0.5	98.4
3	5.0-8.0	0.5	65.6
4	8.0-12.0	0.6	39.4
5	12.0-16.0	0.7	26.2
6	16.0-20.0	0.8	19.7
7	20.0-25.0	0.9	16.4

Table 3. Degree of the soil loss in study area

S. No.	Erosion Class	Erosion Value (tons/ha/year)	Area(Sq. km.)	Percent to Total Area
1	Very Low	0 – 05	429.46	37.49
2	Low	05 – 10	271.44	23.69
3	Moderate	10 – 20	254.72	22.23
4	Moderately High	20 – 40	117.21	10.23
5	High	40 – 80	59.68	5.20
6	Very High	> 80	12.99	1.13
	Total		1145.50	100

Comparison of results

Two empirical relations to estimate the quantity of sediment likely to deposit in any of the proposed reservoir, namely Joglekar's Curve and Khosla's Method were used to compare the results obtained from Universal Soil Loss Equation.

Joglekar's Curve

Joglekar analysed the data from the reservoirs located in Central India, Maharashtra and Vidarbha region and he gave an equation of an enveloping curve to the observe data as:

$$Q_s = \frac{0.597}{A^{0.24}}$$

Where, Q_s is the annual silting rate from

100 sq.km. of watershed area (Mm³/100 sq.km/yr) and ***A*** is the catchment area (sq.km). Therfore, total silt produces from the watershed area of 1145.5 sq.km. comes out to be:

Thus,

Q_s = 0.597/(1145.5)$^{0.24}$

= 0.11 Mm³/100 sq.km/yr

i.e.,

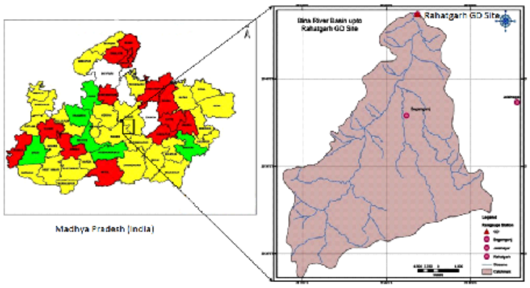

Fig. 1. Index Map Showing Bina River Watershed upto Rahatgarh GD Site

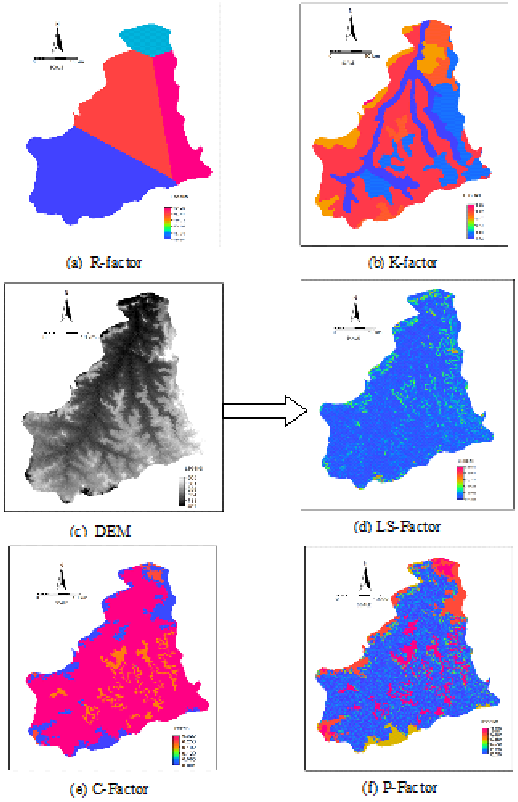

Fig. 2. GIS based maps showing USLE factors R, K, LS, C and P

Q_s = 12.11 tones/ha/yr, assuming silt density of 1.1 t/m³.

Khosla's Method

Khosla analysed the data from various reservoirs in India and abroad and observed that the annual rate of sediment deposition decreased with the age of reservoirs. He plotted a curve between the annual sediment deposited and the catchment area and suggested the following empirical formula.

$$Q_s = \frac{0.323}{A^{0.28}}$$

With the symbols as defined for Eq. (4.1).

Thus

Q_s = 0.323/(1145.5)$^{0.28}$ = 0.045 Mm³/100 sq.km/yr

i.e.,

Q_s = 4.95 tones/ha/yr, assuming silt density of 1.1 t/m³.

In most of the cases the actual sedimentation rate has been found more than three times the value assumed in the design on the basis of Khosla's equation (Mutreja, 1992). Since the several additional parameters such as catchment slope, drainage density and vegetation cover factors which were not covered in the equation of Khosla.

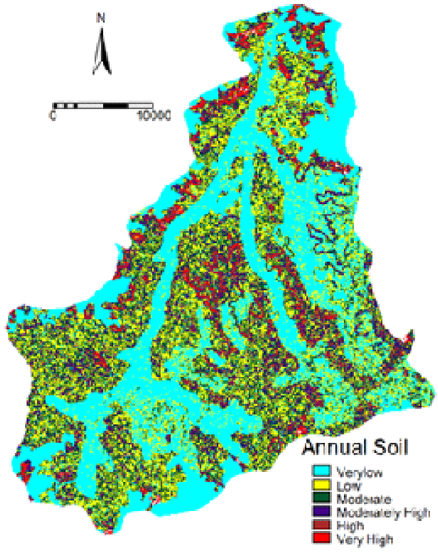

Fig. 3. Map showing severity of the soil loss in Bina river watershed

Thus the expected soil loss from the Bina watershed using USLE, compared with Sediment yield formula using Joglekar's Curve and Khosla's Method is as follows:

Method Used	USLE	Joglekar's Curve	Khosla's Method
Soil Loss in tons/year/ha	12.62	12.11	4.95

CONCLUSIONS

The soil erosion can be controlled effectively if it is predicted accurately under alternate management strategies and practices. The Universal Soil Loss Equation model has been accepted and used most widely all over the world to predict the soil erosion from a watershed. In India also many researchers have applied the model and different model parameters (factors) have been estimated for Indian conditions. The integration of GIS and remote sensing proves to be a time saving and cost effective path way. USLE coupled with GIS gives spatial distribution of the severity of soil erosion, which provides direct information about the locations where the soil conservation practices are to be adopted to reduce the erosion.

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