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Rainfall-Runoff and Soil Erosion Modeling Using Remote Sensing and GIS Technique – A Case Study of Tons Watershed

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ABSTRACT

In the present study, the rainfall-runoff relationship is determined using USDA Soil Conservation Service (SCS) method. The coefficient of determination (R^2) is 0.99, which indicates a high correlation between rainfall and runoff. The runoff potential map was prepared by assigning individual class weight and scores input map. Annual spatial soil loss estimation was computed using Morgan, Morgan and Finney mathematical model in conjunction with remote sensing and GIS techniques. Higher soil erosion was found to occur in the northern part of the Tons watershed. The soil texture in the affected area is coarse loamy to loamy skeletal and soil detachment is higher. Moreover the land use has open forests, which does not reduce the impact of rainfall. The average soil loss for all the four sub-watersheds was calculated, and it was found that the maximum average soil loss of 24.1 t/ha occurred in the sub-watershed 1.

Introduction

Remote sensing and GIS techniques are being increasingly used for planning, development and management of natural resources. GIS technologies in particular help in integrating various data sets and perform spatial analysis for decision making. GIS and remote sensing are presently being used for solving environment problems like degradation of land by water logging, soil erosion, contamination of surface and groundwater resources, deforestation, changes in ecological parameters and many more. Watershed approach for optimal

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planning, development and management aims at harnessing all natural resources for sustainable development and better living. The factors that play a greater role in the planning and development process of a watershed are its size, shape, physiography, slope, climate, drainage, geomorphology, soil, soil erosion zones, landuse/land cover, surface water and groundwater etc. Remote sensing technology provides the vital spatial and temporal information on these parameters. Recently, many hydrological and environmental applications have been reported which use remote sensing and GIS techniques in conjunction or separately. Keshari (2001) presented the hydrogeological risk of arsenic contamination in West Bengal delta and the GIS applicability of risk assessment with conceptual framework. Dhiman and Keshari (2002) used GIS for establishing a correlation between groundwater quality and geological unit. Ambast *et al.* (2002) suggested the use of satellite remote sensing technology to support management of large irrigation system. The Soil Conservation Services (SCS) method has been used by many researches to determined the rainfall-runoff relationship (Jain *et al.*, 1996; Srinvas *et al.*, 1996; Hariprasad and Chakraborty 1997). Jain *et al.* (1998) estimated runoff in part of Sutlej catchment using SLURP model and GIS. The use of digital elevation models (DEM) in soil erosion assessment has been demonstrated by (Burrough,1986; De Roo *et al.*, 1989; Moore *et al.*,1992, 1993). Saha *et al.* (1992) demonstrated the potential use of satellite based digitally classified soil and land use map and conventionally derived slope and rainfall erositivity data for erosion modeling using the USLE. Sherda *et al.* (1993) carried out study to test the application of GIS in watershed prioritization in Ranga Reddy district of Andhra Pradesh in India. The study showed that by creation of computerized database for maps the composite map generation and calculation of area statistics are prepared much faster and accurately compared to conventional method. Ross and Tara (1993) incorporated GIS into hydrologic modeling and concluded that it helps in minimizing user subjectivity in parameter selection and reduces cost analysis owing to significant time saving. Srinivasan and Eagel (1994) interfaced the agricultural non point source pollution model (AGNPS) and GRASS GIS for computation of soil erosion rates. The effect of temporal variations in rainfall on sediments yields can be approximately simulated by analyzing the isolated rainstorms events (Kothyari *et al.*, 1997), while GIS technique is found to be best suited for quantification of the spatial variation in topographical features of a catchment (Shamsi, 1996).

Recently, GIS technique have been interfaced with some standard hydrologic models either distributed type or empirical parameters type, to capture the spatial variation in computed quantities. Marshrigni and Cruise (1997) have used a GIS with the SLURP model for sediment yield modeling based upon homogeneous hydrological and sediment response units. Kothyari and Jain (1997) have used GIS for estimation of sediment yield resulting from isolated storm events. Jain and Kothyari (2000) further studied the sediment yield modeling using GIS. Thus the GIS and remote sensing technique are used for rainfall-runoff and soil erosion modeling for the Tons watershed. The SCS method is used for rainfall-runoff modeling while soil loss estimation for the study area is obtained using the Morgan, Morgan and Finney (1984) method.

Study Area

The Tons river is a fifth order stream (Fig. 3) forming as a major tributary of river Yammuna. Its watershed covers an area of 92 sq.km in the northwest part of Dehradun district of Uttaranchal State. Broadly, Lesser Himalaya in the northeast and Siwalik range in the southwest bound the study area, river Ganges lies on the eastern side and river Yammuna lies on the western side. The study area lies between 30^0 $20'$ to 30^0 $30'$North and $77^0 55'$ to 78^0 $10'$ East. The location map of the study area is shown in

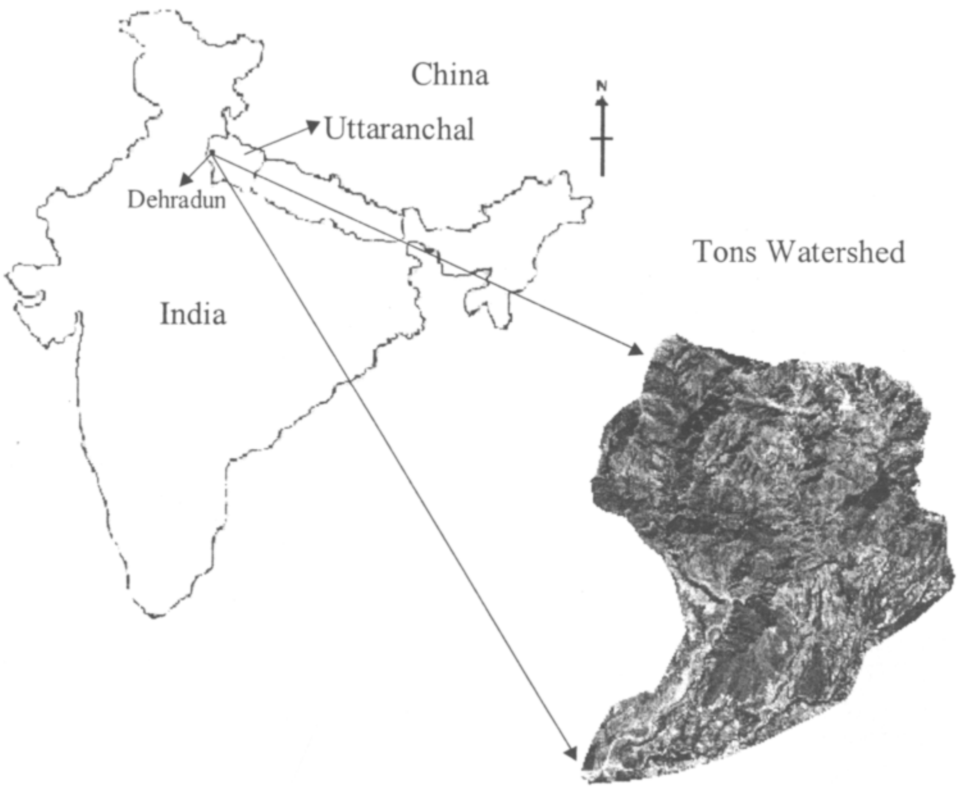

Fig. 1. Location map of the study area.

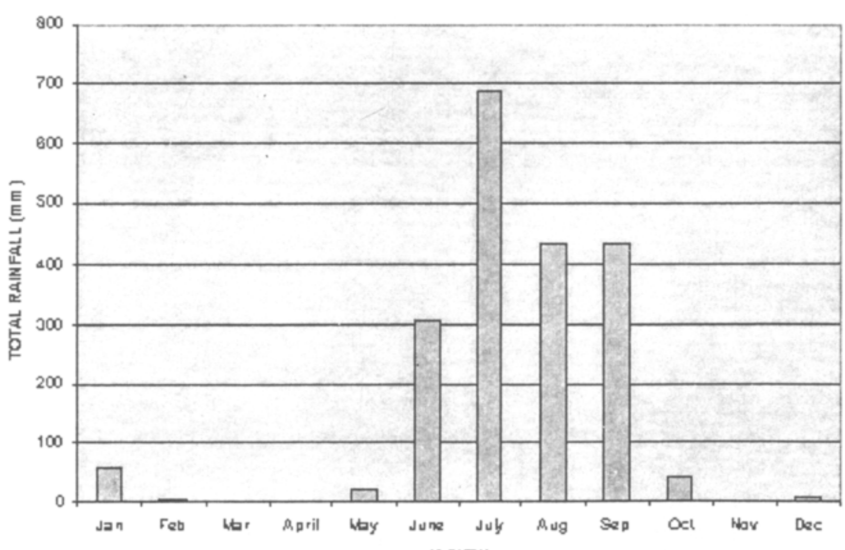

Fig. 2. Monthly rainfall data for the year 1999.

(Fig. 1). The study area enjoys a subtropical to tropical monsoon climate with seasonal rhythm of weather. Three seasons are experienced in the Doon valley i.e. the winter from October to mid March, the hot season from mid March to mid June and rainy season from mid June to September. The monthly rainfall is shown (Fig. 2).

Data Used and Methodology

The base map was prepared using Survey of India (SOI) toposheets (53J/3 and 53f/15) on 1:50 000 scale. Remotely sensed data pertaining to IRS-ID, LISS-111 digital data have been used for the study. Soil map of the catchment area was taken from Soil Division, IIRS, Dehradun. Daily rainfall data for the year 1999 is collected from Forest Research Institute observatory, Dehradun.

The toposheets covering the study area were scanned in TIFF format and imported in the ILWIS software where geo-referencing was done. The geo-referenced image of toposheets was used as background image for all on screen digitizing. The watershed has been delineated. Drainage map has been prepared as a different coverage and each stream has been assigned an order (Fig. 3). Scanned soil map was digitized based on grouping of soil properties. Soil texture map was prepared and a code has been assigned. Land use and land cover maps were prepared using the digital satellite data (Fig. 4). Soil map was classified into two hydrological soil group (HSG) type B and C (Fig. 5) based on the runoff generating potentials. The hydrological soil group 'B' is coarse loamy such as silt loam, loam and the hydrological soil group 'C' is fine loamy such as sandy clay, loam. The contour map was prepared of digitized contour lines at 20m interval and combined with a rasterized spot height map for generating a digital elevation model (DEM) and classified it. The DEM has been used to generate classified slope map (Fig. 6). Geology map has been prepared with different lithology such as Doon Fan Gravel, Old Doon Fan Gravel, Middle Siwalik, Upper Siwalik and Pre-Tertiary rocks (Fig. 7). Geomorphology map has been prepared by digitizing different landform units like Denudation Structure hill, Structure hill, Upper Piedmont, Lower Piedmont and River Terraces (Fig. 8).

Rainfall-Runoff relationship has been determined using USDA Soil Conservation Services (SCS) curve numbers. The curve number method is based on the recharge capacity of the watershed. The recharge capacity is determined by antecedent moisture conditions and physical characteristics to the watershed. The storage capacity is found using the following equation:

$$S = (25400/CN) - 254 \quad \text{.......} \quad (1)$$

Where, CN is the curve number and S (mm) is the storage capacity.

The runoff is calculated using the following equation

$$Q = (P - 0.2*S)^2 / (P + 0.8*S) \quad \text{.......} \quad (2)$$

Where, P is the rainfall and Q is the runoff, both in mm.

The weighted curve number CNII was found using the land use and hydrologic soil group maps in GIS environment. Curve numbers III and I were calculated using the following equations.

$$\text{CN for AMC I} = (23*CNII)/(10+0.13*CNII) \quad \text{.......} \quad (3)$$

$$\text{CN for AMC III} = (4.2*CNII)/(10-0.058*CNII) \quad \text{...} \quad (4)$$

The weighted value for CNII = 52.85

CNI AND CNIII were calculated using CNII and were found to be 32.0 and 72.0 respectively.

Storage capacity and runoff were obtained from the daily rainfall using MS Excel software. The rainfall- runoff relationship for the year 1999 as obtained is shown in (Fig. 9).

Using the second order polynomial, the equation for rainfall- runoff relationship is given as;

$$Q = 0.0038P^2 - 0.0057 *P - 1.9812 \quad \text{.......} \quad (5)$$

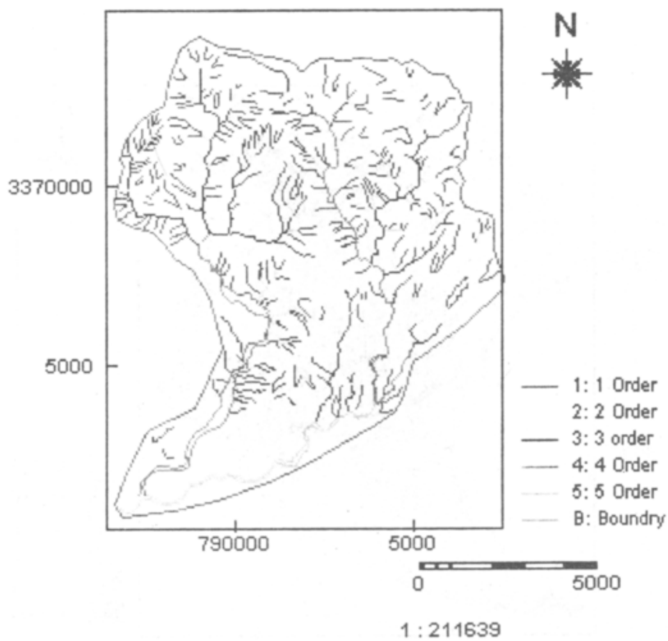

Fig. 3. Drainage map of the Tons watershed.

Where, P = Precipitation in mm. Q= Runoff in mm.

The coefficient of determination (R^2) is equal to 0.99 for the polynomial curve fitted for the study area of Tons watershed.

Runoff Potential Map

The weight and rating system used for runoff potential map is based on the relative importance of various causative factors derived from field knowledge. The various input layers viz, slope, landuse/land cover, geomorphology and geology have been arranged in hierarchical order, in order of importance and a weighting number (5 to 8) is given in each map layer. Similarly each class within a layer has been given an ordinal rating from 4 to 10. Table 1 describes the weights and rating given to each data layer and their classes respectively. These weights and rating values have been re-adjusted using trial and error method (Gupta, *et al.* 1999). The classes of different data layers are assigned the corresponding rating value (Table 1) as attribute information in the GIS and an "Attribute Map" is generated for each data layer. These attribute maps are then multiplied by the corresponding weighting number and then added by the linear combination equation formal in mapcal operation (ILWIS 2.2). The final output map as runoff potential map (Fig. 10) is generated and output map has values ranging between 76 to 236. These values have been further classified by using the slicing operation into four classes of runoff potential (Table 2). The runoff is very high in higher reaches because of very steep slope, denudation structural hill, structural hill, tertiary and middle siwalik rocks occur in these areas.

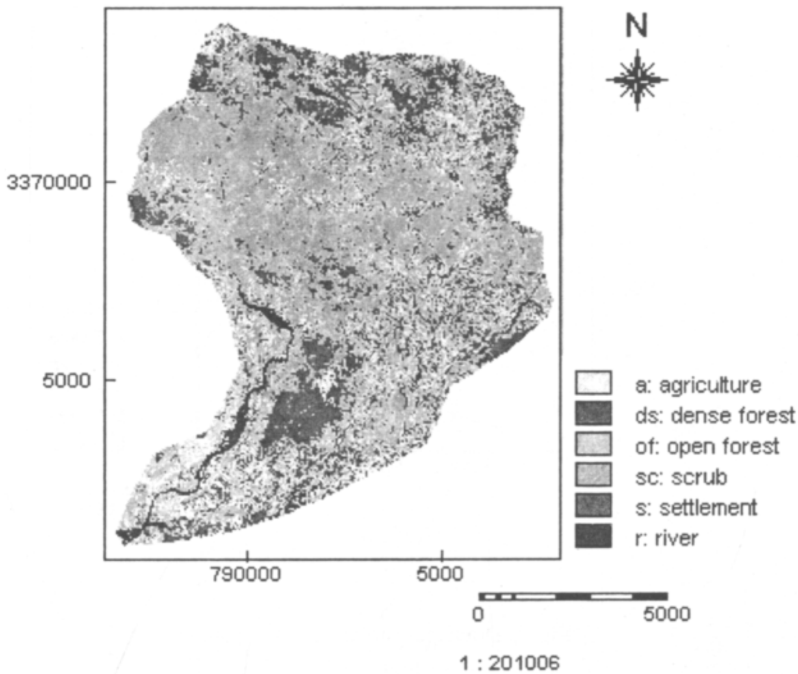

Fig. 4. Land use /Land covers map of tons watershed.

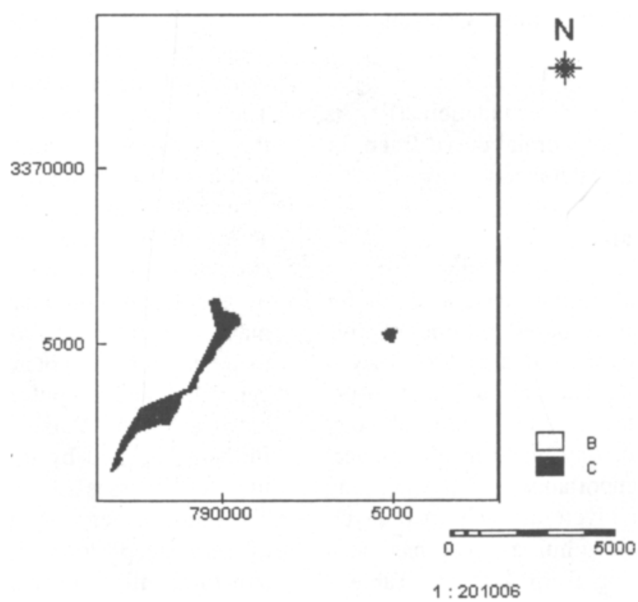

Fig. 5. Hydrological soil group map of Tons watershed.

Table 1. Runoff weightage and rating system adopted in this study

Sl. No.	*Data*	*Classes*	*weightage*	*rating*
1	Slope	Very steep Strongly Sloping Moderate Steep Slope Moderate Slope Gentle sloping Very gentle Sloping Nearly Level	8	10 9 8 7 6 5 4
2	Landuse/ landcover	Agriculture Settlement Scrub Open Forest Dense Forest	7	9 8 7 6 5
3	Geomorphology	Denudation Structural Hill Structural Hill Upper Piedmont Lower piedmont Residual Hill River terrace	6	9 8 7 6 5 4
4	Geology	Pre-Tertiary rocks Middle Siwalik Upper Siwalik Old Doon Fan Gravel Doon Fan Gravel	5	9 8 7 6 5

Estimation of Soil Erosion using Morgan, Morgan and Finney Model

Modeling soil erosion is the process of mathematically describing soil particle detachment, transport and deposition on land surfaces. There are at least three reasons for modeling erosion. Erosion can be used as predictive tool for assessing soil loss for conservation planning, project planning, soil erosion inventories and for formulating regulations. Physically based mathematical models can predict where and when erosion is occurring, thus helping the conservation planner target to reduce erosion. Models can be used as a tool for understanding processes and their interactions for setting research priorities.

For the Tons watershed, Morgan, Morgan and Finney method (1984) is used to estimate soil erosion. In this approach soil erosion takes place by detachment of soil particles by raindrop impact and the transport of these particles by overland flow. The model is process based which means it runs in two phases one being water phase and other being sediment phase. The water phase mainly comprises of prediction of detachment by rain splash. It thus requires data related to rainfall such as intensity of rainfall, number of rainy days, total rainfall. The water phase thus being estimating the kinetic energy of rainfall (J/m2) and volume of overland flow (mm). The sediment phase comprises of two equations, one for the rate of splash detachment and the second for the transport. The operating functions for the Morgan Approach are:

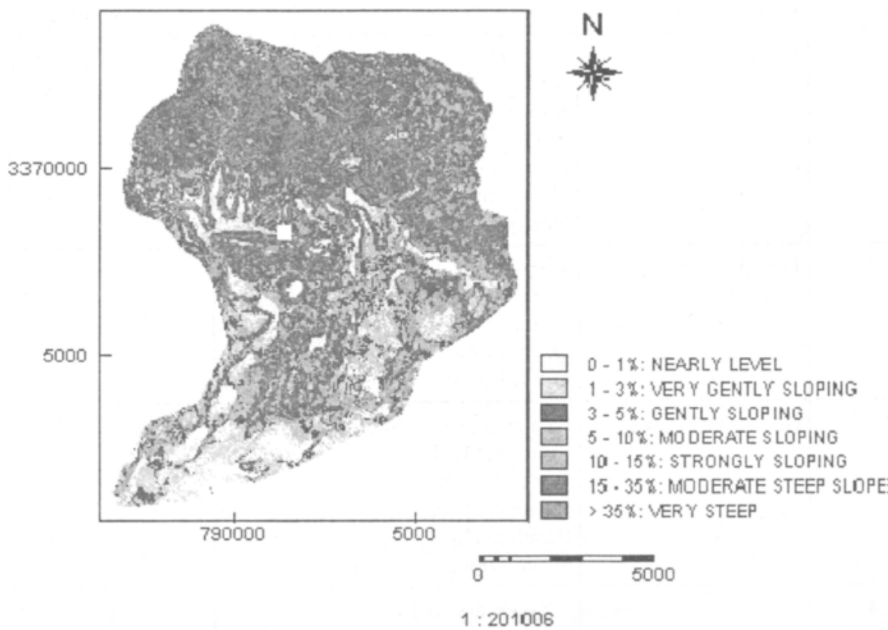

Fig. 6. Classified slope map of tons watershed.

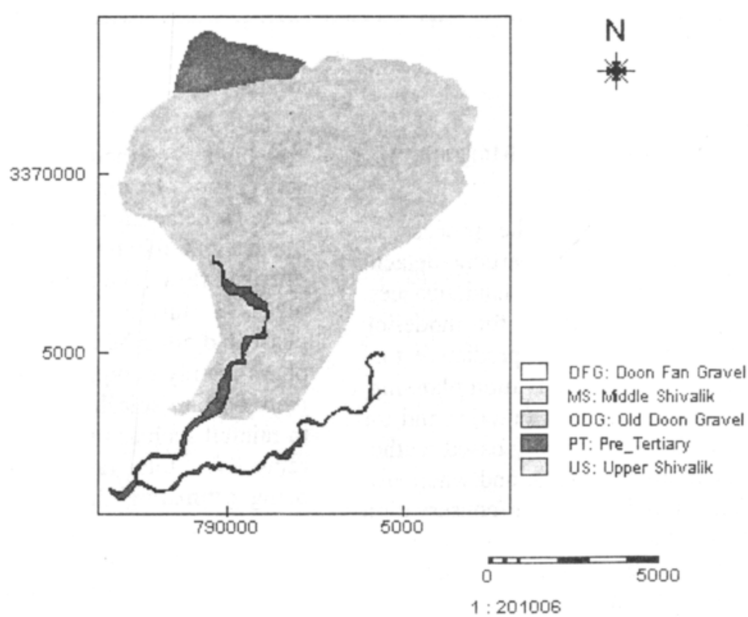

Fig. 7. Geological map of the Tons watershed.

Table 2. Classification of runoff potential values into various Runoff Potential Classes

Runoff Potential Classes	*Values*
Low	<100
Moderate	100-150
High	150-200
Very High	>200

(a) ***Water phase***

E = kinetic energy of the rainfall (J/ m^2).

$E = R\,(11.9+8.7\,\log_{10} I)$ .... (6)

Input parameters required are:
R is annual rainfall for the study area = 1993.1 mm
I is typical value of intensity of erosive rain as 25 mm/hr
$E = 1993.1*(11.9 + 8.7\log_{10}25) = 47{,}958$ (J/ m^2).
Q = volume of overland flow mm

$Q = R*\exp(-Rc/Ro)$ .... (7)

Where, $Rc = 1000*MS*BD*RD*(Et/Eo)^{0.5}$ ...(8)

MS Moisture content at the field capacity (%w/w)

BD Bulk density of the top layer (Mg/m^3)

E_t/E_o Ratio of actual (E_t) to potential (E_o) evaporation

RD Top soil rooting depth (m)

Individual columns were added to the soil texture map for calculating MS; BD. Attribute raster maps were prepared for MS and BD. Rooting depth (RD) map was also prepared. Et/Eo column was added to land use and an attribute map was prepared. All these were used as input to calculate final Rc. Ro was calculated using annual rainfall (R) and number of rainy days, (R_n).

Ro = R/Rn

For R = 1993.1 mm and Rn = 80 days for the study area

Ro = 24.91 mm.

Volume of overland flow Q map was prepared using the following equation:

$Q = R*\exp(-Rc/Ro)$

$Q = 1993.1*\exp(-Rc/24.9)$ .... (9)

(b) ***Sediment phase***

$F = K*(E^{-aA})b * 10^{-3}$ .... (10)

Soil detachability (K), and percentage of permanent interception and stem flow (A) maps were prepared. Final output was F map using the above-mentioned equation in which the constant a and b were assumed as 0.05 and 1.0, respectively. The transport capacity was found using the following equation

$G = CQ^d \sin S * 10^{-3}$ .... (11)

Where, C = crop cover management factor, Q = volume of overland flow.

Sin S = steepness of the ground slope expressed as the slope angle.

C map was prepared. Slope map was derived from DEM. Using C, Q, and slope maps for estimating transport of capicity of overland flow (G) and then final G map was prepared. Minimum from F and G maps for each pixel in these two raster maps is the soil erosion map. Final soil erosion map in annual soil estimation (t/ha) in the study area is shown in (Fig. 11). The study area was divided into four sub-watersheds to estimate the average soil loss in each of them. The sub-watersheds map was crossed with the soil erosion map of the watershed.

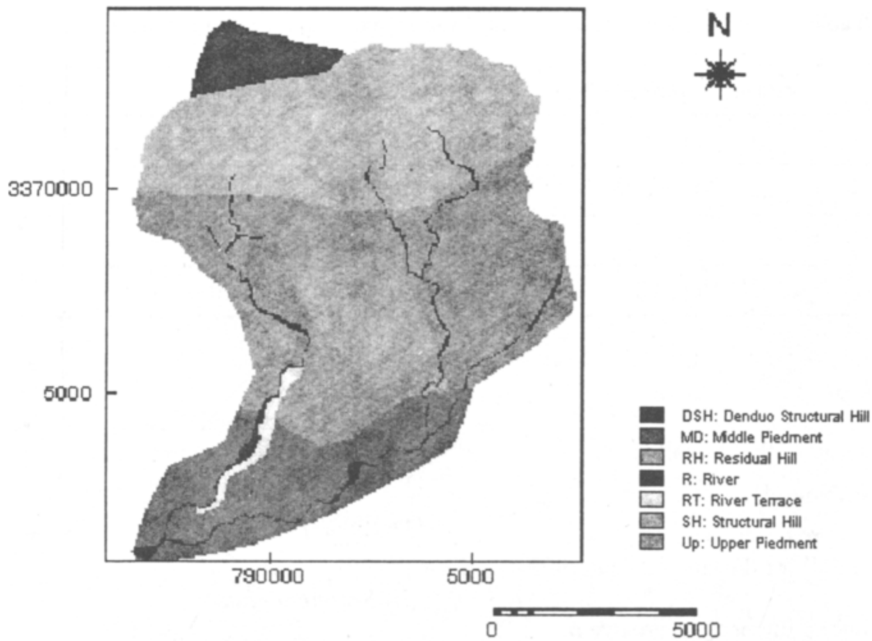

Fig. 8. Geomorphology map of tons watershed.

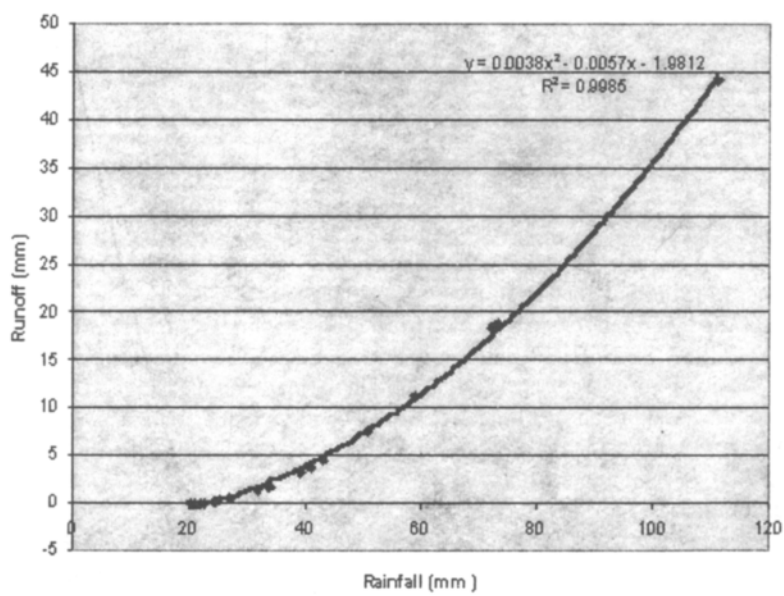

Fig. 9. Rainfall-Runoff relationship for Tons watershed.

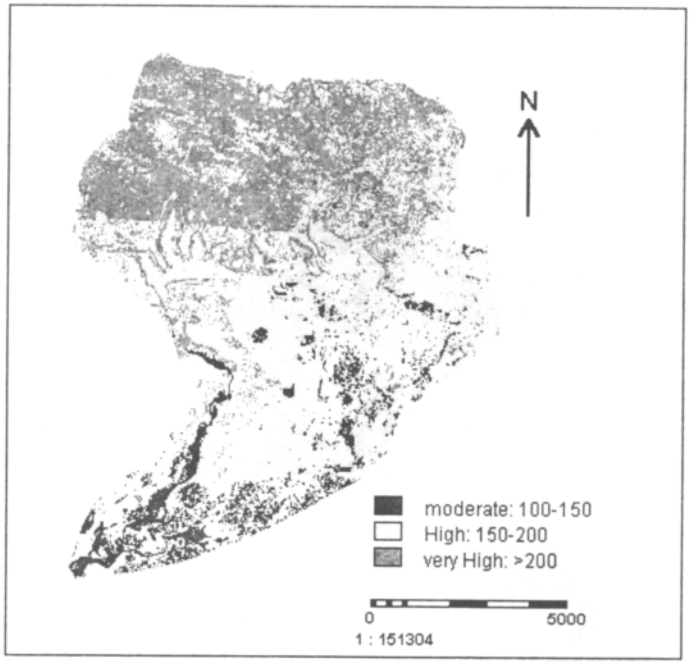

Fig. 10. Runoff potential map of the Tons watershed.

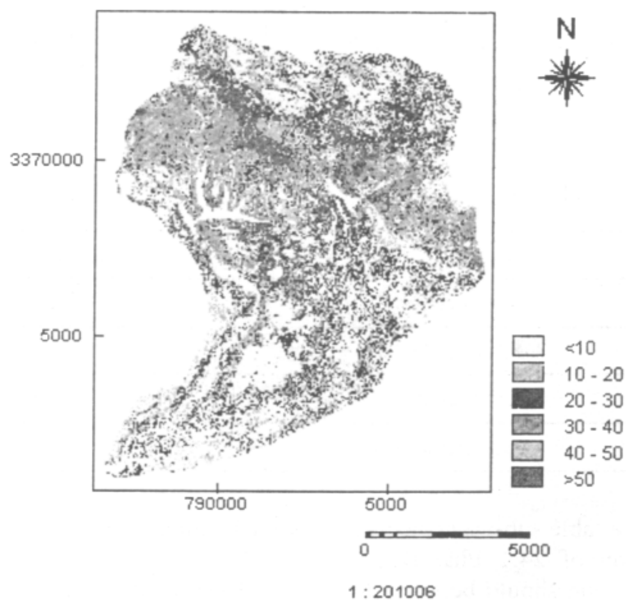

Fig. 11. Annual soil estimation (t/ha) shows in Tons watershed

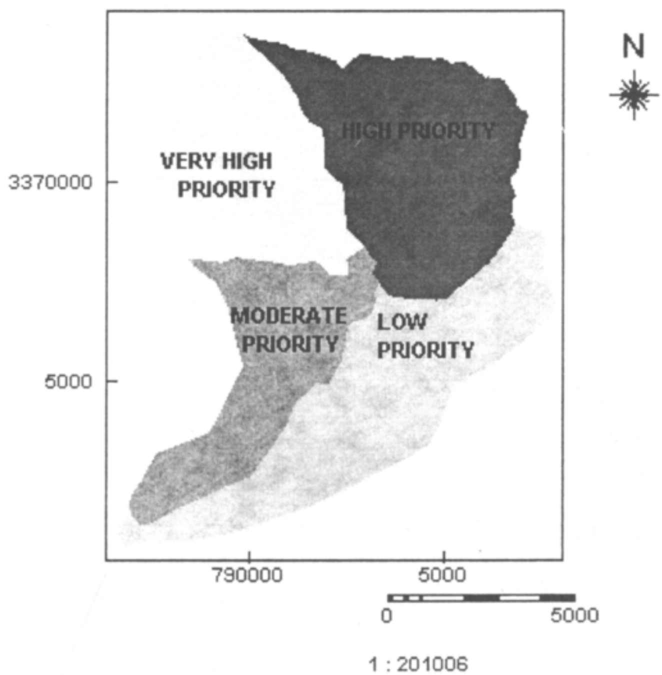

Fig. 12. Priority Sub-watershed Map shows the priority area for soil Conservation

Table 3. shows the average soil loss in the sub-watersheds

Sr no	***Sub-watershed***	***Average Soil loss in t/ha***
1	Subwatershed-1	24.1
2	Subwatershed-2	23.0
3	Subwatershed-3	17.2
4	Subwatershed-4	14.1

As seen in the above table sub-watershed –1 has average soil erosion of 24.1 t/ha. Hence priority for soil conservation should be given to this sub-watershed. Figure 12 shows the priority for soil conservation in the Tons watershed.

Conclusions

The rainfall- runoff relationship for the Tons watershed was obtained using SCS curve method in remote sensing and GIS environment. The coefficient of determination (R^2) is 0.99, which indicates a high correlation between rainfall and runoff.

The runoff potential map was prepared by assigning individual class weights and scores to input maps. Higher runoff occurs in areas where Pre-tertiary and Middle Siwalik rocks exist, geomorphologic units are Structural and Denudation Structure hills, with very steep to steep slopes and land use is mainly scrub land and open forests.

Annual spatial soil loss estimation for the study area was carried out using Morgan, Morgan and Finney mathematical model in conjunction with remote sensing and GIS techniques. Higher soil erosion was found to occur in the northern part of the Tons watershed. The soil texture in the affected area is coarse loamy to loamy skeletal. Hence soil detachment is higher. Moreover the land use has open forests, which does not reduce the impact of rainfall. The average soil loss for all the four sub-watersheds was calculated, and it was found that the maximum average soil loss of 24.1 t/ha occurred in the sub-watershed 1. Hence for soil conservation, very high priority should be given to sub-watershed 1.

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