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APPLICATION OF GEOTECHNOLOGY TO WATERSHED SOIL CONSERVATION PLANNING AT THE FIELD SCALE

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Soil conservation planning in inaccessible mountainous watersheds is a very tedious and expensive job. Generally, in India most soil conservation programs are carried out with physical reconnaissance surveys. However, recent technological advancements have paved the way for planning soil conservation measures on a field scale in the watershed. This paper describes soil conservation planning methods on the basis of the quantified soil erosion rate in the Kuniguda watershed of Orissa and Andhra Pradesh. The soil erosion rate was determined as a function of land topography, soil texture, land use/land cover, rainfall erosivity, and crop management and practice in the watershed using the Universal Soil Loss Equation (for Indian conditions), remote sensing imagery, and GIS techniques. A drainage density map of the watershed was created based on a 1 km x 1 km grid. Land use change analysis of the watershed was performed between 1989 and 1996 using IRS-1A and IRS-1B satellite images, respectively. A systematic soil conservation planning for the watershed was developed using these information sources along with a spatial watershed study. The average soil loss amount was also estimated on a sub-watershed basis to prioritize the requirement of the soil conservation program implementation. the results were validated and compared with results from similar studies using different methodologies. This methods used in this study provide faster and more economical means for spatial soil conservation planning, which can eliminate rigorous and time consuming physical surveys in inaccessible mountainous watersheds in India and elsewhere.

INTRODUCTION

The major environmental concern in industrialized nations, as well as developing countries, is soil and water conservation. In industrialized countries, acceptable yield and production costs are the main concerns, and increased food production to attain self-sufficiency is the major objective (Cyr et al., 1995). A good quality soil is essential to meet these objectives. However, excessive soil erosion is responsible for surface soil loss and a subsequent decrease in soil quality and agricultural production. Thus, two main factors of concern in declining agricultural yield are soil and water erosion.

According to a study conducted by Morgan (1986), the rate of soil erosion of developing and developed countries is at an alarming level. However, some developed countries like the United Kingdom, United States of America, and Belgium have succeeded in minimizing the soil loss to an acceptable level. Soil loss from cultivated and bare land is still very high elsewhere on the globe and soil erosion is the most significant and an ominous threat to food security and development prospects in many developing countries (Bekele, 2003). Soil loss is greater in developing countries where the farmers are totally ignorant of soil conservation practices. An escalating population is also indirectly responsible for this soil loss, especially where farmers desperate to grow enough crops destroy forests and other natural areas.

At the outset, it is essential to establish the extent of soil erosion of an area to develop a good and efficient soil conservation program (Panda et al., 2000). The revised universal soil loss equation (RUSLE) is the most widely used method for estimating the extent of soil loss through erosion (Renard et al., 1991; Mallerowicz et al., 1994; Wang et al., 2000). Use of GIS in soil degradation assessment is accelerating due to a continuously improving technology (Al-Abed et al., 2000; Panda et al., 2000). Currently, the digitized resource databases on spatial information of the earth, digital elevation models (DEMs) of landscapes, and spatial resources are available to quantify soil erosion. Remote sensing is an improved tool that can assist the soil conservationist by accurate land use classification of an area of concern. Temporal analysis of two different date images can provide information regarding changes in land use and can be useful to plan soil conservation programs.

Extensive literature exists on soil erosion studies using remote sensing data (Wu et al., 1997; Chao et al., 1997; Hong et al., 1997; Al-Abed et al., 2000). However, few studies have been completed for estimating soil erosion loss by integrating the USLE, remote sensing, and GIS technology. Mellerwicz et al. (1994) integrated data sets for the USLE factors using digitized maps showing geographic distributions and the Computer Aided Resource Information System (CARIS). They manipulated the individual factor data sets to produce various scenarios of conservation practices and they reported that the use of GIS and digital databases allowed for the assimilation of vast amounts of information and data analysis that would not have been feasible manually. Songkai and Li Wenqing (1999) used a LANDSAT-TM image to calculate the C and P factor to estimate the soil loss of the watershed in Guanji, China. Al-Abed et al. (2000) integrated remote sensing, GIS, and USLE to quantify the soil loss from the Lakhotia district, Syria. They used a SPOT panchromatic image, soil survey data, land use inventory, elevation data, and climatic atlases to generate USLE factors.

Soil conservation programs can be designed after quantification of the amounts of soil erosion. Aerial or remotely sensed satellite images and the GIS technology are essential to develop a suitable soil conservation plan. Padgitt (1989) studied soil diversity and the effects of field eligibility rules in implementing soil conservation programs. He classified lands into different categories depending upon soil erosivity factors. He also suggested different cropping patterns for highly erodible land.

Tagwira (1992) modeled a conservation technique for sustainable crop production in Zimbabwe. Nimbos et al. (1991) formulated a soil conservation program in the Ecuadorian highlands known as the SULAMAN program. It was a labor extensive conservation and sustainable agriculture program and involved the application of contour planting; crop rotation; green manuring and inter-cropping; construction of hillside ditches, bench terraces, and earth reservoirs, etc.

In India, many soil erosion assessments have been conducted for mountainous watersheds. A treatment-oriented land use planning scheme was compiled for a hilly watershed subject to soil erosion in the Western Ghats, India, using a geographical information system (GIS) by Adinarayan et al. (1995). A remote sensing based physiographic soil map and a digital elevation model (DEM) were the sources of soil depth and slope steepness classes, respectively. GIS was used to integrate these databases and manipulate the data.

The USLE was designed to provide a convenient tool for soil conservationists and can be used for any geographic location in the world with modification of its factors (Quyang and Bartholic, 2001). Although, RUSLE provides a somewhat more accurate estimation of soil loss (Renard et al., 1997), it needs a large amount of extra information. In large and inaccessible watersheds, remote sensing and GIS application facilitate the use of USLE to calculate soil loss. The literature suggests that much research has been done in formulating algorithms, methodologies to revise the universal soil loss equation, and integrating geotechnology (remote sensing and GIS) along with USLE to quantify soil loss on a spatial scale. However, very few attempts have been made to provide a field oriented soil conservation program based on the soil loss estimation, information from other remotely sensed image analysis, and GIS technology. Therefore, it is essential to devise a field scale soil conservation planning strategy that can facilitate soil conservation measures in the watershed without any prior reconnaissance survey, which is exceptionally tedious and costly in a mountainous watershed like the Kuniguda watershed in India.

In this paper, the USLE equation in its modified form is adapted to the mountainous watershed conditions of the Indian subcontinent. GIS and remote sensing model development tools were used to construct the USLE equation in a graphical user interface (GUI) composition to obtain a spatial soil loss zoning of the watershed. The objectives of the study are to develop a field scale soil conservation planning strategy framework for the sustainable utilization of land resources based on the plot (area) requirement, and to validate the estimated soil erosion rate with rates calculated for similar physical environments.

MATERIAL AND METHODS

Study area

The study was conducted in the Kuniguda watershed (Figure 1) that extends over two provinces, Orissa and Andhra Pradesh, in India. The geographical extent of the watershed is 82^0 15'-82^0 30' east longitude and 18^0 6' - 18^0 15' north latitude. This watershed contributes runoff to a reservoir for a hydroelectric power station situated at an elevation of approximately 800 meters above mean sea level (MSL). The total watershed area is 180 sq. km. The watershed has been divided into 17 sub-watersheds, according to the drainage pattern. The land use distribution of the watershed in 1996 was with 41% forest, 34% open shrubs, 8% bare land, and only 17% agriculture land. The watershed is mostly undulating topography with rolling uplands. The slope gradient of the region ranges from 1% to more than 90%. The watershed experiences very heavy precipitation with an annual average precipitation of 1654.44 mm (1975-1994). Its topography, in general supports heavy soil loss but good vegetation cover reduces soil erosion to a great extent.

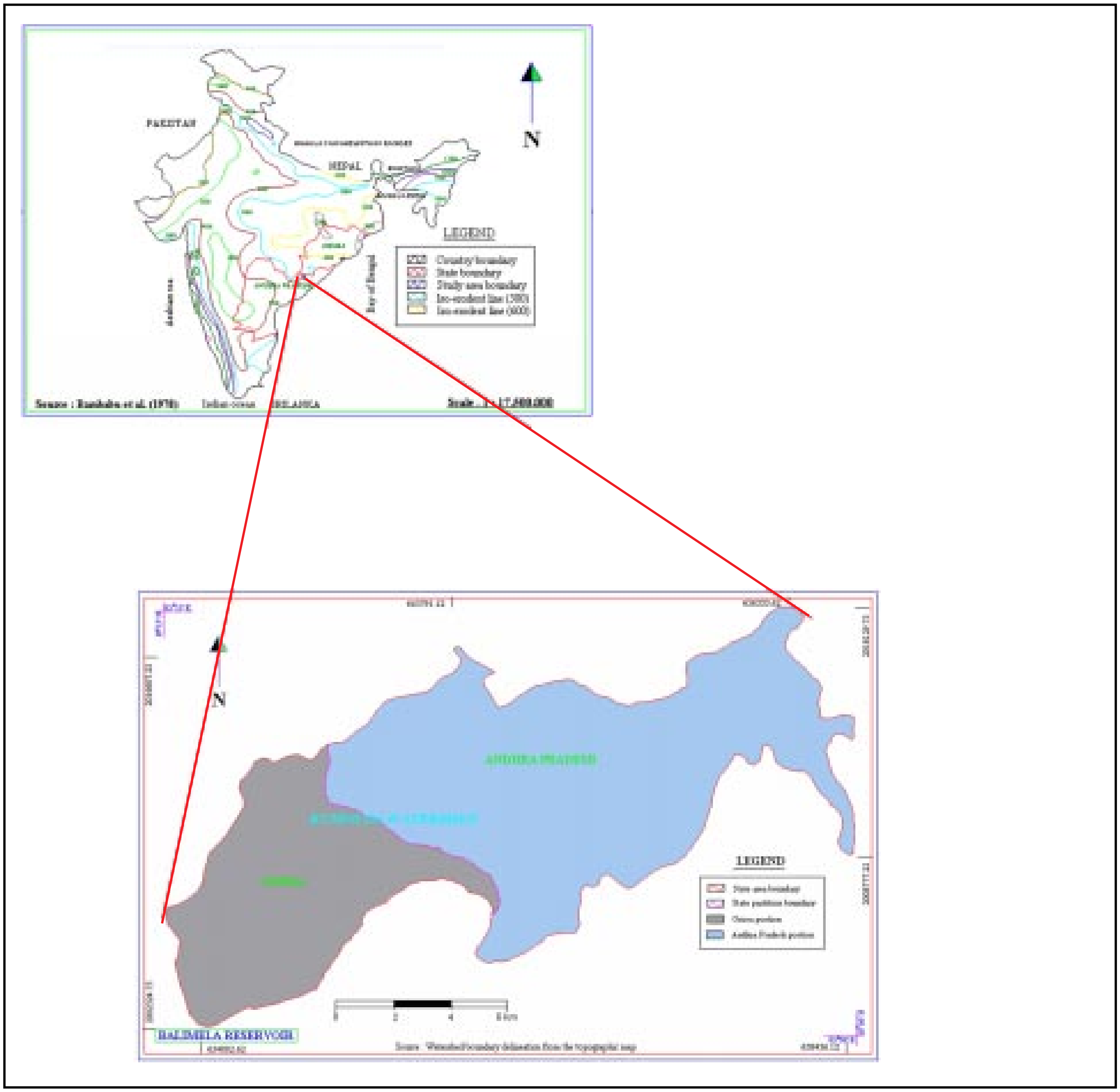


Figure 1. Iso-erodent map of India (top) showing the study area location (bottom).

BACKGROUND OF USLE AND DATA COLLECTION

The soil loss of the watershed was calculated using the USLE (Wischmeier and Smith, 1965) with some modification in its parameter estimation to suit Indian conditions. The general universal soil loss equation is as follows:

$$A = R \times K \times L \times S \times C \times P, \qquad (1)$$

where A is average soil loss (T ha^{-1} yr^{-1}), R is the rainfall erosivity index, K is the soil erosivity factor, L is the slope length factor, S is the slope gradient factor, C is the crop management factor, and P is the supporting conservation practice factor.

For individual USLE parameter mapping the following data were used; the iso-erodent map of India (1978), (scale - 1:17,500,000) for erosivity index computation; the topographic map of the study area (1978), (scale - 1:50,000) for slope length and slope gradient calculation; the Indian

Remote Sensing (IRS)-1B (LISS - II) digital satellite image of the study area (February 9, 1996) for the land use/land cover determination; ground truth information of land use in the watershed based on the ground coordinates for land use classification accuracy assessment; and data on supporting conservation factors such as the tilling practice, direction of tillage, crop rotation in a crop calendar, and so on. The watershed did not have a soil map to support the study. The major soil classification chart by FAO/UNESCO, soil test report of the study area, and a nomograph chart were combined to generate a soil map for the watershed. The soil map assists in obtaining the soil erosivity factor for the study area. The IRS- 1A (LISS - II) digital data of the study area (February was also obtained to perform a land use change analysis of the watershed.

In this study, the Revised USLE program (model) developed by the U.S. Natural Resources Conservation Service (NRCS) was not used. The more basic USLE empirical equation (Equation 1) was used to produce the soil loss quantification of the watershed on a spatial basis. The individual parameters for the USLE equation were developed using the advanced modeling tools of GIS and remote sensing software. A flow chart of the aggregate approach to develop watershed soil loss zone is provided in Figure 2. The spatial maps used to calculate the soil loss in the watershed were created either by means of independent GIS usage or a combined application of both GIS and remote sensing as mentioned in the individual cases. The ultimate objective of the study was to facilitate a soil conservation planning program for the watershed. Therefore, drainage density mapping and land use change analysis were also performed on the watershed.

MAP PREPARATION

Land use/land cover map

Land use of an area is very difficult to determine on a plot-by-plot basis using reconnaissance surveys. Satellite images can provide very up to date information on land use. For this study, IRS 1B (LISS-II) digital cloud free satellite image (February 9, 1996) was used to classify the land cover of the study area. Figure 3 illustrates the process involved in land use classification of the image from the computer compatible tape (CCT). An unsupervised classification technique was used to classify the image. Unlike the supervised classification process, it did not require the information on training points. All possible classes were generated by the ISODATA classification technique of ERDAS (Leica Geosystems GIS & Mapping, LLC; Atlanta, GA, USA). The classification accuracy of the unsupervised classified images was evaluated by selecting 300 (50 from each class) random points and performing ground truth using the global positioning system. The statistical software package SPSS's (SPSS Inc., Chicago, IL) Ward minimum variance method of the cluster merging technique was used to obtain the information on merging of clusters based on the Euclidean distance of cluster center values. Thus, we obtained our required six clusters (land use classes) from the image. Figure 4 shows the land use classified map of the satellite imagery.

Slope and aspect map

Figure 5 illustrates the procedure of the "slope and aspect map" production for the study area. The contour lines of the study area were digitized from the topographic map of the study area in PC Arc INFO (ESRI, Redlands, CA, USA) and later transferred to ERDAS software to prepare the slope gradient and aspect map of the study area (Figures 6 and 7). The surface generation procedure of the ERDAS was used to create the maps (Panda and Andrianasolo, 2000). The aspect map provided the slope direction of the watershed that later helped in slope length calculation for USLE analysis.

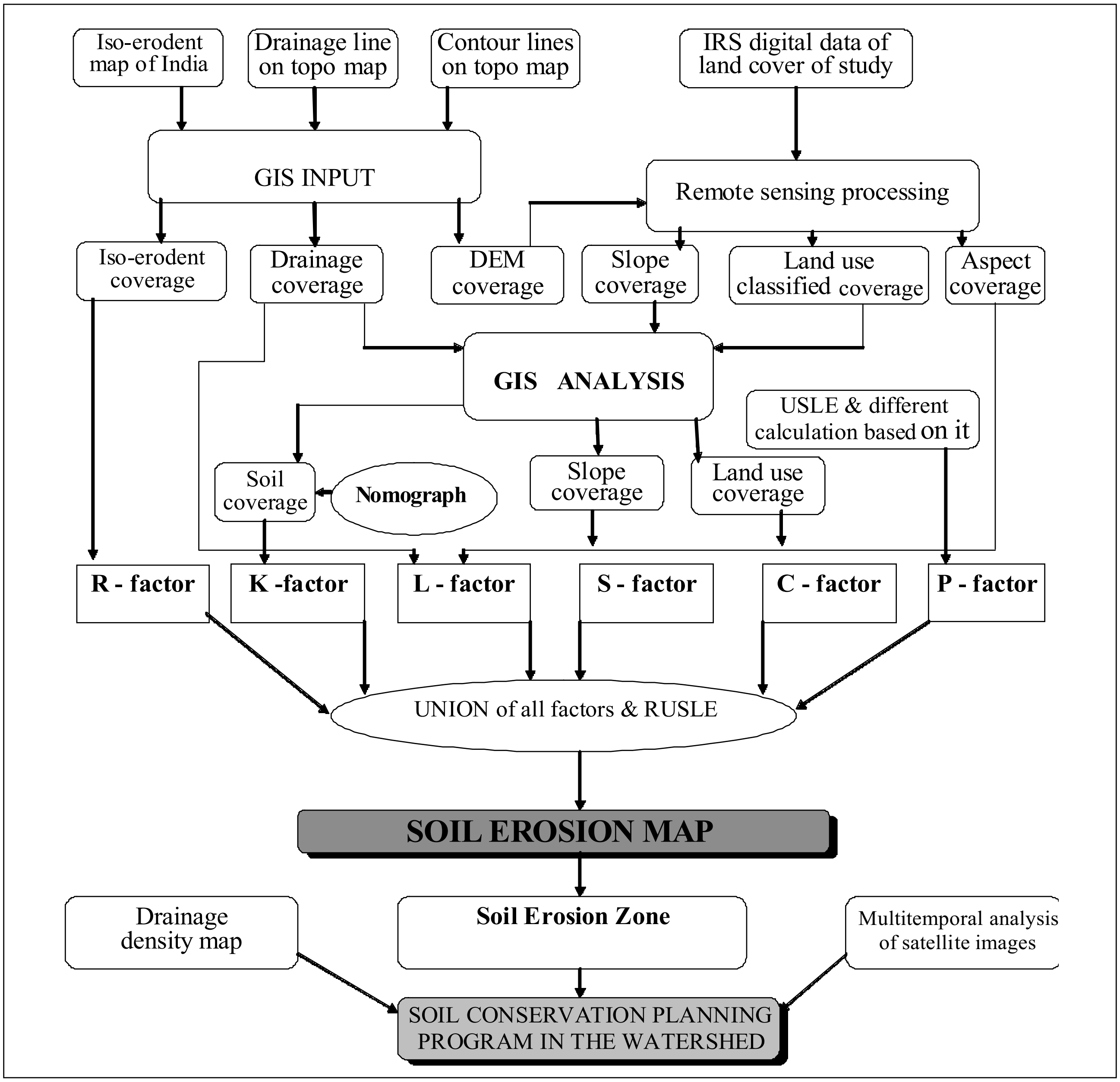


Figure 2. Schematic of the aggregate procedure involved in soil conservation planning program.

Soil map

A soil map was prepared for the watershed as there was no readily available soil map for the watershed. A soil map of the study area was prepared using field verification (ground truth), the laboratory test report of soil from the field, the FAO soil classification chart to interpret the soil class in the field, and personal physical verification in the field to determine the thickness of buffers along drainages (second order). The land use classification map (Figure 4) and the slope gradient map (Figure 6) were used for this purpose. The soil map preparation procedure is shown in Figure 8.

INDIVIDUAL USLE SPATIAL FACTOR DEVELOPMENT

Rainfall erosivity index (R)

The iso-erodent map for India (Figure 1 top) was used to find the rainfall erosivity index factor of the study area (Rambabu et al., 1978). The study area lies between 500 and 600 numeric iso-erodent

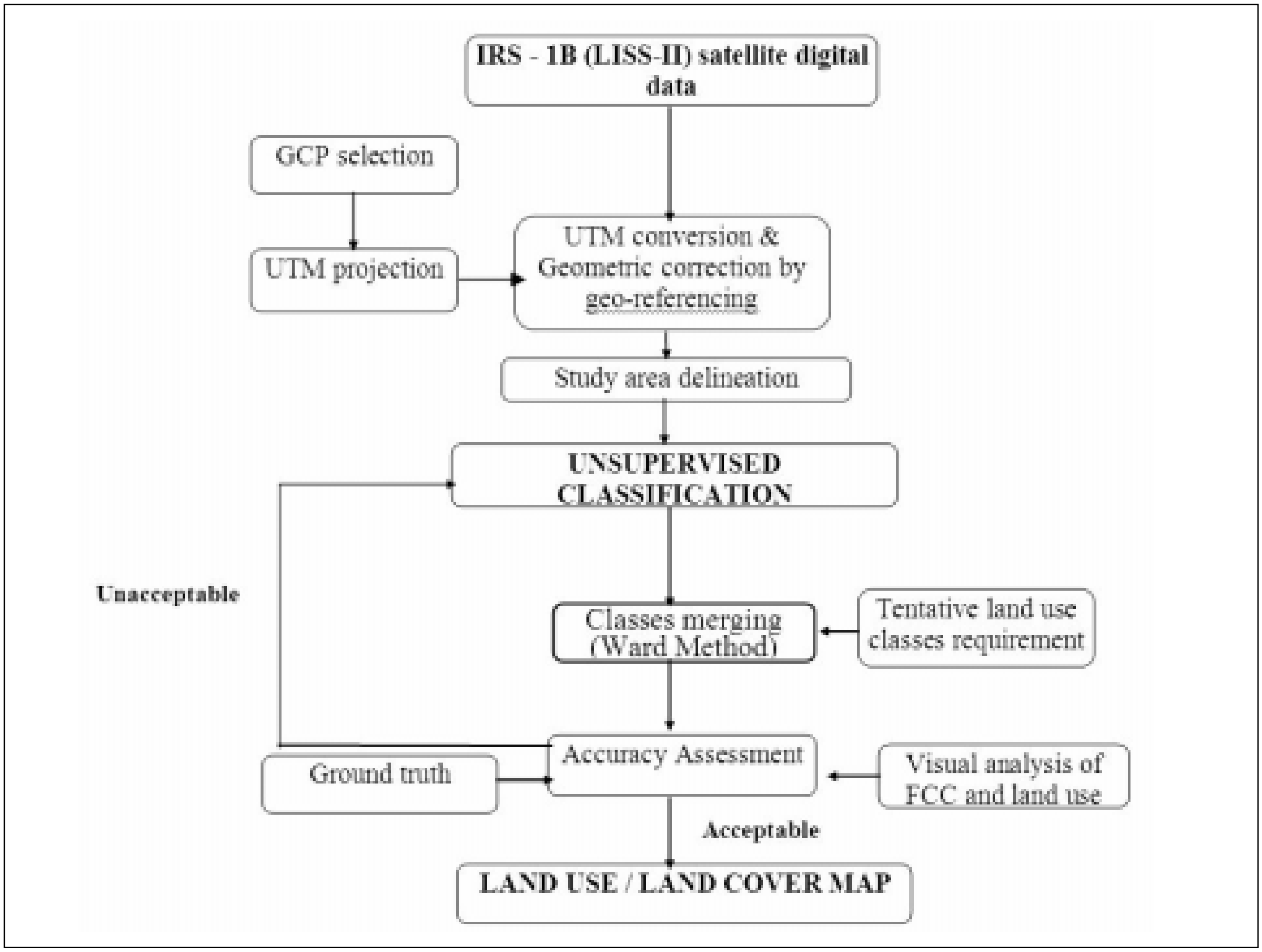


Figure 3. Schematic of land use classification process.

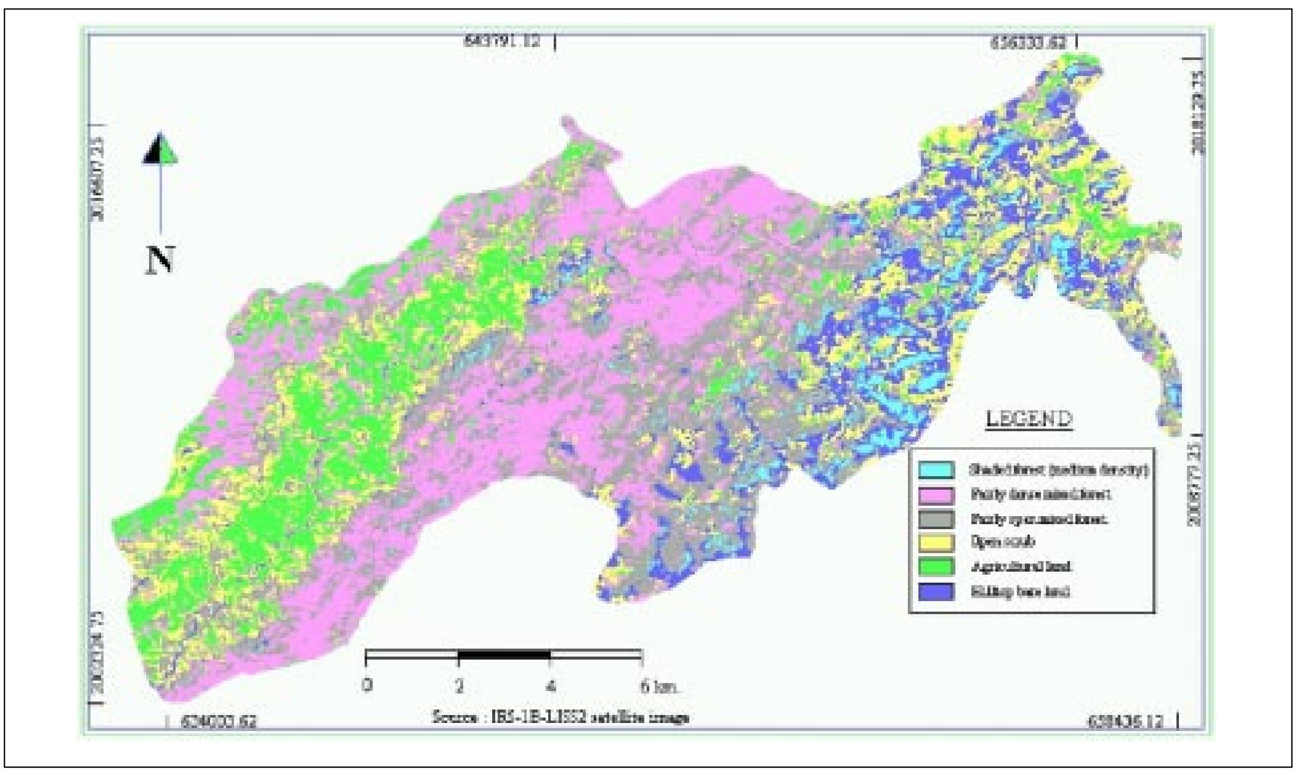


Figure 4. Land use classification map of the study area (1996).

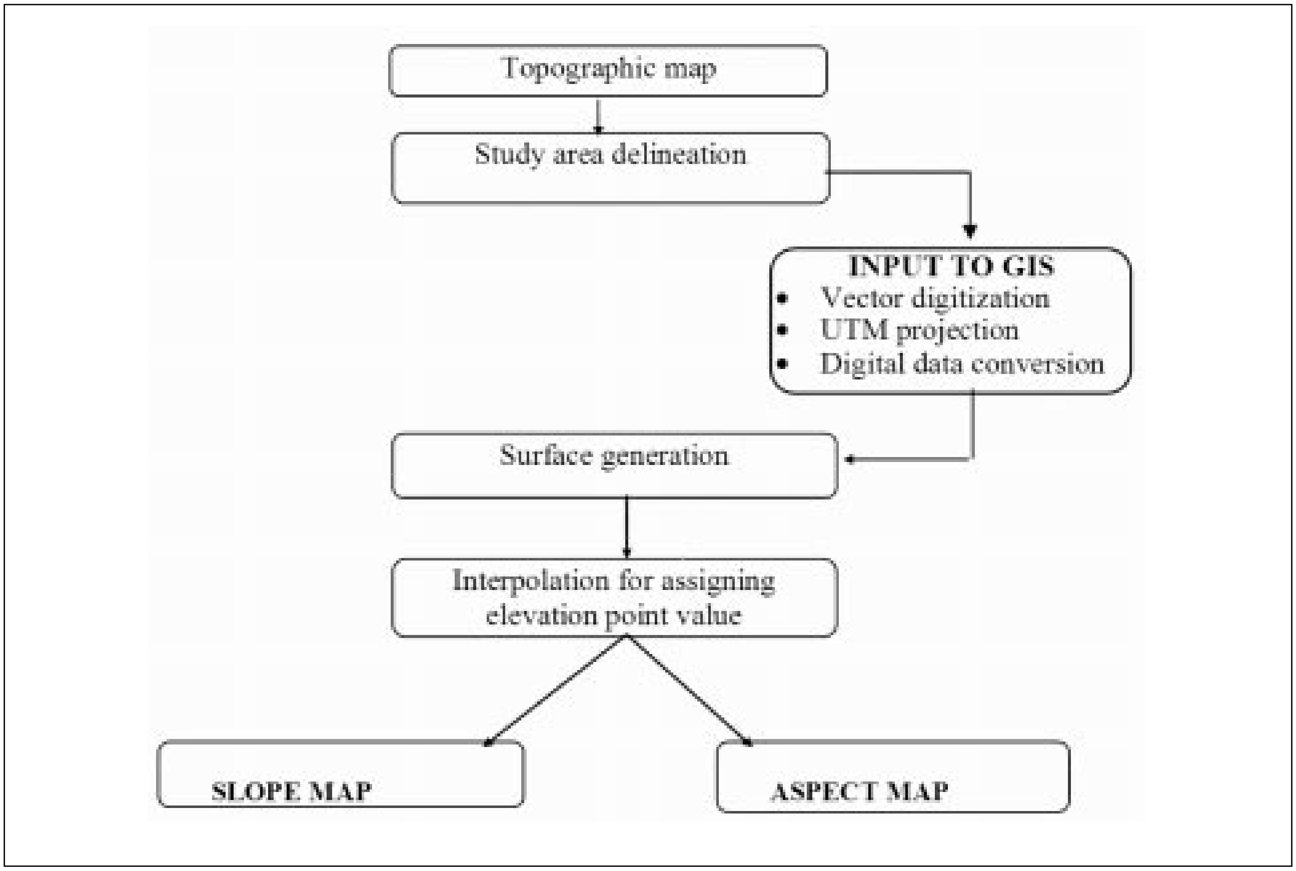


Figure 5. Schematic of 'slope and aspect map' generation procedure.

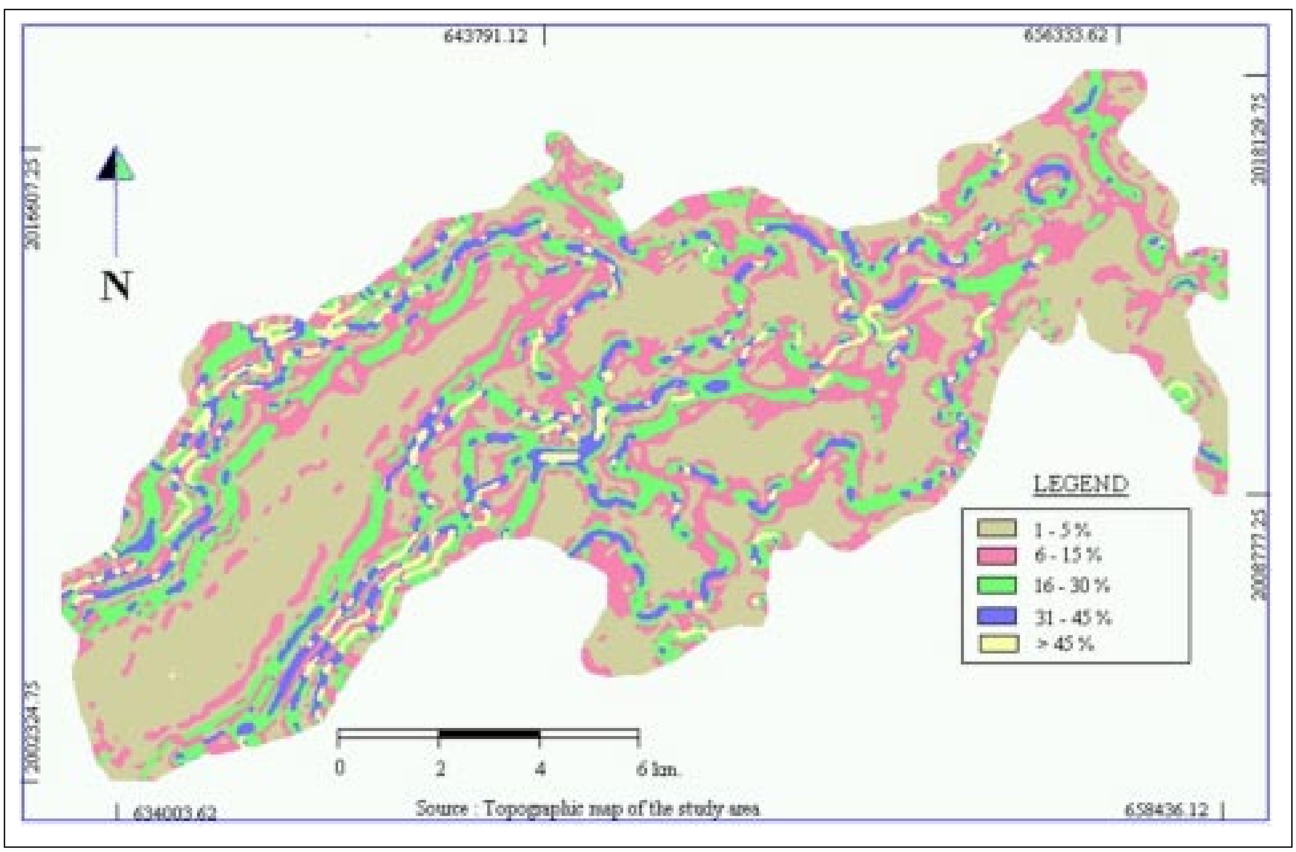


Figure 6. Spatially generated slope map of the watershed.

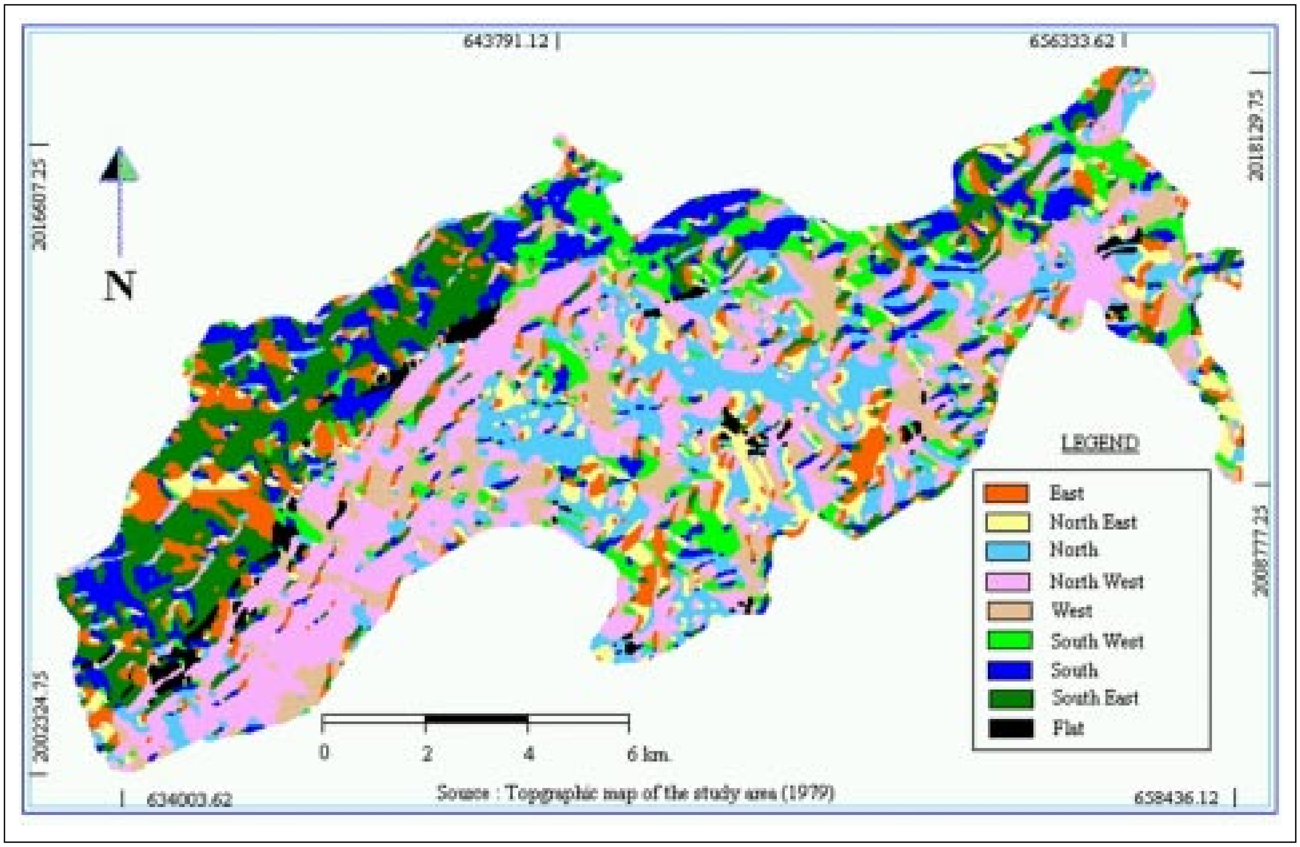


Figure 7. Spatially generated aspect map of the watershed.

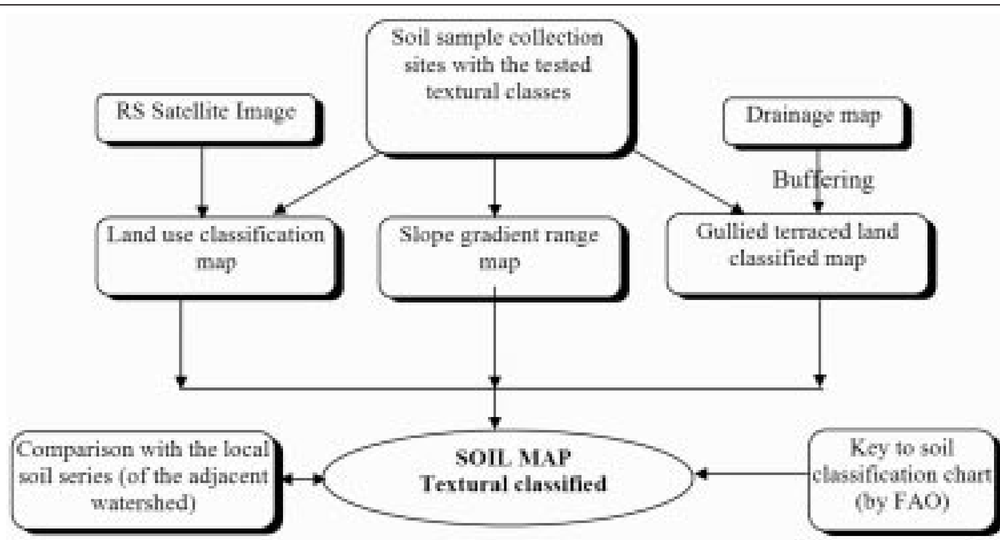


Figure 8. Schematic of soil map preparation procedure.

lines. The iso-erodent line of the study area was approximated by linear interpolation. Thus, the rainfall erosivity index for the watershed was calculated to be 525 metric units.

Soil erosivity factor (K)

The soil erosivity factor, K, relates to the rate at which different soils erode. However, it is different than the actual soil loss because it depends upon other factors, such as rainfall, slope, crop cover, etc. Soil erosivity index factors (K) were evaluated by the soil erosivity nomograph (Wischmeier and Smith, 1978), using soil properties like sand, clay, silt, very fine sand (VFS), organic matter content in soils, structure type, and the permeability of soil (extracted from the laboratory test of soil samples). The K values for each type of soil were calculated as shown in Table 1.

Table 1. Calculated (from nomograph) Soil Erosivity Index Factor Used in the Study

Soil texture	**'K' value**
loamy sand	0.344
sandy loam	0.244
loam	0.377
sandy clay loam	0.277

Slope length and gradient factor (LS)

The following empirical formula (USDA-NRCS, Engineering Division, Washington D.C.) was used to calculate the 'LS' factor for each slope gradient percentage (1 to 45%).

$$\mathrm{LS} = \sqrt{\lambda / 100\left(0.136 + 0.097s + 0.0139s^2\right)} \tag{2}$$

where λ is measured slope length in the field and s is slope gradient in percentage.

For convenience, the LS factor for a slope range > 45% was considered to be 45%, because the area under the >45% slope range was small. The slope gradients were determined by ERDAS software. The area under each slope gradient was also calculated for each sub-watershed. The average slope lengths (λ) were calculated for each 17 sub-watersheds, which represented the entire watershed (Figure 9). We used individual sub-watershed's average slope length as the slope direction, which was quite different in each sub-watershed. The slope length was measured and averaged using the drainage network in each sub-watershed and the aspect map (Figure 7) was used to determine the slope direction. The actual field slope length was calculated using the equation:

$$\mathrm{FSL}_{act.} = \mathrm{MSL}_{avg.} \times \mathrm{MS} \tag{3}$$

where $\mathrm{FSL}_{act.}$ is actual field slope length, MSL_{avg} is average map slope length, and MS is the scale magnitude. The average slope length and the LS factors are provided in Table 2 for each slope gradient range. This is the only modification to the general USLE program that we used in this study. This procedure helped in generalizing our actual SL value for the entire watershed.

Crop cover and management factor (C)

The cropping management factor, C depends upon several factors including crown coverage, ground cover, crop sequence, length of the growing season and tillage practice (furrow cropping). Hence, it was the most complicated of the USLE parameters, as there were many ways of managing the growing crops in the entire watershed. There were also different types of forests according to their density, i.e., fairly dense mixed forest, fairly open mixed forest and open scrub (small/dwarf plants), and shaded forest (a mix of dense and thin forest, i.e., medium density forest). The six land use classes were found in the satellite image as medium density forest, fairly dense mixed forest, fairly open mixed forest, open scrub, agricultural land, and hill top bare land. For this study, the C-factors (Table 3) were considered by referring to the studies of Wischmeier et al. (1978) and Sriniwash et al. (1980). The hill top bare lands were due to the shifting cultivation performed by local tribal and stone quarrying. These areas mostly had long rills (up and down), which could be seen from a very long distance. These rills relate to tilled up and down slope, and the bare lands were continuous fallow.

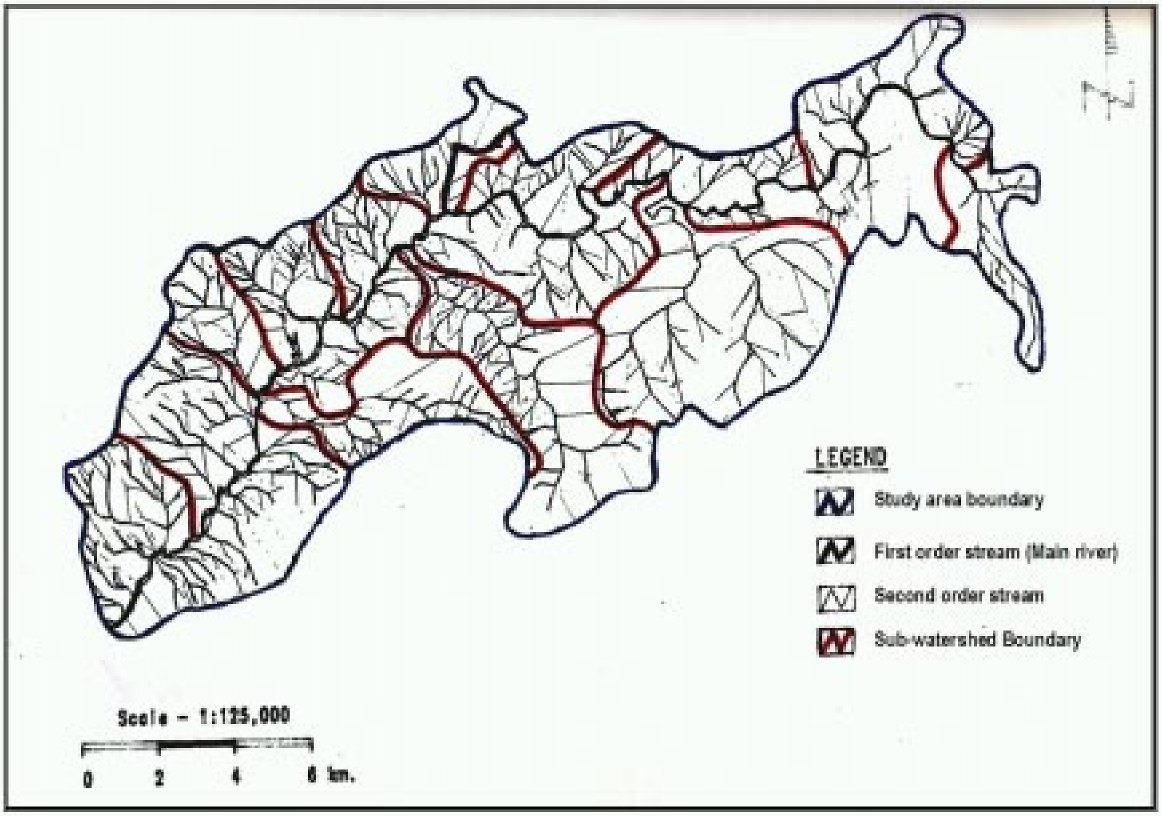


Figure 9. Sub-watersheds in the study area (boundary of sub-watershed includes the part of study area boundary, main river (in the center), and the sub-watershed partition).

Table 2. Average Slope Length and LS Factor for Different Slope Gradient Ranges Used in the Study

Sub-watershed (by nomenclature)	**λ (m)**	**LS factor**				
		1-5%	6-15%	16-30%	31-45%	> 45%
SW11	205	1.98	4.35	8.20	12.77	14.84
SW12	179	1.85	4.06	7.67	11.93	13.88
SW13	178	1.84	4.05	7.66	11.92	13.85
SW14	161	1.75	3.85	7.28	11.32	13.17
SW15	130	1.57	3.46	6.54	10.18	11.83
SW16	239	2.13	4.69	8.86	13.79	16.03
SW17	189	1.90	4.18	7.90	12.28	14.28
SW18	161	1.75	3.85	7.28	11.32	13.17
SW19	212	2.01	4.43	8.36	13.00	15.12
SW21	123	1.53	3.37	6.36	9.90	11.51
SW22	152	1.70	3.74	7.06	10.99	12.77
SW23	129	1.57	3.45	6.51	10.13	11.78
SW24	155	1.72	3.79	7.15	11.12	12.93
SW25	142	1.65	3.62	6.83	10.62	12.35
SW26	227	2.08	4.58	8.65	13.45	15.65
SW27	189	1.90	4.18	7.90	12.28	14.28
SW28	227	2.08	4.58	8.65	13.45	15.65
Watershed average	-	1.82	4.11	7.58	11.79	13.71

Table 3. Crop Cover and Management Practice Factor for the Watershed

Land use type	"C" Factor
Medium density forest	0.004
Fairly dense mixed forest	0.002
Fairly open mixed forest	0.006
Open scrub	0.014
Agricultural land	0.380
Hill top bareland	1.000

Supporting conservation practice factor (P)

In the study area, the general practice of the farmers in the cropland was tilling along the contour lines. The 'P' factors for land uses were based on Indian conditions (Table 4) and are described in Bhatia et al. (1977).

Table 4. Support Conservation Practice Factor for the Watershed

Land use type	"P" factor
Agricultural land	0.39
All other land use except agricultural land	1.00

GIS module for integrating USLE factors

All the USLE parameters determined for the study area were either in spatial format and/or in numerical format. The spatial maps and other factors were integrated and analyzed (Figure 3) with the help of the Arc INFO GIS module. Arc Macro Language (AML) programs were written in Arc INFO to integrate either the spatial or numeric data of all the USLE parameters, representing even the very smallest of the polygons (each pixel of 36.25 m x 36.25 m on ground) of the study area. Each small polygon (area) might have USLE parameters different from the adjacent polygons. We obtained tens of thousands of polygons in the study area with independent parameter values, thus having individual soil loss rates. These values were calculated based on USLE empirical formula (Equation 2) to derive the soil erosion rate. These polygons with independent soil loss values were merged together according to their range of soil loss amounts based on a tolerance level as discussed. As for Indian conditions, the considered soil loss tolerance level is within the range of 4.43-11.2 T ha^{-1} yr^{-1} (Dhruvanarayan et al., 1983). Therefore, a range of classes based on the soil loss quantity in accordance to the tolerance range was considered (Table 5). The sub-watershed boundaries were clipped from the watershed-digitized map. Thus, soil loss information for individual sub-watersheds was also obtained. A similar procedure (with new AML program) was used to obtain the average soil loss from each sub-watershed.

Table 5. Area Under Various Soil Loss Zones (in 1996) of the Watershed

Soil loss zone	Range (T ha^{-1} yr^{-1})	Area (ha)	%
Low	< 4.43	14758.20	81.60
Moderate	4.43 – 11.2*	2026.79	11.21
High	11.2 – 25.0	852.51	4.72
Very High	>25.0	430.50	2.38
	Total area:	18068.00	100.00
Average soil loss	10.80	*(High moderate range of soil loss)*	

Drainage density map preparation

For soil conservation program planning, the spatial analyses of drainage lines are essential. The drainage lines play a vital role in soil erosion. The drainage network of the study area was digitized from the topographic map using PC Arc INFO. The study area was divided into 237 square grids of 1000 m x 1000 m. Only two types of drains were present in the study area. The small drains were considered as the second order drain and the main river as first order. AML codes were written in Arc INFO to calculate the total length of drainage in each grid. The drainage length of the main river (first order) was given twice weight compared to the other second order streams due to its large size. The following equation was used to calculate the grid drainage density.

$$D_d = A_d \times L_d , \quad (4)$$

where D_d is drainage density, A_d is the grid area (1 km^2), and L_d is sum length of the drains in each grid. The area of each grid polygon was calculated and multiplied by the total drainage length in each grid to determine the drainage density. Each drainage grid was assigned to one of four groups based on the drainage density. The drainage density groups were <1 km^3 (low), 1-<2 km^3 (moderate), 2-<3 km^3 (high), and ≥3 km^3 (very high). Figure 10 shows the drainage density map of the watershed.

Land use change analysis

In this study, forest cover change detection was the most important consideration to propose a soil conservation-planning program. It determined the loss of forest cover and other developments in the watershed, thus providing input for a plantation program in the deforested land cover of high and medium slope regions. The two satellite images, IRS-1B (LISS-II) of 9 February 1996 and IRS-1A (LISS-II) of 2 February 1989, were used to obtain the temporal changes in land use and land cover of the study area, which determines the land use changes that occurred during the 7-year period. The land use change analysis for this watershed was carried out in another study by the main author (Panda et al., 2004) and the result from that study is used in this study for the soil conservation program planning for the watershed.

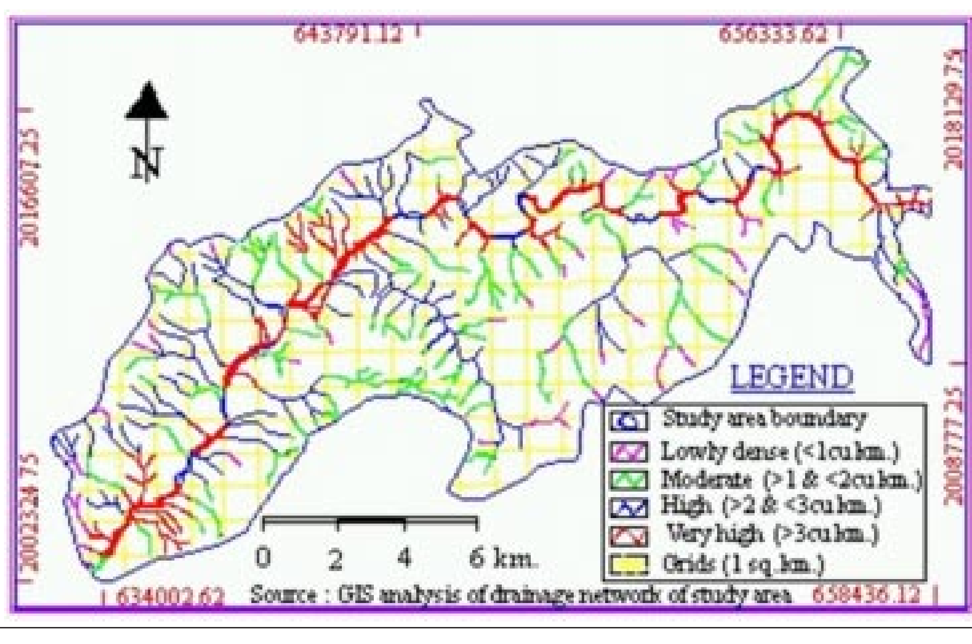


Figure 10. Drainage density map of the watershed.

RESULTS, DISCUSSION, AND SOIL CONSERVATION PLANNING

Spatial soil loss quantification

The soil loss zoning spatial map is provided in Figure 11. The average soil loss of the watershed was estimated to be 10.80 T ha^{-1} yr^{-1}. A very high percentage (81.60%) of the watershed area was in the low range of the soil loss zone, i.e., <4.43 T ha^{-1} yr^{-1} (Table 5). Eleven percent of the watershed area was within the permissible level of soil loss in Indian conditions, i.e., 4.43 - 11.2 T ha^{-1} yr^{-1} (Table 5) (Dhruvanarayan et al., 1983). Only 8% of the land was under the high or very high soil loss category, as most of the watershed was under the forest cover, which has a positive effect on reducing soil erosion. Agriculture and the bare lands made up the major soil erosion potential areas. The geodatabase tool of Arc INFO was used to obtain a quantitative extent of soil loss based on different land use, soil, and slope features of the watershed.

Table 6 provides information on the area covered under different land use types in 1996. Average soil loss from different land uses is also provided. As expected, the hill top bare land had the highest average soil loss, amounting to 85.20 T ha^{-1} yr^{-1}. Agricultural land had the second highest soil loss amount, as the inhabitants of the area followed the 'single cropping season practice' due to dependency on rain because irrigation facilities are absent in the study area. Thus, soil conservation planning should be stressed in agricultural and bare land use areas. Other land use types had low soil loss averages.

Soil loss information for different slopes is provided in Table 7. The area covered under each slope gradient is also provided. The average soil loss increased as slope increased. The 1-5% slope had the lowest average soil loss of 4.32 T ha^{-1} yr^{-1}, while the >45% slope had the greatest soil loss of 26.50 T ha^{-1} yr^{-1}. Thus, more emphasis should be provided to the higher slope gradient area for soil conservation planning.

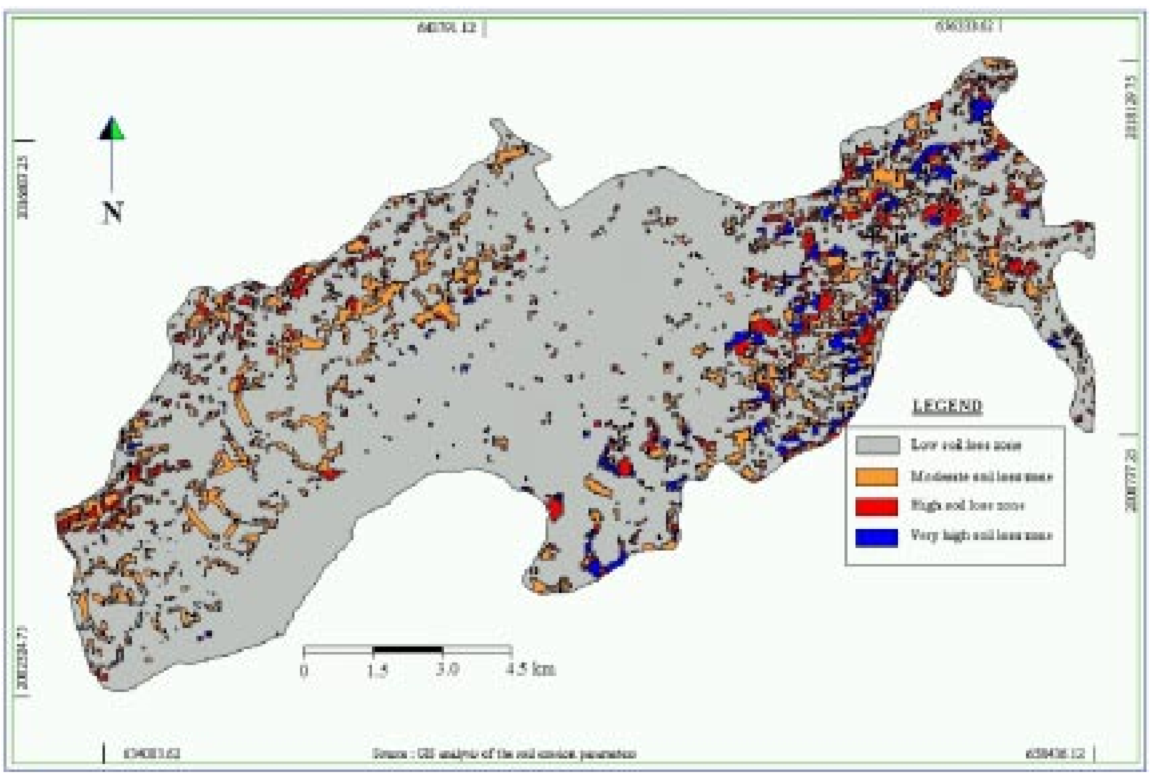


Figure 11. Spatial soil loss zone map of the watershed.

Table 6. Soil Loss Amount from Different Land Use (in 1996) of the Watershed

Land use classes	Area (ha)	%	Average soil loss (T ha^{-1} yr^{-1})
Medium density forest	603.95	3.34	0.412
Fairly dense mixed forest	4955.01	27.42	0.234
Fairly open mixed forest	4976.38	27.54	0.566
Open scrub	2965.94	16.42	1.1
Agricultural land	2723.30	15.07	11.22
Hilltop bareland	1843.41	10.20	85.20

Table 7. Soil Loss Rate in Different Slope Gradient Ranges (in 1996) of the Watershed

Slop gradient ranges	Area (ha)	%	Average soil loss (T ha^{-1} yr^{-1})
1 to 5 %	7626.75	42.21	4.32
6 to 15 %	5058.18	28.00	9.45
16 to 30 %	3323.47	18.39	19.55
31 to 45 %	1361.49	7.54	22.72
> 45 %	698.10	3.86	26.50

Table 8 shows the average soil loss amount based on different soil types in the watershed. The largest area in the watershed has a sandy loam soil with 53.63% coverage and an erosion rate of 6.97 T ha^{-1} yr^{-1}, while the average soil loss from the loam soil was the highest with 61.98 T ha^{-1} yr^{-1} for 5.06% of the area. As the loamy soil was responsible for very high soil loss, emphasis should be given to the area with that soil type while planning soil conservation measures. Loamy sand covering 20.02% of the watershed area, with an average soil loss of 12.56 T ha^{-1} yr^{-1}, needed special care also for soil conservation measures. All this information is used later in the formulation of a soil conservation plan for the watershed.

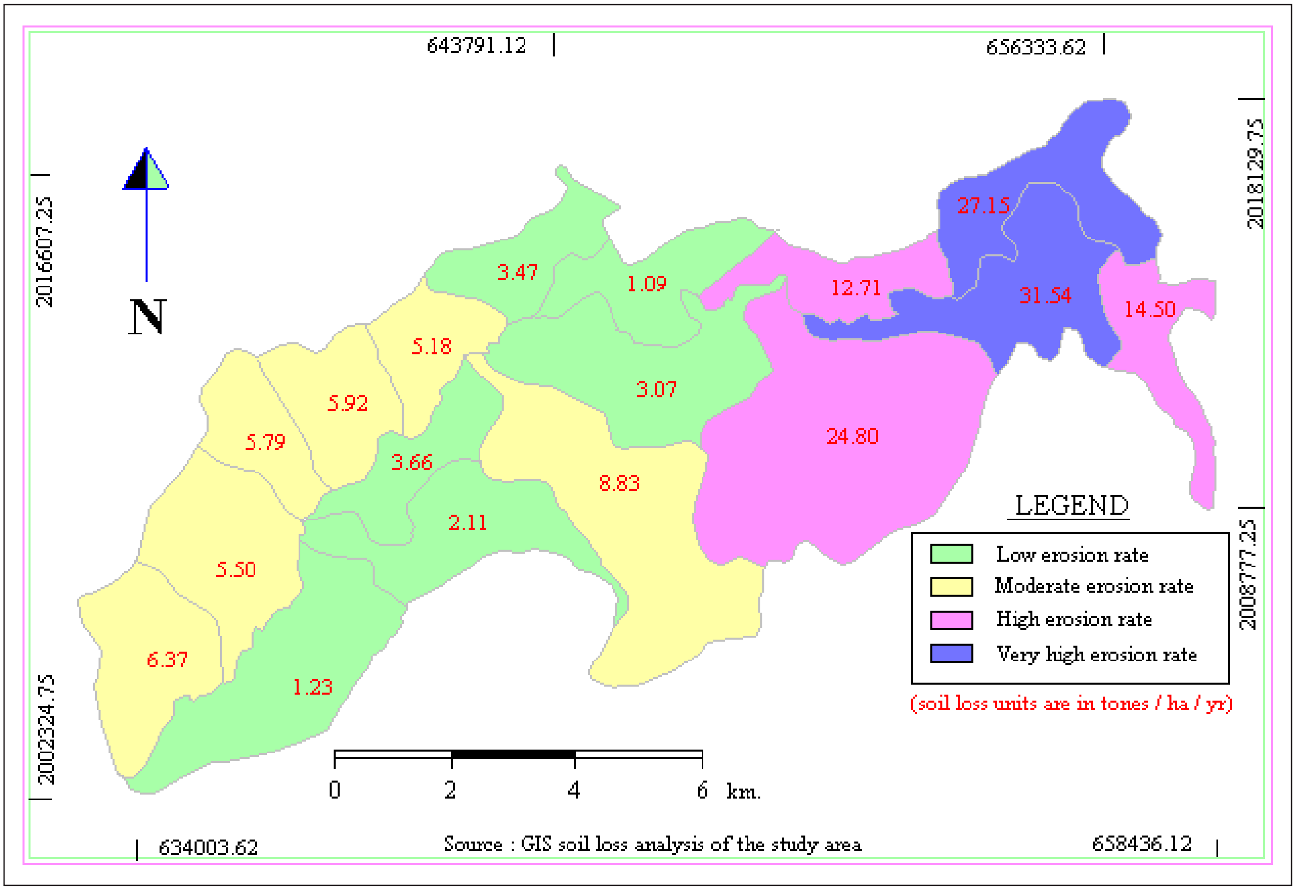
The soil loss amount from each sub-watershed was also calculated. This analysis provides insight to the soil conservationists to prioritize their planning based on the sub- watershed. The highest priority should be given to two sub-watersheds, including SW16 (SW represents the sub-watershed) at the eastern side of the watershed, with the highest average soil loss. However, as three other sub-watersheds were under the high soil loss category with 11.2 - 25 T ha^{-1} yr^{-1} soil losses, they also need immediate care in a soil conservation plan. Figure 12 provides the detailed average soil loss amount and the type of soil loss (on a range basis) in each sub-watershed.

Validation of results obtained from this study

One of the objectives of this study was to validate the spatial soil erosion results obtained from the USLE analysis using GIS and a remote sensing modeling technique. The results obtained from this study were validated with other studies, which used different techniques (mechanical method calculation) under similar land use, topographic, and soil condition as used in this study. The average soil loss from the watershed in 1996, 10.80 T ha^{-1} yr^{-1} was similar to the 12.69 T ha^{-1}

Table 8. Soil Loss Rate for Different Soil Types (in 1996) of the Watershed

Soil classes	Area (ha)	%	Average soil loss (T ha^{-1} yr^{-1})
Loamy sand	3617.78	20.02	12.56
Sandy loam	9689.65	53.63	6.97
Loam	914.52	5.06	61.98
Sandy clay loam	3846.11	21.29	6.64



* The inscribed number inside each sub-watershed represents the average soil loss in tons/ha/yr

Figure 12. Map of the sub-watersheds in the study area based on soil loss.

yr^{-1} measured in 1991 for the same watershed (Report of The Department of Soil Conservation, Orissa, India) using mechanical methods. Therefore, the approach used to calculate soil loss in this study was comparable to soil loss determined for Indian watersheds in other studies. Above all, the technique used in this study can make soil erosion rate estimation a quick and inexpensive process.

In India, there are extensive studies on soil loss estimation in different watersheds, regions, and conditions, such as slope, land use, soil types, and so on. In these studies the researchers used different tools for the soil erosion rate calculation, and these results were useful for comparison with the results obtained from this study. Table 9 provides a comparative statement of these results. This comparison chart supports the validity of our technique for estimation of soil losses for Indian watersheds.

This watershed under study was marked by the federal government of India (Department of Soil Conservation, Orissa) as a medium priority watershed on the basis of soil conservation requirements. This suggested that the average soil loss of the watershed was within the permissible level of soil erosion rate, i.e., 4.5 to 11.2 T ha^{-1} yr^{-1}. The result from this study agrees with the federal government finding.

Decision support on soil conservation planning program

The factors affecting erosion by water are climate, soil type and properties, vegetation (includes the forest cover and cultivation), and to a limited extent, topography (Schwab et al., 1981). In this study, we cannot manage the climate and soil properties. However, the vegetation and the topography of the watershed could be controlled to reduce soil loss due to water erosion. Based on the quantified soil losses due to various land uses, slopes, and soil types, the following soil conservation measures were suggested for the study area to reduce the soil erosion amount. The GIS tool was most useful in delineating the positions of the soil conservation programs and structures in the watershed. A decision support system was developed to construct the soil conservation program in the watershed under study based on the results obtained with geotechnological model development and socioeconomic analysis of the study area.

Water harvesting structures (WHS) (Figure 13) were proposed at a lower part of the second order drainage (small streams) passing through the agricultural lands with low and moderate slope gradient ranges. These structures will harvest runoff and, consequently, will reduce its flow or velocity while flowing through depression zones, and scouring will be minimized. The silt eroding

Table 9. Comparison of the Soil Loss Amount of this Study with Earlier Research Results for Studies Completed in the Indian Condition

Watershed conditions	**Soil loss result from earlier study***	**Soil loss result from our study ***	**Remarks**	**References**
Slope: 4 %; Land use: maize crop (Soil loss was calculated from test plots)	12.4 to 19.9	11.22	As 'jowar followed by horsegram' (in our study area) was much denser in crop growth stage then 'maize cropping' in the field	Bharadwaj et al. (1979)
Land use: 100% dense 'sal' forest (soil loss was calculated using mechanical method)	0.9	0.234	In our study, the dense forest was more homogeneous and denser than the 'sal' forest under comparison	Subbarao et al. (1973)
Land use: 100% dense 'sal' forest; Soil: silty clay loam (soil loss was calculated using mechanical method from a 0.45 hectare watershed)	0.06	0.067	Same behavior due to parameter similarity with our study	Anonymous
Land use: 82% forest & 18% agriculture (thin forest equivalent in our study)	0.4	0.566	Although the land use conditions did not exactly match, still the result was more similar	Dhruvanarayan et al. (1985)
Land use: hilly area agriculture land with soil conservation practice	1.0 to 19.0	11.22	Within the calculated range	Sharma et al. (1975) and Bharadwaj et al. (1979)
Land use: slash and burn agriculture (first year abandoned land); Slope: 60-70%	30.20	37.85	In our study, the fallow agriculture land in the high slope (> 45%) is equivalent to the land use of the comparing research result	Singh (1980)
Land use: bare fallow; Slope: 9%; (in northern Himalayas)	42.2	67.95	Our study has the bareland area in higher slope (> 45%) region, thus, the soil loss quantity was higher	Singh (1985)

away to the river, and subsequently to the reservoir below, will be halted in the WHS. The harvested water could be used for cultivation purposes. Diversion weirs (DW) (Figure 13) were planned in the low or moderate slope gradient ranges. DW and WHS could be alternated based on the field feasibility studies. Gully control structures (GCS) were proposed at the head of the second order streams (Figure 13). These structures when constructed at the gully head will impede gully head advancement. A few earthen check dams (Figure 13) were also proposed to the lower portion of the proposed GCS in the second order streams and above the WHS/DW. These check dams reduce the flow of runoff water and diminish the velocity and scouring potential. They also help in infiltration of runoff, thus reducing further the soil loss potential. A large dam was proposed on the main river just before the upstream of the 'agricultural land zone' (Figure 13) in the watershed. It could help in irrigating the agricultural land and thus increasing vegetation cover to reduce soil erosion.

Based on the slope gradient and vegetation cover determined from this analysis, bench terraces, hillside ditches, individual basins, orchard terraces, mini convertible terraces, and contour bunds were planned in the area of high slopes in the mountains (Figure 6). These structures would help in reducing the slope of the land, and subsequently reduce soil erosion.

The land use change analysis (Panda et al., 2004) of this study area also suggested another feature of the soil conservation program. In the very steep slopes where even terrace construction is not possible, an afforestation program was proposed. This program was planned to change the vegetation density to reduce the soil loss amount. The sites chosen for the plantation measures were hilltop bare land to be determined from the land use classification map, Figure 4. Figure 14 shows the proposed locations for the plantation program. In the study area, it was concluded that the forest cover has increased since 1989. The increase in forest cover and density was due to forest protection measures undertaken by forest protection village committees. Hence the best possibility of reducing the soil loss of the watershed was to implement large-scale forest

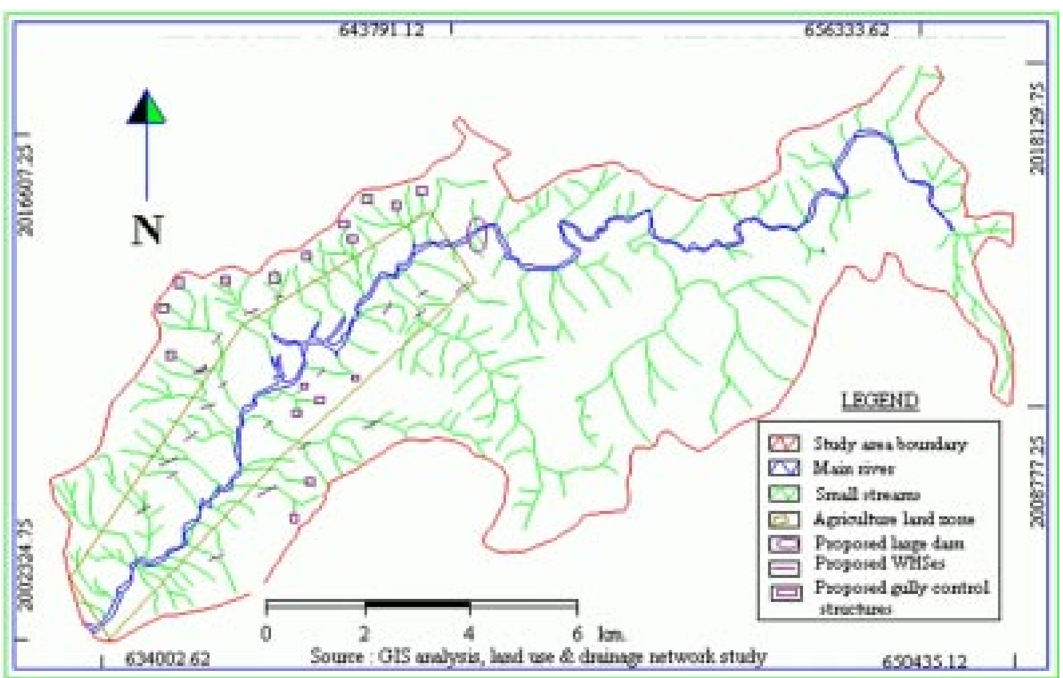


Figure 13. Proposed soil conservation measures (engineering structures) in the watershed.

protection measures. These measures were proposed for the fairly open mixed forest and open shrub areas with a variety of slope ranges.

Large scale avenue plantation (Tree plantation alongside the roads and trails) was proposed in the area devoid of forest cover (agriculture land area). In the moderate slope range of the open scrubland and bare land, a horticulture plantation program was proposed. This program is essential, because of the poor economical condition of the tribal areas in the watershed.

Proper and judicious choice of farming practices could help reduce soil erosion in moderate sloping agricultural lands. Strip cropping and crop rotation were planned to reduce wind and water erosion in these areas. Above all, soil conservation measures should be planned based on land use, topographic condition, road network, drainage network, and land use changes over the years.

Heavy soil loss occurs if the soil of the stream/river bank is loose. Again, if the drainage density in an area is greater, the stream bank erosion is expected to increase. Therefore, with reference to the drainage density map in Figure 10, stream bank erosion control (SBEC) measures were proposed. Soil loss due to gully and stream bank erosion is not accounted for by the soil loss calculation using USLE. Hence, the measures could be most effective in the sense of total soil conservation planning of the watershed. The SBEC measures planned were of two types: a) plantation along the stream banks and b) construction of bunds along the banks with intermediate waterways at the easiest points where the scouring effect is much lower.

As soil conservation measures are generally undertaken by the reconnaissance survey, this study provided a basis of proposing a large-scale soil conservation program without any direct physical information for the watershed. In addition, soil conservation measures could be implemented on a sub-watershed basis considering the same features in each sub-watershed (Figure 12). The soil conservation program should be prioritized in the sub-watersheds, where the soil loss amount is high or very high (Figure 12). However, these soil conservation measures should be verified in the field before actual implementation.

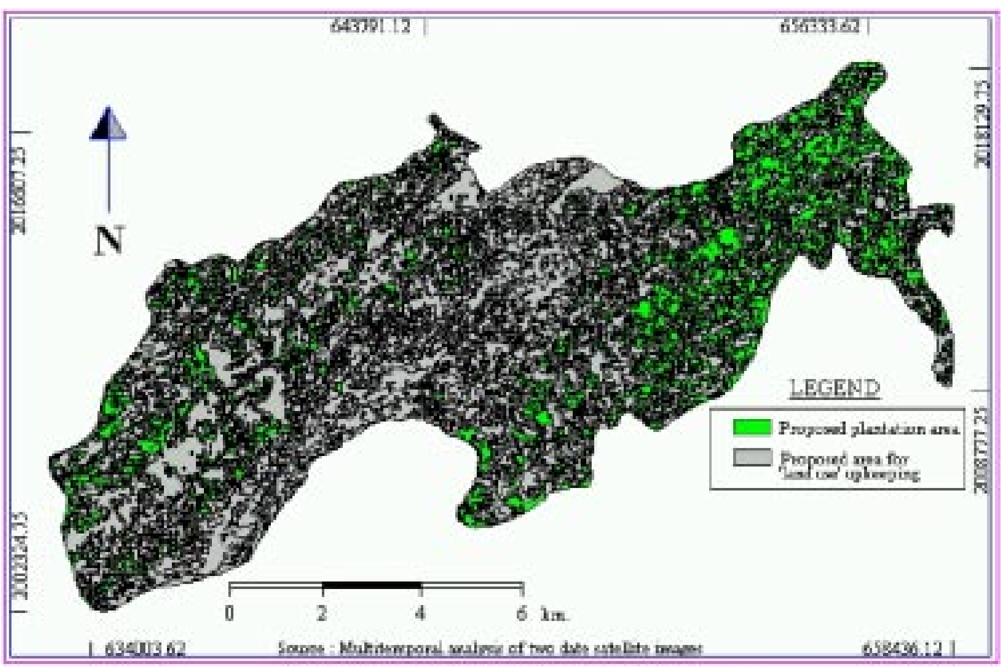


Fig. 14. Proposed plantation program site in the watershed.

CONCLUSIONS

The methodology used in this study provided a promising framework for developing a sustainable and cost effective soil conservation planning program in inaccessible mountainous watersheds. The use of the USLE along with satellite images and GIS techniques provided very useful tools in the study. The results were validated with results obtained from studies using other mechanical methods as well as research using test plots. The comparison of the results was very promising.

It was concluded from this study that an integration of remote sensing, GIS, and the USLE empirical equation could be used in any watershed to determine the soil loss. The advent of GIS technology made it possible to estimate soil loss as a function of land use, soil type, and slope gradient of the watershed. On a sub-watershed basis, soil losses were also estimated. A temporal image analysis was performed to verify the land use changes in the watershed over the years to facilitate recommendations for a soil conservation program in the study area. GIS was a suitable tool for data analysis, management, and storage to obtain the research objectives. The mathematical programming of Arc INFO software was a powerful function that made the calculations based on a huge dataset possible. The following additional conclusions based on soil loss quantifications are drawn from this study.

- Hill top bareland and the agricultural land in the study area had the highest soil loss of 85.20 T ha^{-1} yr^{-1} and 11.22 T ha^{-1} yr^{-1}, respectively, as compared to other land uses. Soil conservation planning should be emphasized on these land use areas. However, areas with medium soil losses covering larger percentage of the watershed should not be overlooked, while planning soil conservation programs.

- The soil loss from areas with 16% or greater slopes was more than the tolerance level of 11.2 T ha^{-1} yr^{-1} (Dhruvanarayan et al., 1983). Thus, more emphasis should be placed on soil conservation planning in areas with slopes > 16%.

- The loamy soil in the study area was most affected by soil erosion, which amounted to 61.98 T ha^{-1} yr^{-1}.

- The soil losses on a sub-watershed basis were calculated from the watershed map. The study found that SW9 and SW 16 were the worst affected by soil erosion and that SW8, SW 15, and SW 17 were also in the high side of the permissible soil loss amount in Indian conditions. It is recommended that these sub-watersheds be prioritized for soil conservation program implementation.

Finally, using those results, GIS and remote sensing integration helped to propose a soil conservation program for the watershed. This study provides the methodology to develop an economical, quick and efficient soil conservation program in similar Indian watersheds as well as in other parts of the world.

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