Tropical Agricultural Research Vol. 13: 177-188 (2001)

Empirical Erosion Modeling in GIS with Multi-Sensor and Multi-Temporal Satellite Data

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ABSTRACT. Modified Universal Soil Loss Equation (MUSLE), while using same empirical principles as Universal Soil Loss Equation, includes numerous improvements, such as monthly factors, influence of profile convexity/concavity using segmentation of irregular slopes and improved empirical equations for the computation of LS factor. In this context, MUSLE was used to assess the soil erosion status in a small watershed in India. IRS-1D LISS III and 1D Pan data were used to identify the land use conditions based on maximum likelihood classifier. Intensive ground verification was carried out to obtain the necessary ground information to train the classifier.

Further, a Digital Elevation Model (DEM) of the watershed was created from the SOI toposheets at 1:50,000 scale. Modified Erosivity factor was introduced through the Modified Fournier index. Slope derived from DEM contributed to generate the LS factor map. The soil map was reclassified for erodibility. The P and C factors were compiled from the data found in literature. Maps depicting each parameter (R, K, LS, C and P) were integrated into a composite map of erosion intensity based on some advanced functionality of GIS. The watershed area was further subdivided into 23 subwatersheds to identify the priority basins in terms of conservation needs. It was identified from the study that the subwatersheds 10, 16, 22 and 23 should be considered for immediate conservation measures. Annual average soil loss for the Bata watershed is 40.12 tones/ha.

INTRODUCTION

Soil erosion has been found to be more and more aggravating with time due to the loss of natural balance in the ecosystems through the transformation of virgin lands into agricultural and other industrial use. However, at present, the available data on soil erosion are of poor quality. Land use planning based on unreliable data can lead to costly and gross errors. Indiscriminate extrapolation of the localized data into a wider spatial domain can also lead to erroneous conclusions. Remote sensing as a data provider and Geographic Information Systems (GIS) as a data processor offer convenient solutions within our resource constraints.

A number of parametric models have been developed to predict soil erosion at drainage basins, hill slopes and field levels. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), which has been derived based on the results of runoff plot studies is the most widely used empirical equation in the assessment of soil erosion even at

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watershed scale. One of the major constraints in applying these models in large watersheds is that input variables are mostly point based measurements or observations and are not suitable for interpolation for large areas. Further, input data are also not representative of the temporal dynamics of the watershed processes. Furthermore, large volumes of data from a variety of different sources and at different spatial scales are difficult to process and organize efficiently within the modeling environment. Data derived from Remote Sensing (RS) methodologies however provide the capability for quantifying watershed parameters or processes both spatially and temporally. Some of the input factors such as ground cover and to a lesser extent supporting conservation practice and soil erodibility can also be successfully derived from remotely sensed data. Modified USLE (MUSLE), while using same empirical principles as USLE, includes numerous improvements, such as monthly factors, influence of profile convexity/concavity using segmentation of irregular slopes and improved empirical equations for the computation of LS factor (Renard *et al.*, 1994).

Remote sensing and GIS hold a great promise in the application of erosion modeling as they allow distributed models to be applied over wide areas at a number of different scales. Further, in these models, erosion predictions can be updated on a monthly or daily basis or at any selected temporal resolution. However, the validity of the empirical models of soil erosion assessment at global, regional or even at watershed scale is undoubtedly questionable since these models have been calibrated only at the field level.

The present study was carried out with the objectives of finding the feasibility application of empirical modeling with remotely sensed satellite data in a GIS environment, and prioritization of the sub-watershed areas based on the erosion intensity estimated through empirical modeling in GIS.

MATERIALS AND METHODS

Study area

Bata watershed in Himachal Pradesh of India was chosen to apply the empirical modeling methodology of soil erosion assessment (Fig. 1). The Bata river is a tributary of Yamuna river. The shape of the Bata river basin is approximately like an elliptically shaped saucer with the broader portion lying towards the east and gently narrower portion tapering towards the west. The surrounding water divides roughly form a smooth boundary. It is located between 30° 25' 3.33" N to 30° 35' 13.71" N latitude and 77° 22' 34.75" E to 77° 39' 42.31" E longitude. The maximum stretch of this region is from east to west 26.68 km, whereas its north-south stretch is only 14.7 km. The total area drained by the river Bata being 268.68 km^2. The Bata watershed, which is bounded by the sinuous and meandering Giri river in the North and East, by the mighty Yamuna in the South-East. The location of study area is shown in Fig. 1.

The Bata watershed has a sub-continental mountain type of sub-tropical monsoon climate with moderately warm to hot summers, high monsoon rains and a cool to cold winter season. Warm summers, high montane monsoon showers and cold winters give a peculiar type of seasonality to this region. The winter commences from October onwards, whence the temperature drops down sharply, and low temperature continues up to the middle of March, followed by the warm-dry season up to June. With the beginning of June, the South-West monsoon sweeps the study region bringing welcome showers after warm (sometime hot) and dry season. The mountains rain type of season prevails from June to September. The months of July and August observe the highest rainfall of the region. The monthly distribution of rainfall in the Bata watershed is shown in Fig. 2.

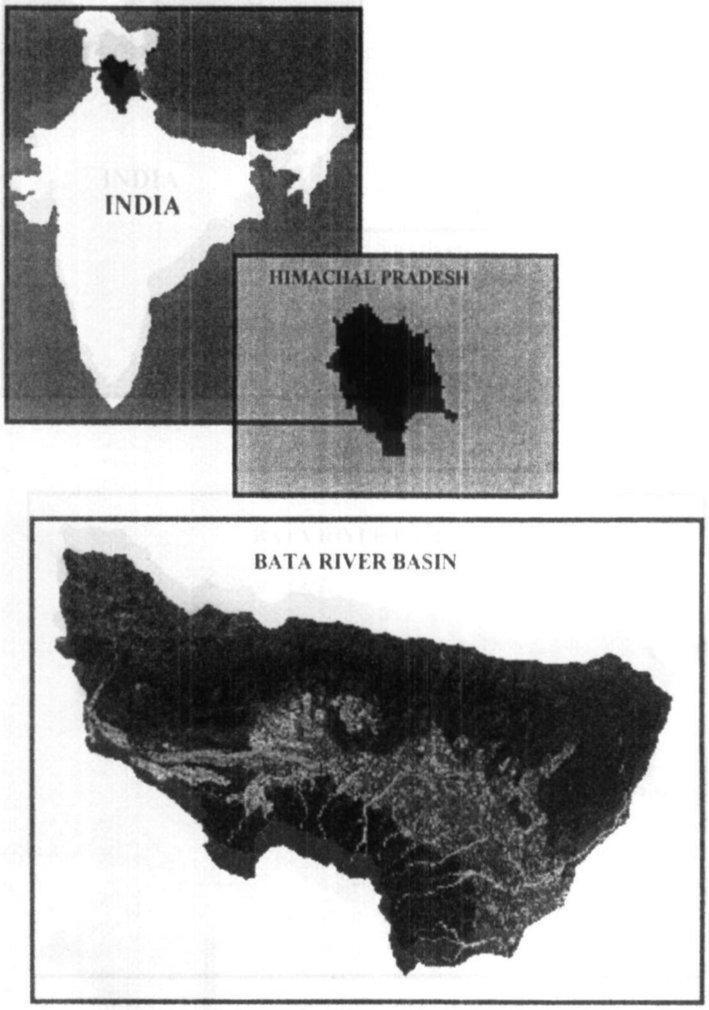

Fig. 1. Location of study area.

Materials used

The materials used in the study are as follows:

a) Remote Sensing Data

	Path	Row	Date
a. IRS-1D LISS III	96	50	12th October 1998
b. IRS-1D LISS III	96	50	01st March 1998
c. IRS-1D Pan	96	50	08th October 1999

b) SOI Toposheets

Sheet No:	53 F/6, F/7, F/10 and F/11
Scale:	1:50,000
Date surveyed:	1965

c) Ancillary data

Meteorological data station	Date
Dhaulakuan	1998-99
Paonta	1968-77
Renuka	1971-91
Nahan	1971-91

Pedological map (Geoscience Division, IIRS)

Soil map (Dept. of Soil Science, Krishi Vishwavidyalaya, Palampur, 1997).

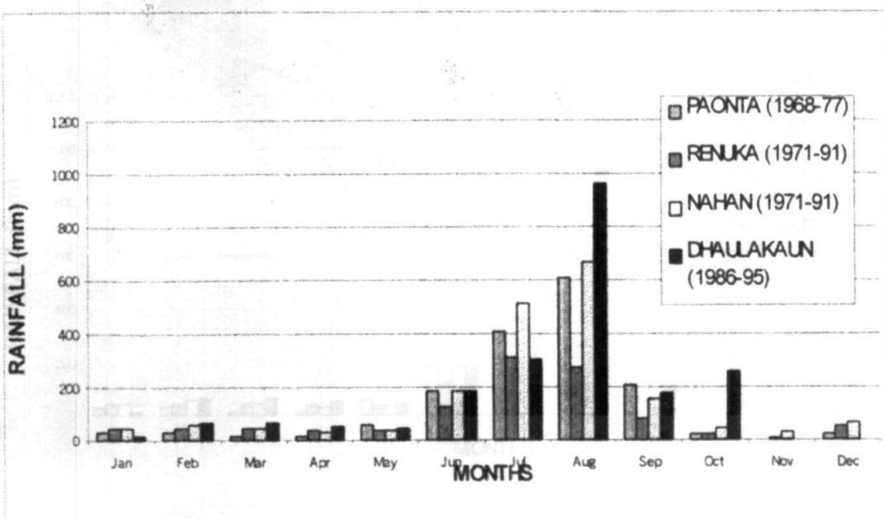

Fig. 2. Monthly distribution of rainfall in the Bata watershed.

Preprocessing of IRS imagery

Inherent geometric distortions are common in satellite images. These geometric distortions are due to sensor geometry, scanner and platform instabilities, earth rotation, earth curvature, *etc.* further, there is no commonality between the file coordinates of the image with the global geometric coordinates. The process of geo-referencing registers each pixel on the image with the corresponding ground are by means of a co-ordinate system such as TM, UTM or any other reference map projection.

After the process geo-referencing, the image includes co-ordinates for each pixel, but its geometry is not corrected for geometric distortions and not adapted to a master map. In order to create a distortion free image, the transformation that is defined during geo-referencing is executed. This process, called geo-coding, results in a new image in which the pixels are arranged in the geometry of a raster image or a map. Here SOI toposheets have been used for geo-coding the images.

Classification for surface cover

Supervised classification of IRS imagery was carried out to determine the land-use/land-cover status of the watershed. Maximum likelihood classifier provided the best results in the classification process. Spatial extents and boundaries of eight (8) landuse/landcover classes namely Dense Forest, Moderate Forest, Open Forest, Wheat Crop, Sugarcane, Settlement, River Bed and Water Body were demarcated in the watershed.

Digital elevation model and derived products

Contour segment map and spot-height point map were digitized based on the SOI toposheets in order to derive the DEM. Final DEM was derived as the combined product of both these data sources. A detailed account of the methodology adopted for the study is described in Fig. 3.

Modified USLE and parameter definitions

Modified R factor

The climate index C developed by Fournier (1960) could be considered as a substitute for erosivity index for watersheds where long term records are not available. The mathematical basis of this index can be summarized as follows:

$$C = r^2/P$$

$$C_i = \sum_{i=1}^{12} (r_i^2/P)$$

where, r is the rainfall amount in the wettest month and P is the annual rainfall amount, C_i is the climate index, r_i is the rainfall in month i. This index summed for the whole year, was found to be linearly correlated with EI_{30} index (R) of the USLE as follows:

$$R = b + a*(C_i)$$

where, the constants a and b vary widely among different climatic zones.

Table 1 shows the estimated values of C_i and R factor for the study area.

Table 1. Estimation of climate index and R factors for Bata watershed.

	Dhaulakuan (1997-1998)	Paonta (1968-1977)	Renuka (1971-1991)	Nahan (1971-1991)
Annual average	2130.60	1611.40	1082.50	1883.80
Climate index	547.91	386.20	191.34	413.06
R factor	1189.30	1055.56	894.61	1077.75

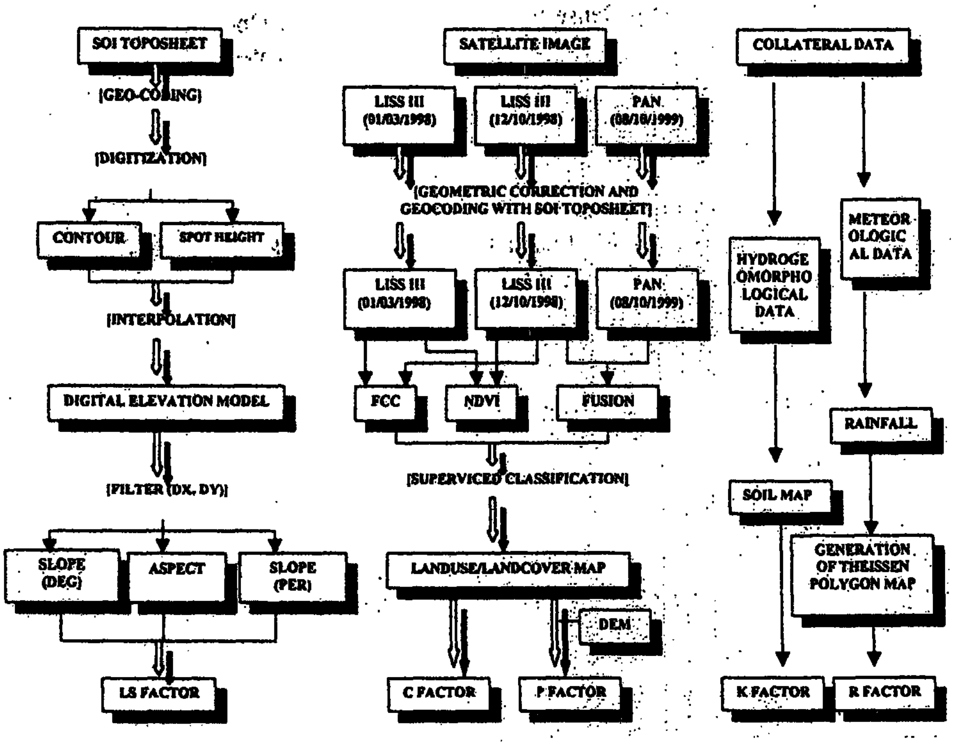

Fig. 3. Flow diagram showing the adapted methodology.

LS factor and modifications

There were two relationships used to derive degree of slope and slope length parameters in the modeling framework. For slope steepness up to 21%, the relationships detailed in the original USLE formula was used and above 21% of slope Gaudasasmita equation was employed. The mathematical representation of these equations can be summarized as follows:

For slope < 21%,

$$LS = (L/72.6)*(65.41*\sin(S) + 4.56*\sin(S) + 0.065)$$

For slope ≥ 21%,

$$LS = (L/22.1)^{0.7}*[6.432*\sin(S)^{0.79}*\cos(S)]$$

where, LS = Topographic factor, L = Slope length (m), S = Slope steepness (radians).

C factor

In MUSLE, the cover factor is assumed to be derived from five sub-factors (Laflen and Reddy, 1985) as detailed below:

$$C = PLU*CC*SC*SR*SM$$

where, PLU is prior land use factor, CC is crop canopy factor, SC is surface or ground cover factor (including erosion pavement), SM is soil moisture factor and SR is surface roughness factor.

These components are expected to account for the residual effects of cropping. The CC expresses the effect of vegetative canopy on reducing rainfall energy impacting the soil surface. The SC affects erosion by reducing transport capacity of runoff water (Foster, 1982), by causing deposition in ponded areas (Laflen and Reddy, 1985), and by decreasing the surface area susceptible to raindrop impact. The SR has been shown to affect soil erosion considerably (Cogo *et al.*, 1994). Increasing surface roughness decreases transport capacity and detachment of runoff by reducing flow velocity.

The estimation of these sub factor values requires long term commitment of collecting field records. Alternatively, in this study, crop factor values were prepared from land-use/land-cover map, which was developed as a product of supervised classification of FCC of LISS III images.

Erodibility factor

The map of erodibility was developed from the soil map as a reclassification product considering each variable affecting erodibility of the different soil types found in the watershed.

Conservation practice factor

The conservation practice factor map was derived based on the spatial extents of the developed land-use/land-cover map incorporating the research findings of Central Soil and Water Conservation Research and Training Institute, Dehradun regarding the conservation practices adopted for each land-use or cover scenario.

The maps of each factor developed for input as spatially distributed parameters in the model are shown in Fig. 4.

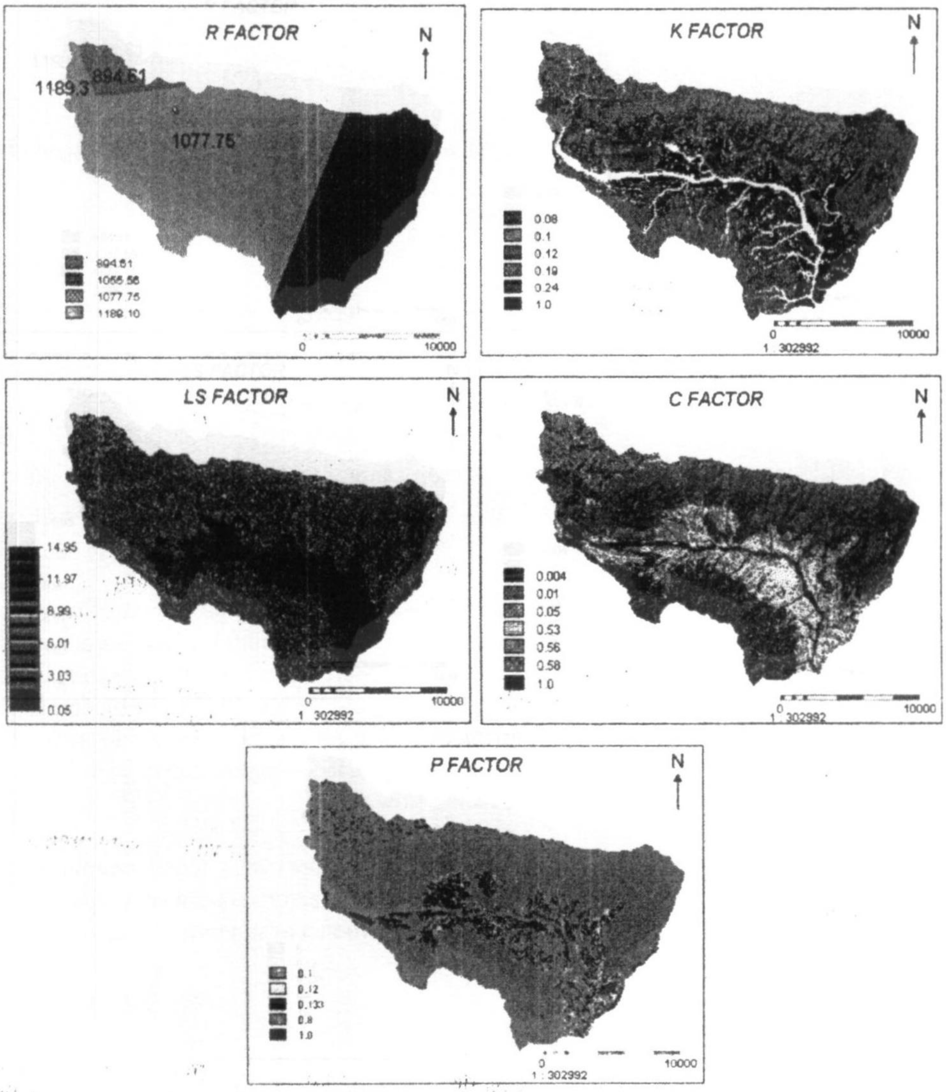

Fig. 4. Maps showing modified R, K, LS, C and P factors.

Modeling methodology and summary of results

Each factor was assumed to be contributing to erosion as detailed in the MUSLE and a composite map of erosion intensity was derived accordingly. The factors used and the resulted soil losses are given in Table 2. Prioritization was done based on five different classes of erosion intensity. The watershed was further subdivided into 23 sub-watersheds to determine the resource allocation for conservation (Table 3). Each sub-watershed was analysed individually in terms of soil type, average slope, drainage length, drainage density, drainage order, height difference, land-use/land-cover and average NDVI with respect to soil erosion to finalise the dominant factor contributing towards higher erosion intensity. The slope distribution and the corresponding soil loss in the sub-watersheds are shown in Fig. 5. The relationship between soil loss and derived NDVI values for each sub-watershed is shown in Fig. 6.

DISCUSSION

A useful set of information has been obtained from the comprehensive study of the watershed characteristics such as soil type, average slope, drainage length, drainage density, drainage order, height difference, land-use/land-cover and average NDVI with soil erosion.

Sub-watersheds 16, 17, 18, 20 and 21 showed nearly 30% of area occupied by dense forest, while sub-watersheds 6, 7, 8, 9 and 10 were having around 10% dense forest cover. Sub-watershed 10 occupied around 60% moderate forest. Sub-watersheds 13 and 14 were having around 55% open forest. Wheat/Paddy occupied 45% of sub-watershed 6. Overall weighted average of NDVI for each sub-watershed showed that the sub-watersheds 12, 17, 20 and 21 had the higher value, while sub-watersheds 6 and 11 showed the lowest (Fig. 5).

Table 2. Factors and predicted soil losses.

Land-use classes	R factor	K factor	LS factor	C factor	P factor	Slope (%)	Area (km^2)	Soil loss (ton/ha/yr)
Dense forest	1132.82	0.14	4.52	0.004	0.80	22.3	96.01	2.24
Mod. forest	1136.83	0.15	4.27	0.010	0.80	31.8	56.01	5.49
Open forest	1100.04	0.16	3.68	0.050	0.80	35.0	38.45	25.64
Wheat/paddy	1114.70	0.22	1.78	0.530	0.10	5.4	25.02	22.10
Sugarcane	1084.83	0.21	2.14	0.580	0.12	9.0	4.66	31.17
Barren land	1143.42	0.26	1.83	1.000	1.00	3.1	12.88	215.81
Total	1127.85	0.17	3.60			21.10	268.68	40.12

Table 3. Sub watershed characteristics and annual average soil loss.

Sub basin	Area (km^2)	Drainage order	Drainage density	Drainage length (km)	Elevation difference (m)	Average slope (%)	Soil type	Soil loss (tonnes/ha/yr)
1	10.52	4	1.80	5.97	280	23.40	Sandy loam	09.77
2	3.81	2	1.30	3.91	260	13.50	Sandy loam	26.28
3	5.90	3	1.40	6.74	250	15.00	Sandy loam	20.49
4	6.45	3	1.00	6.02	250	10.40	Sandy loam	24.10
5	4.76	3	1.40	5.96	270	10.20	Sandy loam	39.09
6	9.11	2	0.60	6.17	260	06.50	Sandy loam	61.80
7	7.16	2	1.40	5.95	130	16.50	Sandy loam	33.29
8	2.96	3	1.50	4.16	230	08.00	Sandy loam	49.70
9	6.66	3	1.20	5.52	260	10.30	Sandy loam	47.68
10	22.70	4	1.80	9.51	552	14.80	Sandy loam	31.18
11	10.93	2	0.90	1.67	590	13.90	sl + ls	49.22
12	5.90	3	2.10	4.59	670	35.20	Loamy sand	12.93
13	8.10	5	2.60	5.04	750	49.20	Loamy sand	17.04
14	7.68	4	2.00	6.52	570	40.90	Loamy sand	18.63
15	16.10	2	1.80	3.08	940	23.90	ls + sl	32.51
16	34.30	4	1.50	12.94	700	26.90	ls + sl	20.21
17	11.66	4	1.30	6.68	800	29.50	ls + sl	22.80
18	6.45	3	1.50	6.11	800	24.50	Loamy sand	12.80
19	3.89	2	1.20	3.16	280	12.20	Loamy sand	30.18
20	12.18	3	1.10	6.52	920	32.00	Loamy sand	24.29
21	15.88	4	1.20	7.58	900	29.60	Loamy sand	23.17
22	26.59	3	1.10	12.76	910	17.70	Loamy sand	27.74
23	28.99	4	1.20	14.52	580	10.70	Sandy loam	27.04
Total	268.70	5		36.40	880	24.44		42.20

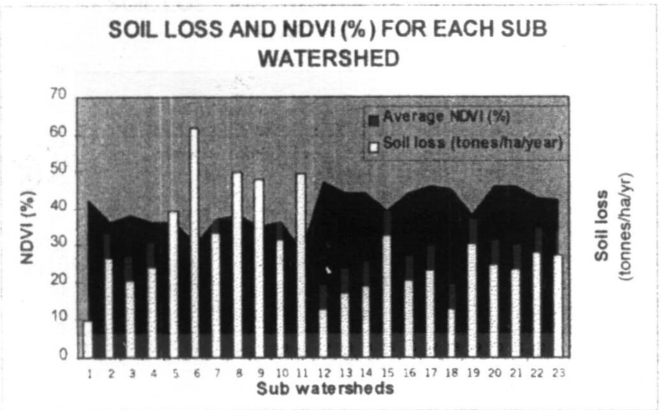

Fig. 5. NDVI and corresponding soil losses.

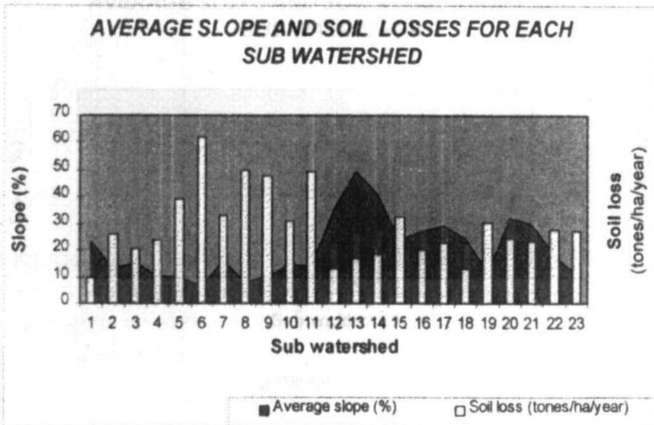

Fig. 6. Slope and corresponding soil losses.

Sub-watershed 6 indicated the highest soil loss though it had the lowest slope. Likewise, the sub-watershed 13 showed the highest slope with low soil loss. The average NDVI of sub-watershed 6 was very low (Fig. 6). It was further revealed that this lowest NDVI was because of low forest cover and high Wheat/Paddy cultivation (harvesting period). Around 45% of NDVI is contributed by the cultivation. As such sub-watershed 13 showed the lowest cultivated area and high extent of open and dense forest cover.

Even though a higher erosion was expected from the sub-watersheds 10, 11 and 12 with very steep slopes, the out put maps showed comparatively lower soil loss. According to the present observations the sub-watersheds 10 and 11 are falling under Renuka meteorological station, which gauged the lowest average rainfall, though the slope steepness is very high the slope lengths are short, which results lower LS factor values. Also, those sub-watersheds are being covered by dense forest and very smaller area under terrace cultivation.

Crop cover is found to be very effective in controlling the direct impact of rainfall on soil particles. In view of this, it can be recommended that all barren lands in Bata watershed need to be converted to agricultural land or forest plantations through proper land reclamation procedures.

This study has shown the potential of the GIS to model the soil erosion, but the improved models will give more realistic estimation since the model used here (modified USLE) will estimate only the sheet and rill erosion. The accuracy of the values has not been estimated due to the time constraints, but they closely match with the regional estimations of soil erosion rates.

CONCLUSIONS

Annual average soil loss for the Bata river basin is 40.12 tones/ha and barren lands are contributing much for this soil loss (215.81 tones/ha/year). Wheat/Paddy and Sugarcane mainly occupied more flat land on lower elevation, yielding 22.1-31.17 tones/ha/year soil loss. Areas of 22.74 and 13.61 km^2 fall under very high and high priority classes respectively for entire Bata watershed. Modified USLE is found to be a very useful model for the qualitative as well as quantitative assessment of soil erosion intensity in view of conservation management. Multi-temporal, multi-sensor and multi-spectral remote sensing data provide data directly for parameter estimation in the model. GIS has demonstrated the capability of data integration and processing with large and complex databases.

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