ASSOCIATION OF PUNJAB GEOGRAPHERS
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A JOURNAL OF THE ASSOCIATION OF PUNJAB GEOGRAPHERS, INDIA

VOLUME 8 OCTOBER 2012

SOIL EROSION ASSESSMENT IN SOLANI WATERSHED USING GEOSPATIAL TOOLS

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Abstract

Soil loss is a global phenomenon. However, the developing countries like India are more prone to this problem because of the inability of their agricultural communities to replace lost soils and nutrients. Soil erosion has direct varying bearing on the soil health and agricultural production in different topographic conditions. The soil erosion rate in the northern Himalayan region varies between 20 to 25 ton/ha/yr which is much higher than the permissible limit. The present study is an endeavour to investigate the soil erosion potential of Solani watershed largely located in the Shiwaliks using geoinformation technologies and Revised Universal Soil Loss Equation (RUSLE) model. The study is based on LISS-IV MX (3bands) satellite images of 5.0 m spatial resolution acquired on December 2, 2011, SOI toposheets, rainfall data and soil texture information. The quantitative assessment of soil loss on pixel basis reveals that the average annual soil erosion for Solani watershed is 3.647 t ha^{-1} $year^{-1}$. More than 90% of watershed area is found under minimal and low erosion classes largely comprising low height areas. About 5.65% of watershed is under high to extreme erosion risk category (> 10.1 t ha^{-1} $year^{-1}$) mostly found in steep slopes and river beds. It necessitates the protection of existing forests and afforestation of steep barren lands and other suitable sites.

Introduction

The detachment of soil particles from the impact of raindrops is the first stage in the process of erosion and is the primary cause of erosion on short, steep slopes (Wu et al.1996). The processes involved in onset of soil erosion and its varying impact is important to study to gain a greater understanding of the concept. Soil erosion in watershed areas and the subsequent deposition in rivers, lakes and reservoirs are of great concern for two reasons. Firstly, rich fertile soil is eroded from the watershed areas. Secondly, there is a reduction in reservoir capacity as well as degradation of downstream water quality (European Environment Agency, 1995). Although sedimentation occurs naturally, it is aggravated by poor land use and land management practices adopted in the upland areas of watersheds. Uncontrolled deforestation due to forest fires, grazing, unscientific agricultural practices and incorrect methods of tillage are some of the poor land management practices that accelerate soil erosion, resulting large increases in sediment inflow into streams (Pimental, 1998). Therefore, prevention of soil erosion is of utmost significance in the management and conservation of natural resources (Morgan,1995; Sadeghi et al. 2007).

For estimation of soil erosion and to

develop optimal soil erosion management plans, many erosion models, such as Universal Soil Loss Equation (USLE), (Wischmeier and Smith, 1978), Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995), Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) and European Soil Erosion Model (EUROSEM) (Morgan et al. 1998) have been developed and used over the years. Among these models, the USLE model has remained as the most practical method for estimating soil erosion potential in fields and estimating the effects of different control management practices on soil erosion for nearly 40 years (Dennis, and Rorke, 1999; Kinnell, 2000 and Pandey et al. 2007). The other process-based erosion models require intensive data and thoughtfully computation steps. The new version of the USLE model, called the Revised Universal Soil Loss Equation (RUSLE), a desktop-based model, was developed by modifying the USLE to more accurately estimate the R, K, C, P factors of soil loss equation, and soil erosion losses (Renard et al. 1991). RUSLE is a field scale model, thus it cannot be directly used to estimate the amount of sediment reaching downstream areas because some portion of the eroded soil may be deposited while traveling to the outlet of the watershed, or the downstream point of interest. To account for these processes, the sediment delivery ratio (SDR) for a given watershed may be used to estimate the total sediment transported to the outlet. Erskine et al. (2002) compared RUSLE estimated soil loss with the measured sediment yield for 12 sub-watersheds in Australia. The coefficient of determination was 0.88 for this comparison.

The application of RS and GIS techniques makes soil erosion estimation at reasonable costs and provides better accuracy in larger areas (Millward and Mersey, 1999 and Wang et al. 2003). A combination of RS, GIS and RUSLE is an effective tool to estimate soil loss on a cell-by-cell basis (Millward and Mersey, 1999). Boggs et al. (2001) assessed soil erosion risk based on a simplified version of RUSLE using digital elevation model (DEM) data and soil mapping units. Bartsch et al. (2002) used GIS techniques to interpolate RUSLE parameters for determining the soil erosion risk in sample plots at Camp Wiliams, Utah. Wilson and Lorang (2000) reviewed the applications of GIS in estimating soil erosion. Wang et al. (2003) used a sample ground dataset, Thematic Mapper (TM) images and DEM data to predict soil erosion loss through geo-statistical methods. They showed that such methods provided significantly better results than using traditional methods. In general, remote sensing data were primarily used to develop the cover-management factor image through land-cover classifications (Millward and Mersey, 1999 and Reusing et al. 2000), while GIS tools were used for deriving the topographic factor from DEM data, data interpolation of sample plots, calculation of soil erosion loss and sediment yield (Cerri et al. 2001; Bartsch et al. 2002; Wang et al. 2003 and Pandey et al. 2007).

Soil loss is a global phenomenon but the developing countries are more prone to this problem because of the inability of their farming populations to replace lost soils and nutrients (Erenstein, 1999). India is the second populous country in the world where agriculture constitutes the backbone of the national economy. The sustainable land management practices are urgently required to preserve the production potential and ensure adequate supply of nutritious food for ever-growing population in this country. Soil erosion has direct varying bearing on the soil health and agricultural production in different topographic conditions. The soil erosion rate in northern Himalayan region ranged from 20 to 25 ton/ha/yr (Garde and Kothyari, 1987). According to Singh et al. (1992), the Shiwalik hills, north-western Himalayan region, ravines and shifting cultivations are under severe erosion- more than 20 ton/ha/yr. Catchments and watersheds have been identified as planning units for administrative purpose to conserve the land and water resources (Honore, 1999). Considering the gravity of soil erosion, the rate and amount of soil loss has attracted a lot of attention from a wide range of researchers and policy makers. Several studies have been conducted to estimate soil loss employing Remote Sensing and GIS techniques in different parts of the world. Remote Sensing and GIS are the most advanced and efficient tools for watershed development, management and studies on prioritization of micro-watersheds for development (Ratnam et al. 2005). Chakraborti (1991) has used remote sensing data for predicting sediment yield and prioritization of watersheds. Mani and Chatterjee (2003) employed remote sensing and GIS technique to assess the soil erosion rate in Majuli River- Island. Besides predicting the soil erosion at the field level, the integration of universal soil loss equation with GIS environment has also enabled applications in large areas and satisfactory results have been reported for delineation of erosion prone areas and prioritization of micro-watersheds for conservation planning purposes (Mellerowicz et al. 1994). The present study is an attempt to investigate the soil erosion potential of Solani watershed using geo-information technologies and RUSLE model.

Objectives of the Study

The present study seeks to investigate the following two fold objectives:

1. To derive rainfall erosivity, soil erodibility, slope length, slope steepness, land cover and management practices of Solani watershed using Geospatial tools.
2. To estimate the amount and spatial distribution of soil loss potential in the watershed under study.

Database and Methods

The present study is based on LISS-IV MX data (3bands) of 5.0 m spatial resolution acquired on December 02, 2011. ASTER DEM of 30 M spatial resolution as open source data bank has also been used in the present study. The Survey of India toposheets - 53 F/15; 53F/16; 53G/13; 53J/3; 53J/4 of 1:50,000 scale and 53/F; 53/G; 53/J; 53K of 1:2,50,000 scale as collateral source of information have also been used in the present study. The satellite data have geometrically rectified with respect to the Survey of India toposheets of 1:50,000 scale. The existing land use and land cover (LULC) has been extracted and mapped from linearly stretched standard false colour composite (SFCC) of LISS-IV satellite data. Supervised classification technique was used for preparing the LULC of study watershed. The accuracy assessment of classified land use was also undertaken with the help of reference points generated through GPS survey and reference toposheets. The database has been generated using ERDAS Imagine 9.2 and Arc GIS- 9.3 tools.

In the present study, RUSLE input parameters and Raster Calculator in GIS environment have been used to estimate spatial soil erosion potential of study watershed. The RUSLE-soil erosion model predicts soil loss for a given site as a product of six major erosion factors (equation), whose values at a particular location can be expressed numerically. The soil erosion is calculated as follows:

$$A = R.\ K.\ L.\ S.\ C.\ P$$

Where **A is the average soil loss per unit area by erosion (t ha^{-1} year^{-1})**

R = Rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1})

Annual Relationship: $R_a = 81.5 + 0.380\ P_a$
Seasonal Relationship: $R_s = 71.9 + 0.361\ P_s$
R= Average Erosion Index, P = Average rainfall (mm), Subscript 'a' and 's' stand for annual and seasonal relationship. In the present study, average annual rainfall available for two years has been considered.

K=Soil erodibility factor (t h MJ-1 mm-1)

$$K = \frac{2.1 \times 10^{-4} (12\text{-OM}) M^{1.14} + 3.25(s-2) + 2.5(p-3)}{759.4}$$

K= Soil erodibility (tons-year MJ-mm), OM = percentage organic matter, p = soil permeability code, s = soil structure code, M = a function of primary particle size fraction given by
M = (% silt + % very fine sand) x (100 - % clay)

L = Slope length factor

$L = [\lambda/22.13]^m$

Where, 22.13 = RUSLE unit plot length (m) and m is variable slope - length exponent. Slope length λ is horizontal distance from the origin of overland flow to the point where either (1) the slope gradient decreases enough that deposition begins or (2) runoff becomes concentrated in a defined channel. Slope length exponent m is calculated as:

$m = \beta / 1 + \beta$

$\beta = (\sin\theta / 0.0896 / [3.0 (\sin\theta)^{0.8} + 0.56]$

where θ is slope angle; L= (Flow Accumulation x Grid Size / 22.13)^m

S = slope steepness factor

It has been evaluated as per McCool et al. 1987and 1993.

$S = 10.8 \sin\theta + 0.03 \quad S < 9\%$ (i.e. $\tan\theta < 0.09$)
$S = [\sin\theta / \sin 5.143]^{0.6} \quad S > 9\%$ (i.e. $\tan\theta > 0.09$)

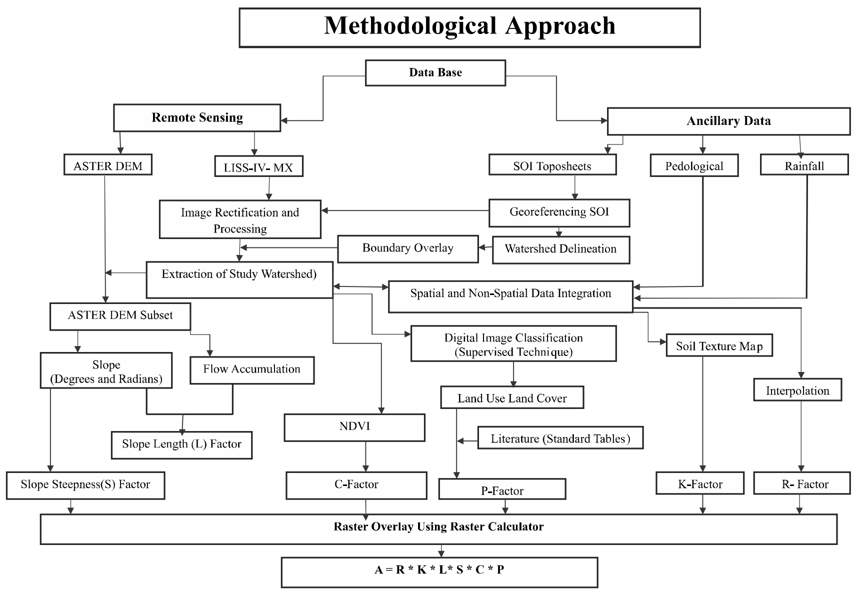
C = **plant cover and management practice factor**. Based on De Jong (1994) work NDVI map can be used to formulate linear equation between NDVI and C-factor. The regression equation developed for C factor is:

$C_i = 0 \qquad \textit{if } NDVI \leq 0$
$C_i = -[1 / NDVI_{max}]\ (NDVI)_I + 1 \quad \textit{if } NDV_I > 0$

P = conservation support practice factor, since the P factor reflects the impact of support practices dealing with average annual erosion rate. It is the ratio of soil loss with conservation practices to that with straight row farming up and down slope. The lower the P value, the more effective the conservation practice is deemed to be at reducing soil erosion. The P values for every landuse class derived from latest satellite imageries have been taken from Hann et al. (1994).

The detailed step-wise analytical methodology adopted for the present study is given in the following flow diagram:

Regional Setting of Study Area



The Solani watershed covering an area of about 939 sq km is located between 29°47'57''N to 30°16'17''N latitude and 77°43'58"E to 78°04'26"E longitude (Fig. 1).

The Solani watershed is relatively a young watershed still passing through its early stage of geomorphic evolution. The relief structure varies from relatively plain topography in the south to hilly parts of Shiwalik ranges in the northern part. Solani River is a moderate size right bank tributary of the river Ganga. The Solani river originates from the northeast part (Shiwalik hill, 787m) of Saharanpur district near the Kaluwala pass (30°15'59''N latitude and 78°53'17''E longitude). The river flows essentially SW to SE for 60.18km to join the Ganga river near Jansath town of Muzaffarnagar district (U.P.). It traverses over Roorkee tehsil of Haridwar district of Uttrakhand and Saharanpur and Muzaffarnagar districts of Uttar Pradesh. About three-fourth of its catchment lies in Uttrakhand state.

Soil Texture

The soil texture of the watershed under study can be classified into following four classes based on Inaris code (table 1).

It is evident from the Table 1 that loamy soil class dominates the study watershed. Sandy and loamy skeletal are other soil classes observed in the study area. This typology of

Table 1
Solani Watershed: Soil Surface Texture

Inaris Code	Taxonomy	Class
1	Typic Ustipsamments	Sandy
2	Udic Haplusteps	Loamy
2	Dystric Eutrudepts	Loamy
2	Typic Udorthents	Loamy
2	Fluventic Dystrusteps	Loamy
2	Fluventic Haplusteps	Loamy
2	Udifluventic Haplusteps	Loamy
24	Typic Udorthents	Loamy Skeletal
102	102	Water

Source: Derived from Soil map prepared by National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur

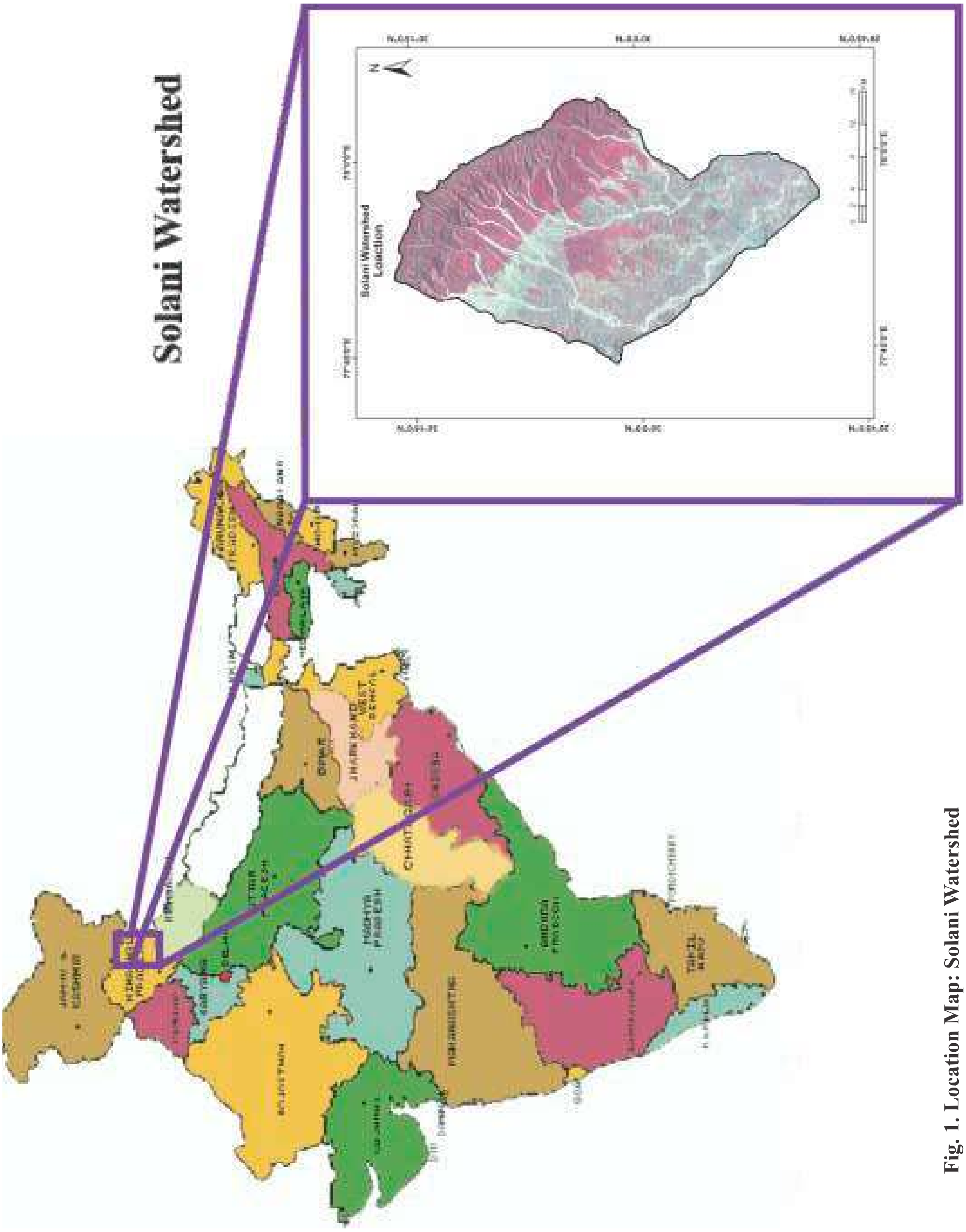


Fig. 1. Location Map: Solani Watershed

Table 2
Solani Watershed: Area under Different Land Use Categories

Land Use Category	Area (Sq Km)
Dense Vegetation	187 (19.91)
Sparse Vegetation	294 (31.31)
Agricultural Land	227 (24.17)
Fallow Land	165 (17.58)
River Bed	38 (4.05)
Water Bodies	10 (1.06)
Built up Land	18 (1.92)
Total	**939 (100.00)**

Source: Classified by author based on LISS-IV (MX) Satellite Images Figures in parentheses show the percentage to total watershed area

soils as per their erodibility has been used for deriving the K-factor.

Land Use / Land Cover

The most common landuse category is forests which together constitute more than half (51.22 %) of total geographic area, in which, sparse vegetation accounts for about 31% and dense vegetation about 19%. Spatially, vegetation both dense and sparse largely dominates the Shiwalik areas in the north and some patches in central part of watershed. Agricultural land comprises about one-fourth of total area followed by about 17% fallow land. The red patches on the landuse map indicate the presence of settlements and other built up use which constitute about 2 % of total area of the watershed (Fig. 2 and Table 2).

Results and Discussion

Rainfall Erosivity Factor (R)

Rainfall erosivity is defined as the ability of the rain to cause erosion. The most common rainfall erosivity index is the R factor of USLE and RUSLE. The R factor is considered to be the most highly correlated index to soil loss at many sites throughout the world. The R factor for any given period is obtained by summing the product of total storm energy (E) and the maximum 30-min intensity (I30) for each rainstorm. In this study, in order to estimate the R factor, the annual rainfall quantities computed on daily basis for 2 years (2009 and 2010) were obtained from the records of 2 stations namely Roorkee (within watershed) and Mujjafarabad (outside watershed). The point data of these two weather stations was interpolated using inverse weighted distance (IWD) interpolation

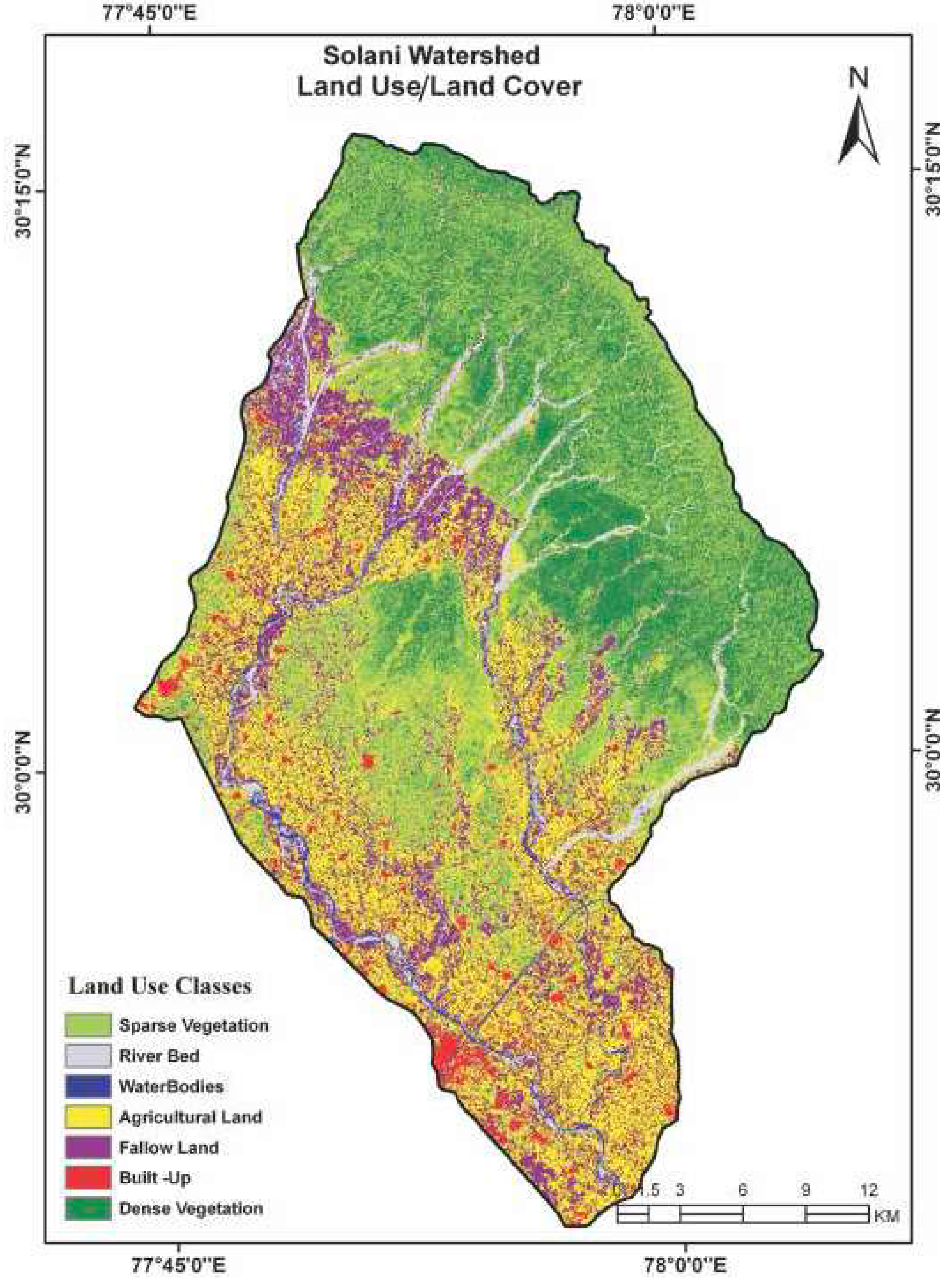

77°45'0"E
78°0'0"E
Solani Watershed
Land Use/Land Cover
N
30°15'0"N
30°0'0"N
Land Use Classes
Sparse Vegetation
River Bed
WaterBodies
Agricultural Land
Fallow Land
Built -Up
Dense Vegetation
0 1.5 3 6 9 12
KM

Fig. 2

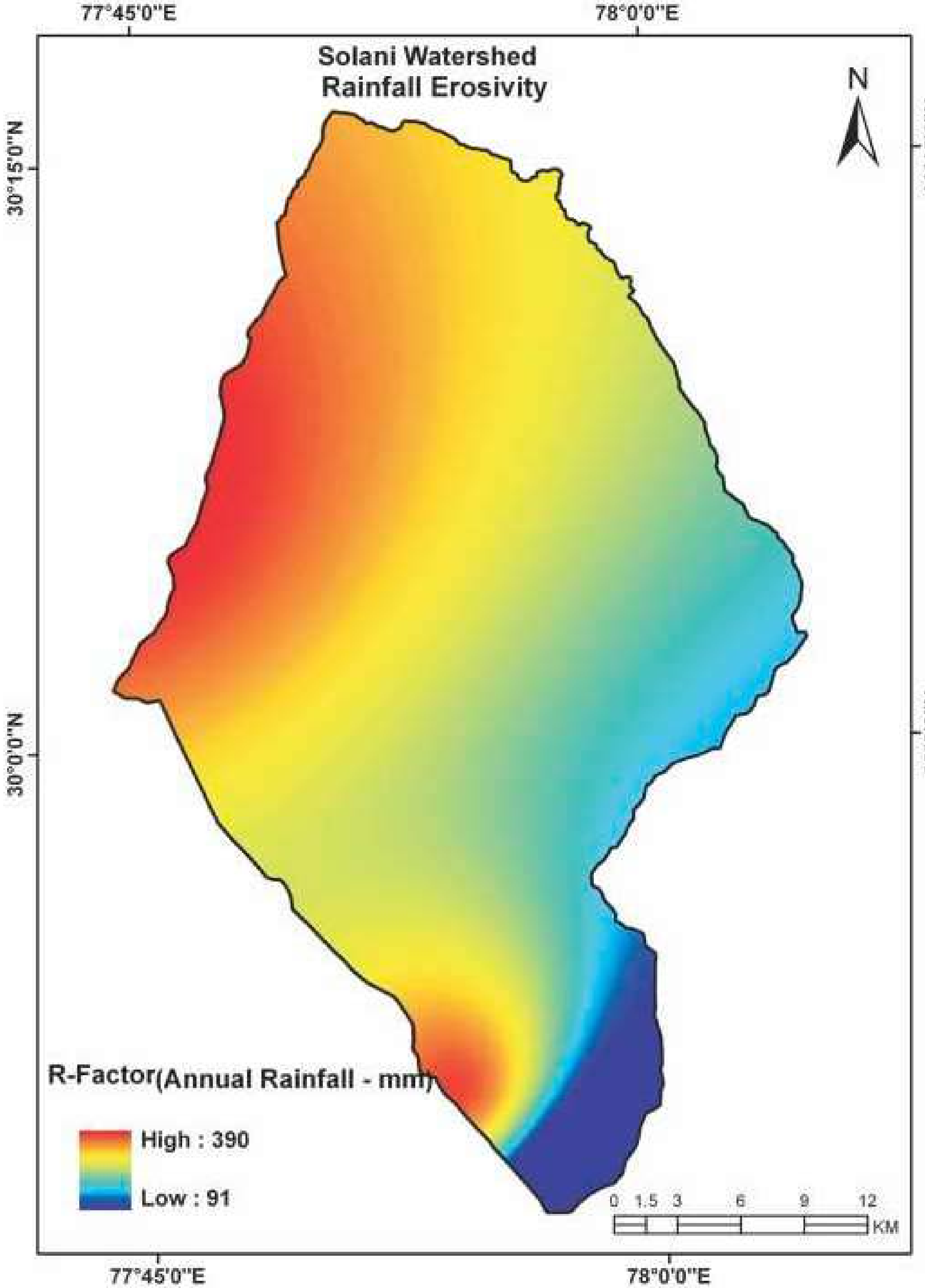

77°45'0"E
78°0'0"E
Solani Watershed
Rainfall Erosivity
N
30°15'0"N
30°0'0"N
R-Factor(Annual Rainfall - mm)
High : 390
Low : 91
0 1.5 3 6 9 12
KM
77°45'0"E
78°0'0"E

Fig. 3

technique in ArcGIS. The fig. 3 shows that R-factor in the study area varies between lowest 91 to highest 390. R-factor map clearly indicates the effect of spatial autocorrelation on the distribution of rainfall erodibility.

As one moves away from the rainfall recording stations (Roorkee - representing centre in a small crescent shaped red colour in southwest of watershed and Mujjafarabad although outside watershed portraying similar behaviour in northwest of watershed) the 'R' factor witnesses decreasing trend outwards. This anomaly may affect the rate and amount of soil loss in any catchment.

Soil Erodibility Factor (K)

The soil erodibility factor (K) is the rate of soil loss per rainfall erosion index unit as measured on a standard soil plot and often determined using inherent soil properties. The 'K' values are usually estimated using the soil erodibility nomograph method, which uses % silt plus very fine sand (0.002 mm-0.1 mm), % sand (0.1 mm-2 mm), % organic matter and soil structure and permeability classes to calculate 'K'. However, the data on soil structure and permeability class from the soil survey data sources is difficult to obtain.

Fig 4 reveals that K factor based on soil class, textural properties, organic matter and soil permeability code varies from 0.063 to 0.107 in the study watershed. The K-factor in RUSLE model relates to the rate at which different soils will erode.

Topographic Factor (L S)

These factors in RUSLE reflect the effect of topography on erosion. It has been observed that increase in slope length and slope steepness can produce higher overland flow velocities and correspondingly higher erosion. Moreover, gross soil loss is considerably more sensitive to changes in slope steepness than to changes in slope length. Slope length has been broadly defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough where deposition begins or the flow is concentrated in a defined channel.

The specific effects of topography on soil erosion are estimated by the dimensionless LS factor as the product of the slope length (L) and slope steepness (S). In the present study, LS-factor maps (5 and 6) respectively were derived from ASTER DEM of the region using the Spatial Analyst extension of Arc GIS 9.3.

Fig 5 reveals that slope length factor varies from lowest 0.100 to 579 in study area. In contrast, the slope steepness factor ranges from 0.03 in the plains in the southern part of the watershed to 3.62 in the Shiwalik region located in the northern reaches of the study watershed. The topographic factors clearly indicate the higher occurrence of soil erosion in hilly region.

Cover Management Factor (C)

The 'C' factor reflects the impact of cropping and agricultural management practices and the effect of ground, tree and grass covers on reducing soil loss in non-agricultural situation. As the vegetation cover increases, the soil loss decreases. Benkobi et al. (1994) and Biesemans et al. (2000) have observed that 'C' and LS are the most sensitive factors to soil loss. In USLE/RUSLE model, the 'C' factor is derived on the basis of empirical equations with measurements of ground cover, aerial cover and minimum drip height (Wischmeier and Smith, 1978). The most extensively used indicator of vegetation growth based on the RS technique is the Normalized Difference Vegetation Index (NDVI), which ranges from -1.00 to + 1.00. Fig. 7 exhibits the 'C' factor derived from NDVI calculation. It is evident from the figure that there is inverse

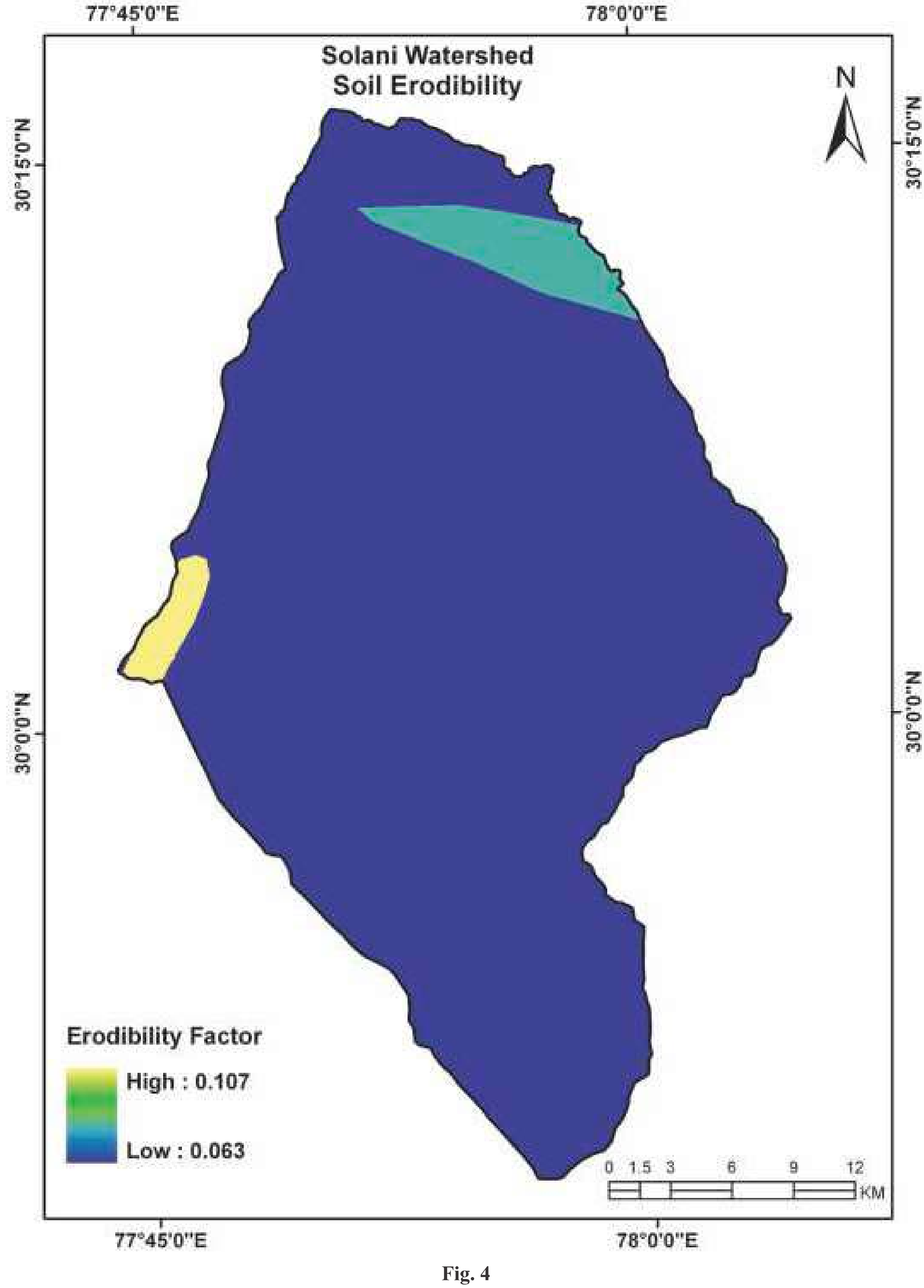

77°45'0"E
78°0'0"E
Solani Watershed
Soil Erodibility
N
30°15'0"N
30°0'0"N
Erodibility Factor
High : 0.107
Low : 0.063
0 1.5 3 6 9 12
KM

Fig. 4

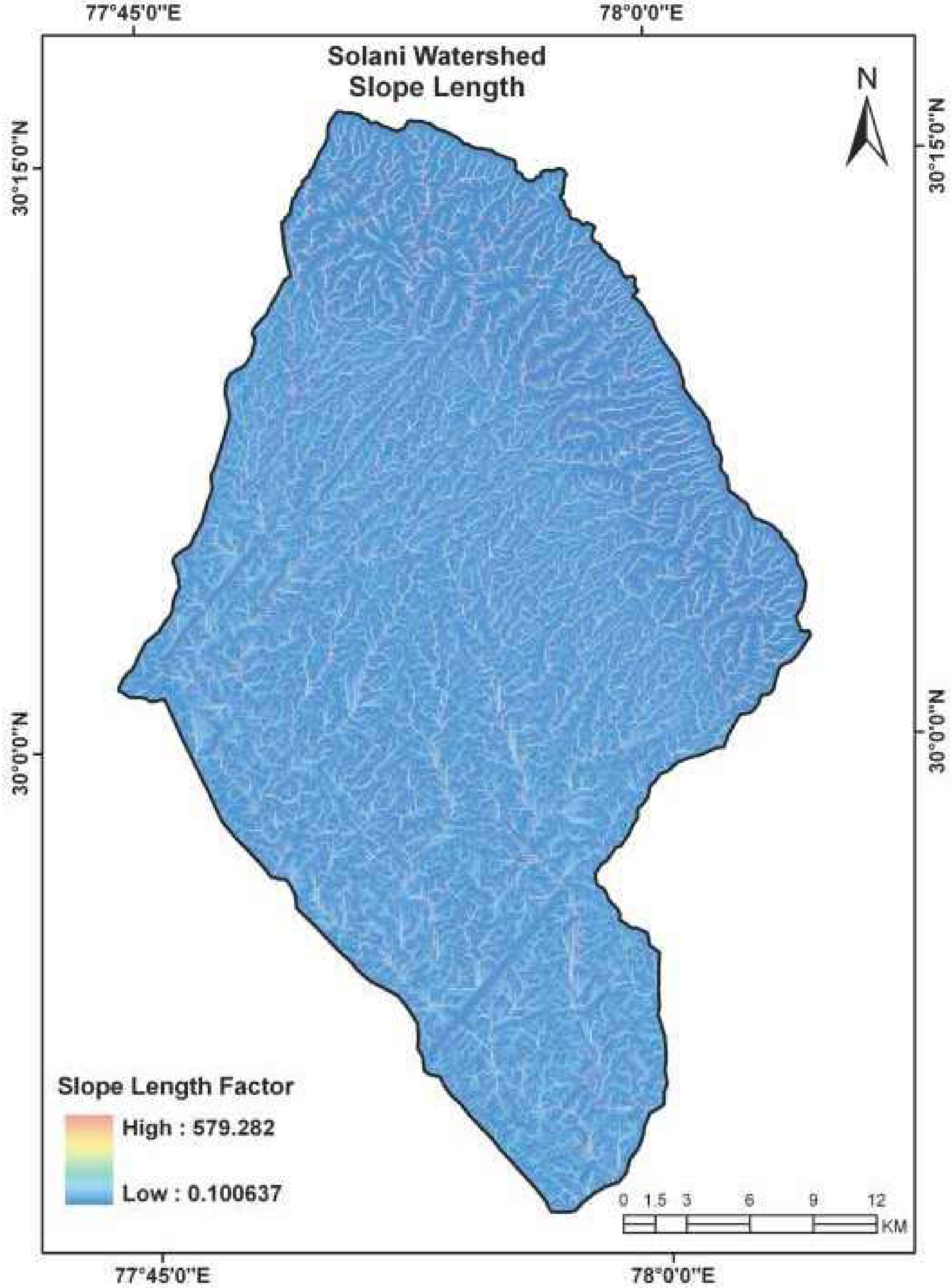

77°45'0"E
78°0'0"E
Solani Watershed
Slope Length
N
30°15'0"N
30°0'0"N
Slope Length Factor
High : 579.282
Low : 0.100637
0 1.5 3 6 9 12
KM
77°45'0"E
78°0'0"E

Fig. 5

relationship between the vegetal cover and C-factor. Higher vegetal cover is related with low possibility of soil loss. Therefore, all vegetated areas in the map are exhibiting low C- values in blue color (Fig. 7) indicating possibility of low soil loss. The river beds and surrounding lands have shown higher C-factor values (red colour) indicating possibility of higher soil loss.

Conservation Factor (P)

As with other factors, P-factor differentiates between cropland and rangeland or permanent pastures. In this study, it has been assumed that conservation practices (P) are not adopted in vegetated areas. Therefore, as the conservation practice factor (P) value ranges from 0.0-1.0 and highest value is assigned to areas with no conservation practice, the maximum value for 'P', that is 1.0, is assigned to highly conserved areas (Fig. 8).

It is evident from Fig 8 that P-value is very low in Solani river bed and its tributaries and other agricultural areas shown in blue colour. The highest P-Value shown in red colour is clearly evident in areas supporting dense vegetation closely followed by sparse vegetation.

Annual Soil Loss Estimation (A)

Average annual soil loss was estimated by multiplying R, K, LS, C and P factors using raster calculator in ArcGIS package. The output map of the study watershed is presented in Fig. 9. Notably, the highest soil loss value 12795(t ha^{-1} $year^{-1}$) from some pixels was also observed in the output calculation which was further normalized using conditional statement in raster calculator and upper limit was fixed at 100(t ha^{-1} $year^{-1}$). It is clear from table 3 and Fig. 9 that annual soil loss values range between 0 and 100 t ha^{-1} $year^{-1}$ at the pixel level, with mean value of 3.647 (t ha^{-1} $year^{-1}$) in Solani watershed.

The Fig. 9 and table 3 show that about 58% of the watershed area falls under less than 2 t ha^{-1} $year^{-1}$ category of soil erosion. The spatial distribution of soil erosion assessment map reveals that as topography changes, the soil loss potential also varies in the study area. The entire alluvium tract except active river channels, adjoining river beds and exposed hills in the western mid part of the watershed are least prone to soil erosion.

The study reveals that as the soil loss value increases, the area under particular soil erosion category decreases. It is evident from the fact that 2-5 (t ha^{-1} $year^{-1}$) soil loss category occupied a little more than one-fourth area whereas 10.1-20 (t ha^{-1} $year^{-1}$) erosion category comprised merely 3.28% of total area. About 2.37 % area has witnessed the possibility of severe soil loss in Solani watershed. Fig. 9 shows that areas under steep slope, although under dense vegetation, have also witnessed higher soil loss potentiality. Overall, it could be said that about 5.65 % area of watershed lies beyond the permissible soil erosion limit [5.1-10 (t ha^{-1} $year^{-1}$) in India as computed by Central Soil and Water Conservation Research and Training Institute, Dehradun]. These areas witnessing higher annual soil loss are largely concentrated in entire Shiwalik zone and river beds of the study watershed. Therefore, with regard to the spatial variation, the north, northeast and western-central part of the watershed are prone to more erosion than the south, southwest and southeast parts. However, it should be noted that areas showing erosion greater than 5.1-10 t ha^{-1} $year^{-1}$ have shown uneven distribution at pixel level in the watershed (Fig. 9). The higher soil loss 10.1-20 t ha^{-1} $year^{-1}$ is closely related to its dynamic relationship with topography (LS factor). This area needs suitable conservation measures on a priority basis.

Main Findings

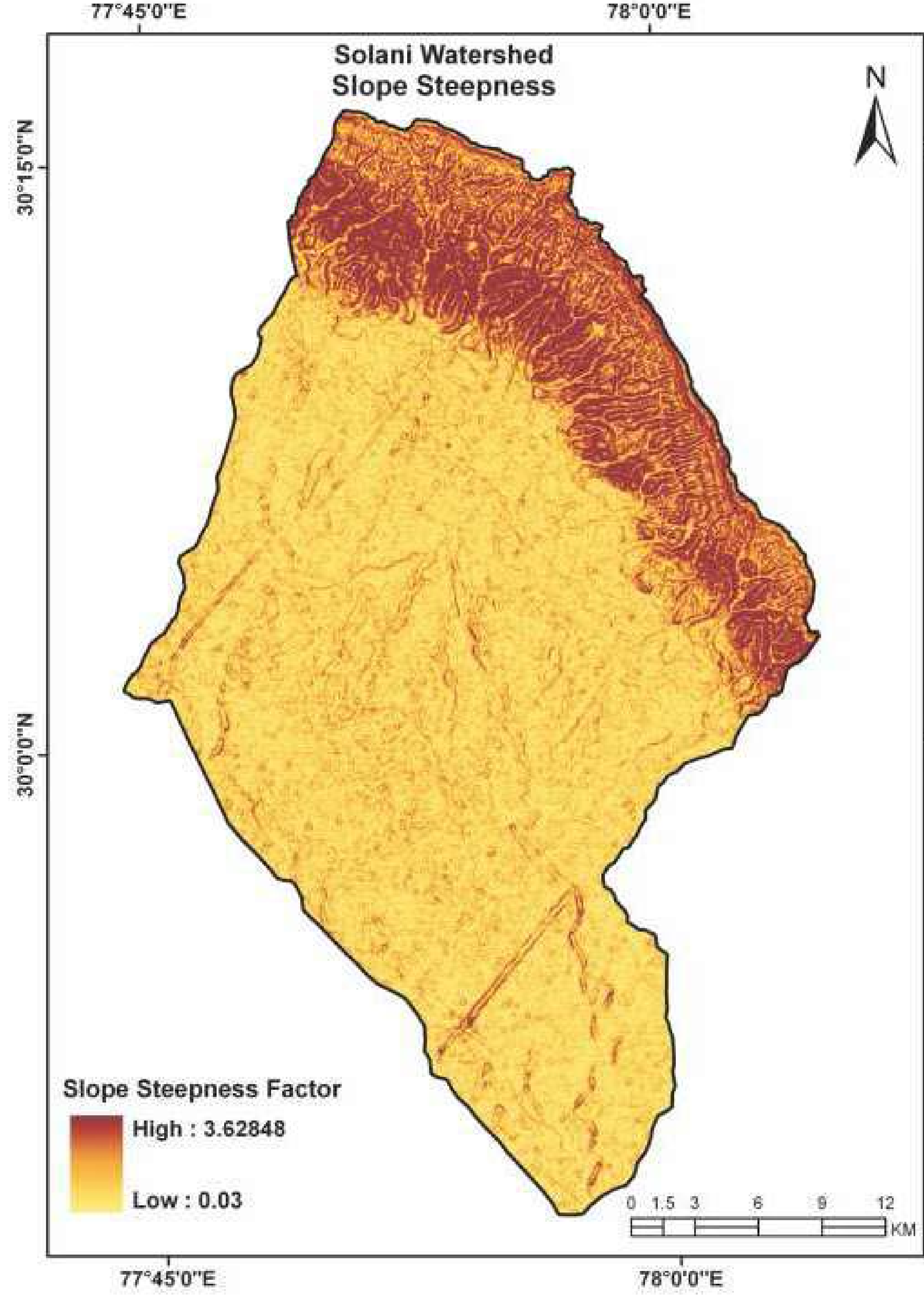

77°45'0"E
78°0'0"E
Solani Watershed
Slope Steepness
N
30°15'0"N
30°0'0"N
Slope Steepness Factor
High : 3.62848
Low : 0.03
0 1.5 3 6 9 12
KM

Fig. 6

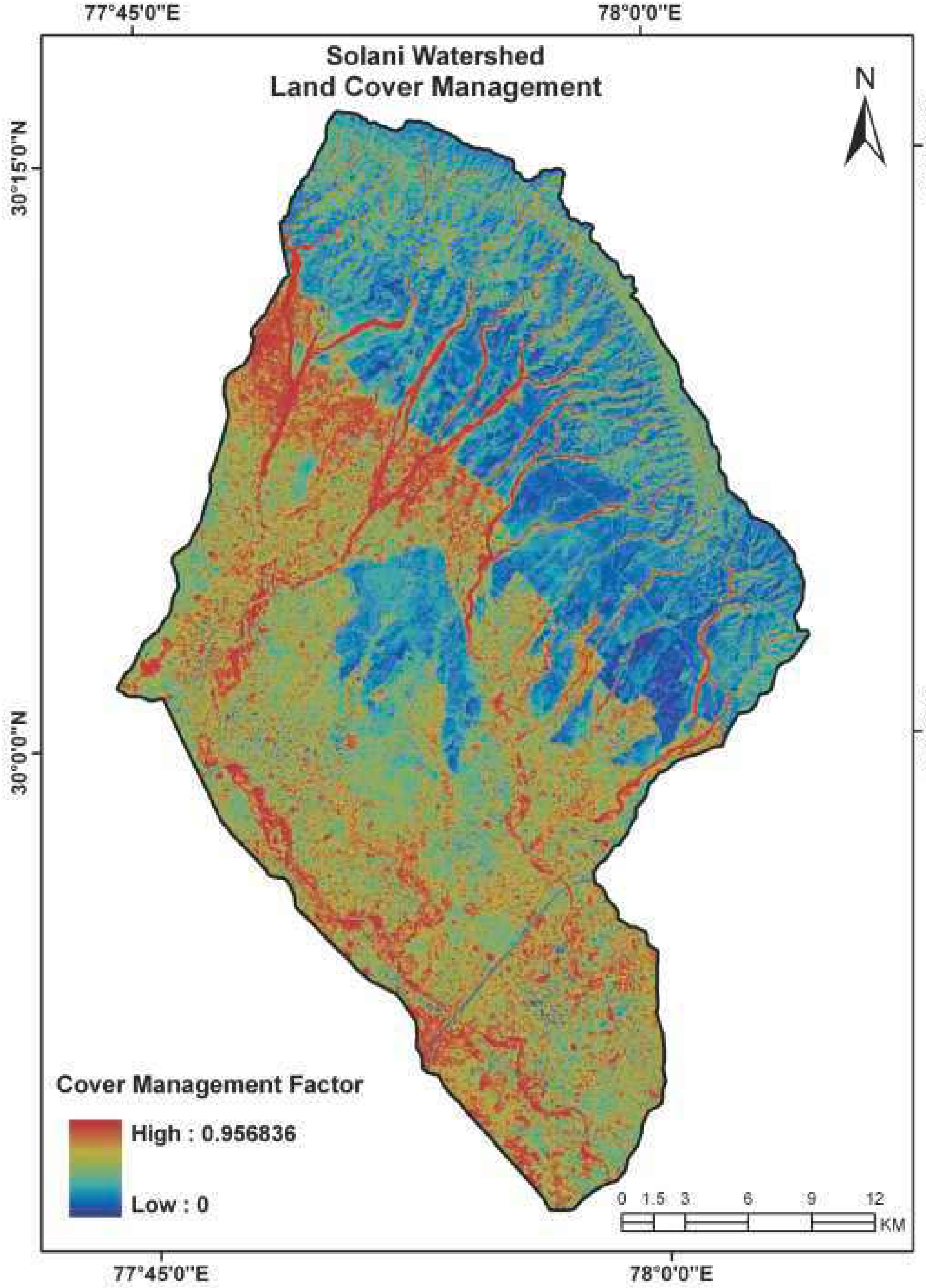

77°45'0"E
78°0'0"E
Solani Watershed
Land Cover Management
N
30°15'0"N
30°0'0"N
Cover Management Factor
High : 0.956836
Low : 0
0 1.5 3 6 9 12
KM

Fig. 7

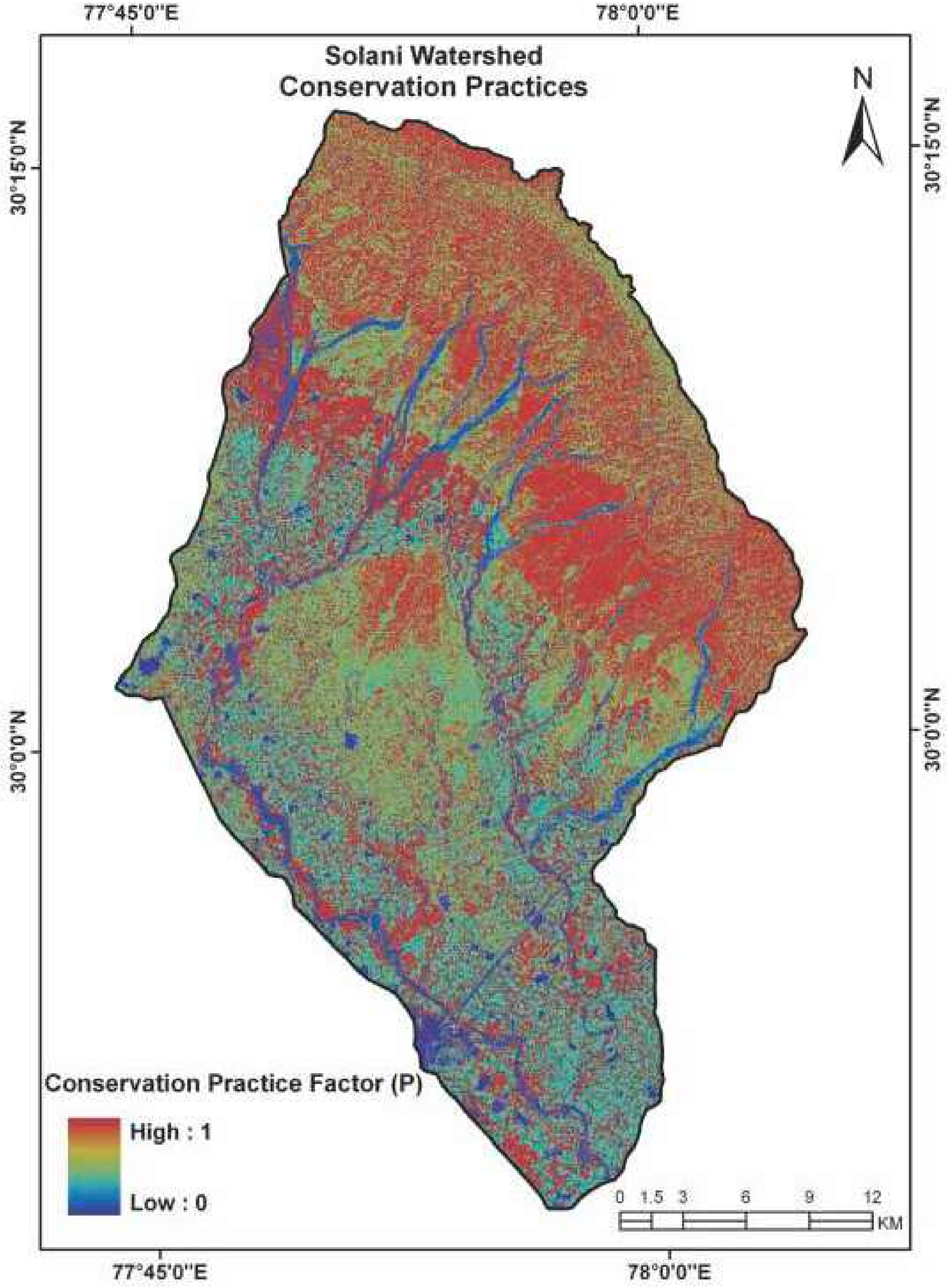

77°45'0"E
78°0'0"E
Solani Watershed
Conservation Practices
N
30°15'0"N
30°0'0"N
Conservation Practice Factor (P)
High : 1
Low : 0
0 1.5 3 6 9 12
KM

Fig. 8

A quantitative assessment of soil loss on pixel level has been carried out by using the well-known RUSLE model with a view to identify the critical soil erosion prone zones for conservation planning in Solani watershed. Detailed data for computation of 'R' factor were not available, therefore, this parameter has been estimated by average annual rainfall data available for two years only. The average annual soil erosion for Solani watershed has been found to be 3.647 t ha^{-1} $year^{-1}$. More than 90% of the watershed area is found under minimal and low erosion classes partaking alluvium tract or plain areas of the watershed. About 5.65% of the watershed mostly under steep slopes and river beds is found under high to extreme erosion risk category (> 10.1 t ha^{-1} $year^{-1}$). Therefore, priority be given for protection of forest and afforestation of steep barren lands and maximization of plant coverage along suitable slopes. Briefly, it could be inferred that RS and GIS techniques play an important role in generation of input parameters for the purpose of soil erosion modeling as well as overall watershed management. These techniques can assist in developing management scenarios and provide options to policy makers for handling soil erosion problem in the most efficient manner which could further help in prioritization of watershed areas for treatment.

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Table 3
Solani Watershed: Annual Soil Loss Estimation (Ton /ha/Year)

Soil Loss Categories	Area (Sq Km)
Less than 2	547.78 (58.30)
2-5	255.02 (27.14)
5.1- 10	83.57 (8.90)
10.1-20	30.86 (3.28)
More than 20	22.30 (2.37)
Total	**939.54 (100.00)**
Average annual soil loss	3.647 t ha^{-1} $year^{-1}$

Source: computed by author
Figures in parentheses show the percentage to total study area

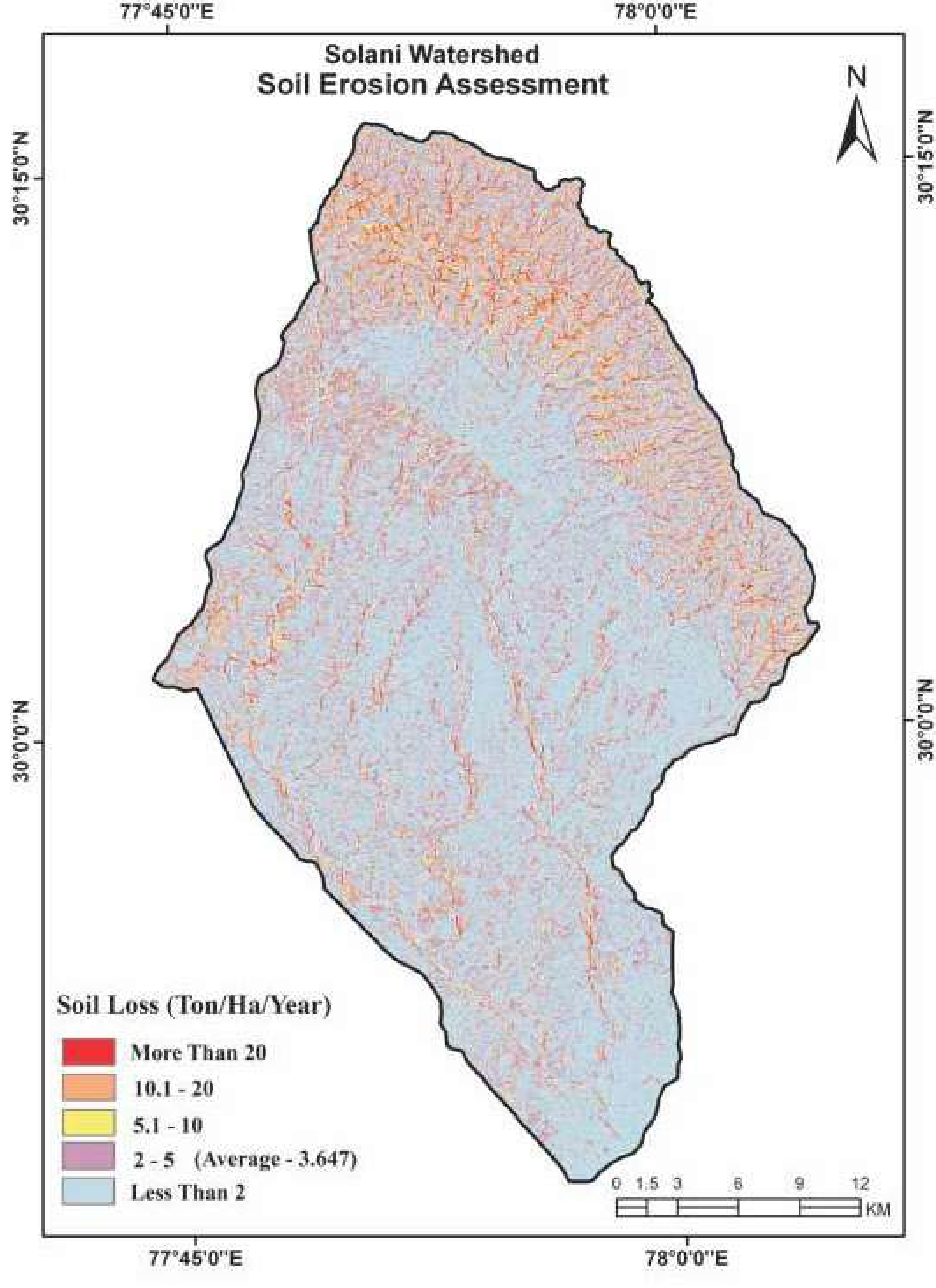
77°45'0"E
78°0'0"E
Solani Watershed
Soil Erosion Assessment
N
30°15'0"N
30°0'0"N
Soil Loss (Ton/Ha/Year)
More Than 20
10.1 - 20
5.1 - 10
2 - 5 (Average - 3.647)
Less Than 2
0 1.5 3 6 9 12
KM

Fig. 9

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