Journal of the Andaman Science Association Vol. 27(2):246-255 (2022)
ISSN 0970-4183, Printed in India

Digital Terrain Modelling and Soil Erosion Risk Assessment for Enhancing Land Productivity

Anwar M. and Kumar S.
[1]*Pandung Institute of Technology, Indonesia*
[2]*Indian Institute of Remote Sensing, Dehradun, India*
Corresponding author's Email: *anwarmd_pand@gmail.com*

Abstract

Soil erosion by water is pronounced a critical problem in mountainous and undulating terrain. Therefore, its assessment and mapping of erosion prone area are very essential for soil conservation and watershed management. In recent years, digital terrain modelling (DTM) has been used to represent the terrain surfaces for hydrologic modelling, sediment transport and soil erosion estimation. The present study delineated soil erosion susceptibility zones by integration of terrain and vegetation indices. The primary and secondary terrain attributes, landforms were derived from DTM. Vegetation indices representing NDVI, was calculated by Using Landsat-8 satellite data. Land use and land cover, watershed and sub watersheds of Chamoli district, Uttarakhand was delineated using satellite data after ground trothing. Slope analysis showed 13.64 % area under gentle sloping, 38.07 % moderate slope and 48.28 % steep slope. Delineation of landform elements indicated 16.69 % area under valley, 32.39 % lower slope, 35.28 % upper slope and 15.63 % ridge. Weightage was given to the each individual class in individual thematic map and overlaid to each thematic layer to assess the soil erosion by integrating these thematic layers. The final result was classified by threshold into five classes such as very less erosion (0.12%), less erosion (9.93%), moderate erosion (22.44 %), severe erosion (43.51 %) and very severe erosion (23.97 %). The study demonstrated the importance of soil conservation and watershed management for improving the land productivity.

Key words: *soil erosion, hierarchical approach, terrain modeling*

Introduction

Terrain characterization signifies the sum of all physical features and conditions at or near the earth surface (Pandey and Shedha, 1981). Understanding the terrain characteristics and processes and their usefulness to various users is the terrain purpose of terrain analysis (Kirkby, 1976). Important terrain characteristics for studying soil erosion are slope gradient, length, aspect and shape (Taiwan, 2001).

Soil erosion is considered as one of major land degradation process which is also the main source of environmental deterioration. It creates negative impacts on agricultural production, infrastructure and water quality (Vrieling, 2006). Therefore, soil erosion risk by accelerated water and wind constituted a serious primary problem to terrains, especially in developing countries of tropics and subtropics (Biswas, Sudhakar and Desai, 1999). Soil erosion is a crucial problem in India where more than 70% of land in degraded condition. Erosion models can be used as the tool for predicting the soil loss and conservation planning.

Socio-economic and environmental changes have impacted heavily on land use in the region, mainly due to the extension of cultivation into marginal land and forested areas. Topography is one the major factors that heavily influence the development of soil and soil erosion prediction. Role of satellite RS and GIS in watershed prioritization and management offers scientific input for the formulation of proper watershed management programmed and also addresses some of the parameters related to watershed develop-ment (Kumar et al., 1998; and Singh et al., 2002). A number of parametric models have been developed to predict soil erosion and with a few exceptions, these model are based on soil, land use land cover, landform, climatic and topographic information (Singh, 1994). Integrating satellite imagery with GIS is useful for study in land use change and another parameters (Halim et al., 2006).

The study for the delimitation of the zone of high runoff and consequently soil erosion can prove to be of immense value to the decision makers for implementing better land management practices in the area. Thus the main objective of this study was assessing soil erosion risk by integrating terrain and vegetation parameters. This also develop methodologies for qualitative regional erosion modeling which should be easily applicable in tropical environments.

Materials and methods

Study area

The present investigation was carried out in Chamoli district which lies in the northeastern part of Uttarakhand state (Fig. 1). The geographical area of the district is 7216.84 sq. km. As the elevation of the district ranges from 752 meters to 7785 meters above sea level the climate of the district very largely depend on altitude. The winter season is from about mid-November to March. As most of the region is situated on the southern slops of the outer Himalayas, monsoon currents can enter through the valley, the rainfall being heaviest in the monsoon from June to September. The tract of Chamoli district consists of outward succession of ridges viz. Greater Himalaya and Lesser Himalaya of decreasing height. These hills possess very little level land. The soils have developed from rocks like granite, schist, gneiss, phyllites, shales, slate etc. under cool and moist climate.

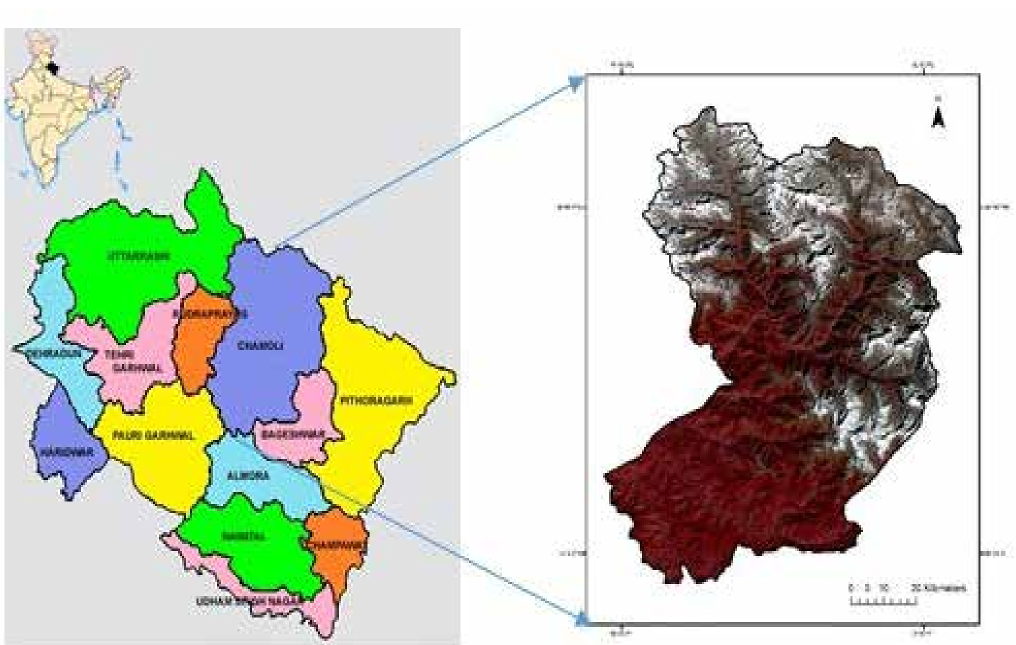

Fig. 1. Location of the study area

Dataset

Landsat 8 data products are produced to be consistent with the existing standard Level-1 (orthorectified) data products created using Landsat 1 to Landsat 7 data. The standard Level 1 Product, along with the Landsat Look (full-resolution jpg) images were also used in this study. Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) images consist of nine spectral bands with a spatial resolution of 30 meters for Bands 1 to 7 and 9. The resolution for Band 8 (panchromatic) is 15 meters. Thermal bands 10 and 11 are useful in providing more accurate surface temperatures and are collected at 100 meters. Approximate scene size is 170 km north-south by 183 km east-west (106 mi by 114 mi). Advanced Space borne Thermal Emission and Reflection

Radiometer (ASTER) data can be used in various application viz., land-use studies, resource mapping, geology, water resources, coastal resources, environment and generation of digital elevation models. In this study the DEM was used to derive land form map.

Methodology

The estimation of soil erosion prone area consisted of five processes viz. deriving primary terrain attributes, secondary terrain attributes vegetation indices, weightage and integrating of all weighted maps, and finally classification. The details of the methodology are described below (Fig. 2).

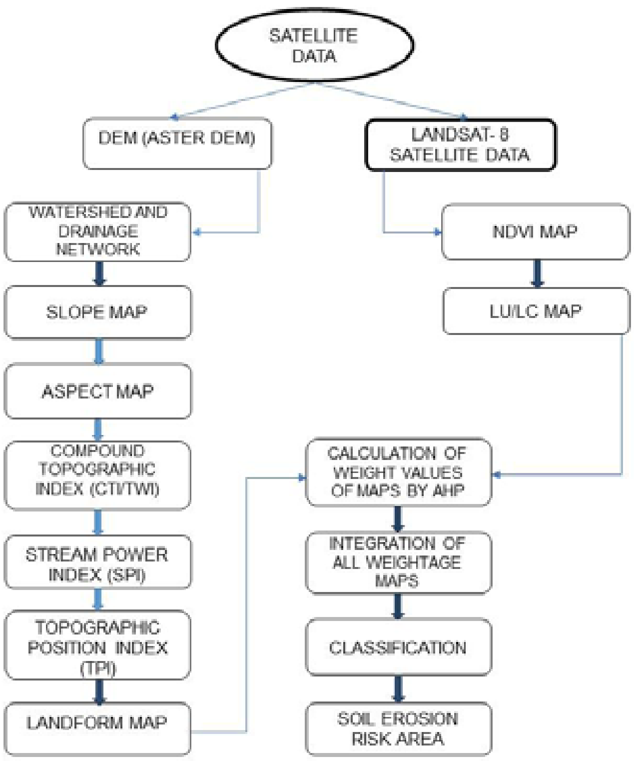

Fig. 2. The Flow chart of the methodology and procedure

Delineation of terrain and watershed

Watersheds are those areas from which runoff resulting from precipitation, flows past a single point into a large stream a river, lake or an ocean. Hydrologic Engineering Centre's Geospatial Hydrologic Modelling Extension, HEC-GEO HMS, are used to delineate sub watersheds of the study area. By using GEO HMS, 21 sub and micro watersheds were delineated in the study area (Fig. 3).

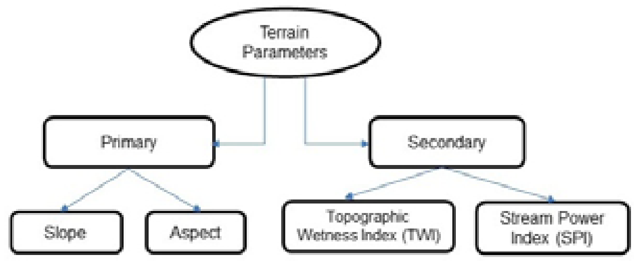

Fig. 3. Flow chart to derive terrain parameters

Secondary Terrain Parameters

Topographic Wetness Index

The Topographic Wetness Index (TWI) can quantify the effect of topography on runoff generation and serves as a physically based index approximating the location of zones of surface saturation and the spatial distribution of soil water. In a catchment, areas having same value of topographic wetness index are assumed to have similar hydrological response to rainfall when other environmental conditions (such as land cover, soil) are the same or can be treated as being the same.

$$TWI = \ln (As/\tan\beta)$$

A = Upstream contributing area in m^2;
B = Slope raster, filename = SLOPE

TWI represents topographic wetness index, as indicates specific catchment area, m^2, β represents local slope gradient for reflecting the local drainage potential.

Stream Power Index

Stream power index is the rate the energy of flowing water to carry the amount of soil particles or sedimentation. Stream power index measures erosive power of flowing water based on the assumption that discharge is proportional to specific catchment area. It can be described as:

SPI = ln (As * tanβ)

SPI represents Stream Power index, as indicates specific catchment area, m², β represents local slope gradient for reflecting the local drainage potential. In this study stream power index is find out by using flow accumulation and slope derived from DEM. The formula of Topographic Wetness Index representation are as follows.

SPI = Ln("Flow accumulation"+0.001) *(("slope"/100) +0.001)

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a numerical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum. The Normalized Difference Vegetation Index (NDVI) shows patterns of vegetative growth from green-up to senescence by indicating the quantity of actively photosynthesizing biomass on a landscape (Burgan, 1996). In this study NDVI is derived based on the difference between the maximum absorption of radiation in red, certain pigments of vegetation or plant leaves strongly absorb Red spectral band and the maximum reflection radiation in NIR, vegetation themselves reflect wavelength of Near Infrared.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

The equation produces values ranging from (–1 to 1). Negative values are indicative of clouds, snow, water and other non-vegetated, non-reflective surfaces, while positive values denote vegetated or reflective surfaces (Burgan 1993).

Weightage assignment using Analytical Hierarchy Process (AHP)

AHP is one of the multiple criteria decision-making method which provides measures of judgement consistency. It derives priorities among criteria and alternatives and simplifies preference ratings among decision criteria using pair wise comparisons (Table 1). Soil Erosion Risk Index is related by the sets of attributes called decision factors, which are identified and then further, the sub–factors (a set of alternatives) for the concern decision factors are to be decided to better described the decision factors.

Table 1. Number of comparisons

Number of things	1	2	3	4	5	6	7	n
number of comparisons	0	1	3	6	10	15	21	$\frac{n(n-1)}{2}$

The scaling is not necessary 1 to 9 but for qualitative data such as preference, ranking and subjective opinions, it is suggested to use scale 1 to 9. Pair wise comparison using the fundamental scale of absolute numbers (Saaty, 1980) of decision matrix and their sub–factors. When a number greater than 9 is suggested by the inconsistency checking, this means that the elements you have grouped together are too disparate. You may input a number greater than 9, but perhaps you should re-organize your structure so that such a comparison is not required. It will do no great damage to allow numbers up to 12 or 13, but you should not go much beyond that. Matrix multiplication is done between matrix in which pair wise comparison was done and the consistency index (CI) is calculated by following formulae.

$$CI = \frac{\lambda MAX - N}{N - 1}$$

Where,

CI= Consistency index; N=Number of criteria.

λMAX is priority vector multiplied by each column total (λMAX) is maximum of Matrix multiplication/

average and N is number of criteria. It reflects the consistency of one's judgment.

Weightage and Integration of all weighted maps

In this research pairwise comparison of thematic layers with each other based on their relative importance was done followed by weights of individual thematic layers for weighted index overlay analysis (WIOA). The classes and weights assigned were based on the influence and strength of association that the different layers have with the soil erosion process. In every layer each class was assigned by weightage index and each class erosion response then estimated as the geometric mean of its own sub-layers. After weightage given to all layer we can perform overlay analysis by using overlay tool in ArcGIS. We could obtain results of overlay analysis and that can be perform Geometric Mean method for the final required result. In this analysis Geometric Mean algorithm was used (Basso et al. (2012) as described below:

$$Erosion_x = (layer\ 1_{ij} * layer\ 2 *_{ij}\ layer\ 3 *_{ij} * \ldots\ldots * layer\ n_{ij})^{(1/n)}$$

Where: I, j = A single class of each layer; N = number of layers

Hydrologic Modelling Using GIS

The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) has been developed as a geospatial hydrology toolkit for engineers and hydrologists with limited GIS experience. HEC-GeoHMS uses ArcGIS and the Spatial Analyst extension to develop a number of hydrologic modeling inputs for the Hydrologic Engineering Center's Hydrologic Modeling System, HEC-HMS. Using an elevation raster or digital elevation model (DEM) as input, it is possible to automatically delineate a drainage system and quantify the characteristics of the system.

Results and discussion

Using remote sensing and GIS, spatial erosion modelling by making use of Geo-spatial Hydrologic Model was performed to predict soil loss. Various thematic layers have been prepared through different sources of the available data sets based on the understanding of the causative factors of soil erosion in the study area.

Terrain parameters

In this study, terrain parameters were used to find out soil erosion prone areas of Chamoli district. Six parameters have been considered namely slope, aspect, topographic wetness index, stream power index, land use/ land cover and NDVI. The results obtained in the study are presented as below:

Drainage network were delineated from DEM using ArcGIS. There are six kinds of stream orders found in the study area (Fig. 4). The drainage density is 1.16 kg/ km^2 and it has 0.53 circulatory ratio (Table 2). Streams order map was used to delineate sub watersheds of the study area. Area of watershed is 6927.48 km^2. From the same watershed a total of 21 sub watersheds were also delineation.

Table 2. Areal Characteristics of Chamoli

S. No.	Parameter	Value
1	Drainage Density	1.16 km/km²
2	Circulatory Ratio	0.53
3	Elongation Ratio	0.96
4	Form factor	0.42

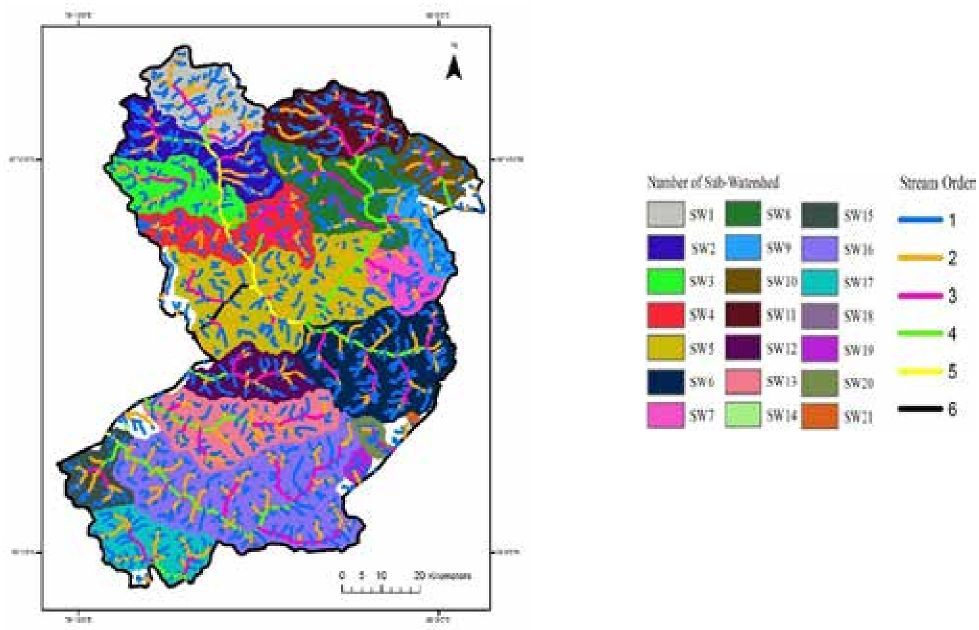

Fig. 4. Drainage network over lying on delineated watershed map

Topographic wetness index derived from Aster-DEM is given in Fig. 5. Topographic Wetness Index was derived from combination of Flow accumulation and slope map. Topographic Wetness Index was classified into five classes and these classes were very low, low, moderate, high, and very high. The TWI values ranges from (-6.69 to 21.09). The high values indicating more wetness and low values indicating less wetness or dry area.

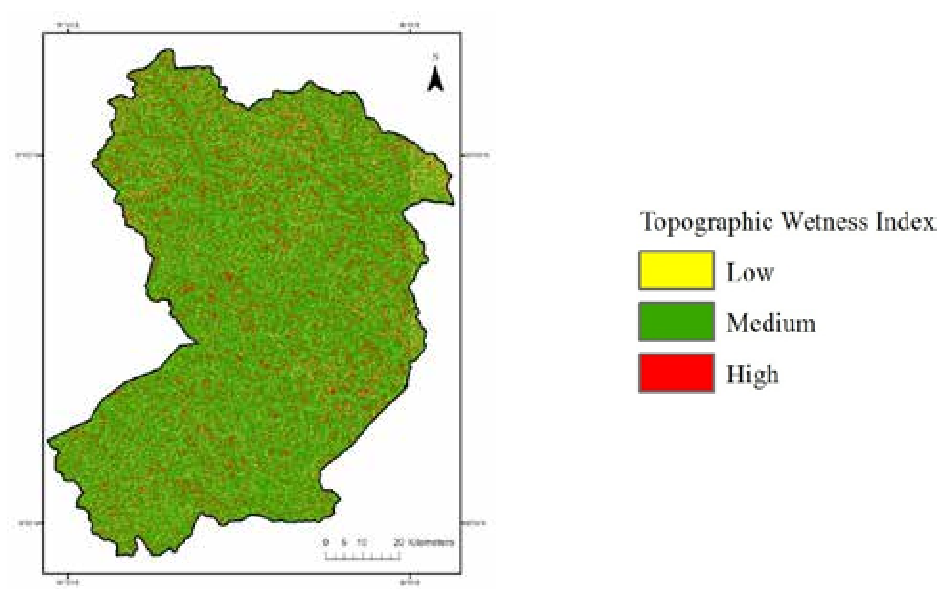

Fig. 5. Topographic wetness index map

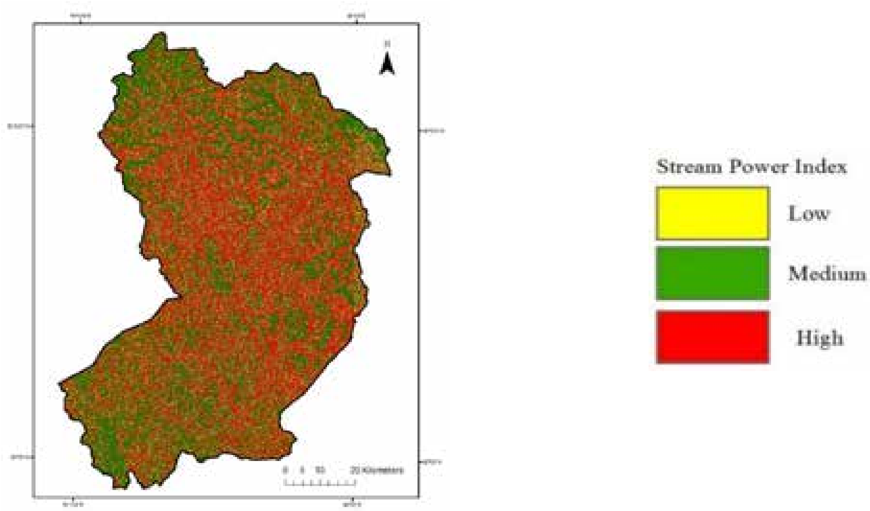

Fig. 6. Stream power index map

Stream power index (Fig 6) derived from Aster-DEM depicts erosive power of flowing water based on the assumption that discharge is proportional to specific catchment area. Stream power index also derived from Slope and Flow accumulation are as inputs. The SPI values ranges from (-43.48 to 44.15). This range were classified as five classes as Very high, high, moderate, low and very low. High value of Stream Power Index indicates the more potential to get more soil erosion.

Similarly the Aster-DEM was used for delineation of landform elements on the basis of slope position and the major landforms delineated were valley, lower slope, upper slope and ridge/hill. The satellite image (Landsat-8) of October 1920 was used for Land use/Land cover classification. Land cover map revealed area under very dense forest, dense forest, open forest, agriculture, barren land, built-up land, water body and snow. NDVI helped to derive vegetation cover of the study area. It was calculated by using NIR and Red band (Fig. 7). The NDVI of the study area was classified into three classes *viz*. Low, Medium and High.

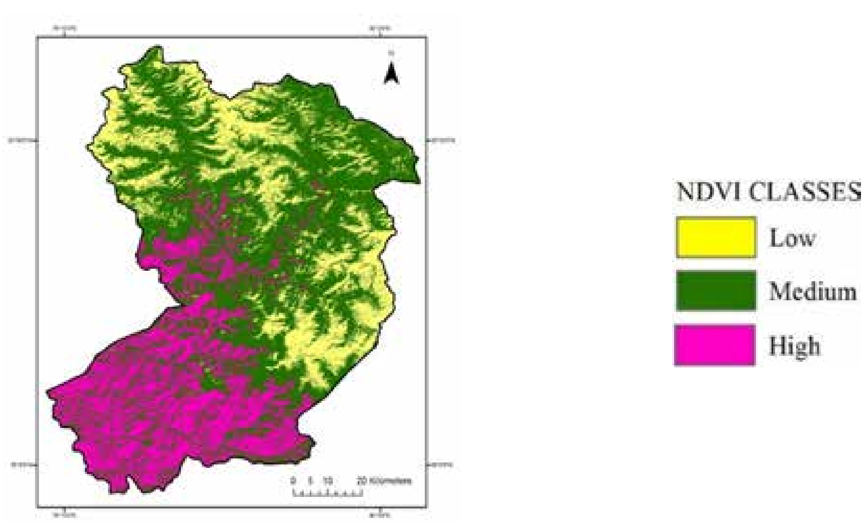

Fig. 7. NDVI map of the study area

Assessment of soil erosion risk zones

After the hierarchy has been established, the criteria must be evaluated in pairs so as to determine the relative importance between them and their relative weight to the global goal. At the same time, in order to interpret and give relative weights to each criterion, it is necessary to normalize the previous comparison matrix. The normalization is made by dividing each table value by the total column value as given in table 3.

Table 3. Comparison matrix for soil erosion after normalization

	Slope	**Landform**	**LU/LC**	**TWI**	**NDVI**	**Aspect**
Slope	1	3	5	7	9	9
Landform	1/3	1	3	5	7	7
LU/LC	1/5	1/3	1	3	5	5
TWI	1/7	1/5	1/3	1.00	3.00	3.00
NDVI	1/9	1/7	1/5	1/3	1.00	1.00
aspect	1/9	1/7	1/5	1/3	1.00	1.00
Total	1 8/9	4 5/6	9 3/4	16 2/3	26	26

Table 4. Inconsistency index derived by each cell divided by its column total

	Slope	Landform	LU/LC	TWI	NDVI	Aspect
Slope	0.52	0.62	0.51	0.42	0.34	0.34
Landform	0.17	0.20	0.30	0.3	0.26	0.26
LU/LC	0.10	0.06	0.10	0.18	0.19	0.19
TWI	0.07	0.04	0.03	0.06	0.11	0.11
NDVI	0.05	0.02	0.02	0.02	0.03	0.03
Aspect	0.05	0.02	0.02	0.02	0.03	0.03

The contribution of each criterion to the organizational goal is determined by calculations made using the priority vector (or Eigenvector). The Eigenvector shows the relative weights between each criterion it is obtained in an approximate manner by calculating the arithmetic average of all criteria. We can observe that the sum of all values from the vector is always equal to one (1). The exact calculation of the Eigenvector is determined only on specific cases. This approximation is applied most of the times in order to simplify the calculation process, since the difference between the exact value and the approximate value is less than 10% (Kostlan, 1991). The inconsistency index is based on Maximum Eigenvalue, which is calculated by summing the product of each element in the Eigenvector by the respective column total of the original comparison matrix (Table 4). It also demonstrated the calculation of Maximum Eigen value (λMAX). It can be observed that the approximate and exact values are very close to each other, so the calculation of the exact vector requires a mathematical effort that can be exempted (Kostlan, 1991). The values found in the Eigenvector or average have a direct physical meaning in AHP. They determine the participation or weight of that criterion relative to the total result of the goal.

Table 5. Weightage of different parameters used in the erosion model

S. No.	Parameters	Percentage of Influence
1	Slope map	46
2	Landform map	25
3	LU/LC map	14
4	TWI map	7
5	NDVI map	4
6	Aspect map	4

Weighted overlay operation of six thematic layers with their weight and overall percentage of influence as derived in (Table 5) generated Soil Erosion Potential Zone Map (Fig. 8). The delineation of erosion potential zones was carried out by reclassifying into five different soil erosion potential zones: Very less, less, moderate, severe and very severe. Soil erosion risk zones were derived from integrating of Slope map, Landform map, LU/LC map, TWI map, NDVI map and Aspect map. Terrain parameters and vegetation indices were considered to assess soil erosion instead of soil type and soil texture whereas soil is the dominating factor in soil erosion by water. The percentage area in different erosion class is given in Fig. 9. It was observed that the maximum area was under severe erosion category followed by severe, moderate and less. As the very severe and severe category falls under moderate to high slope with less dense vegetation, this showed the dominant influence of terrain factors in accelerating erosion.

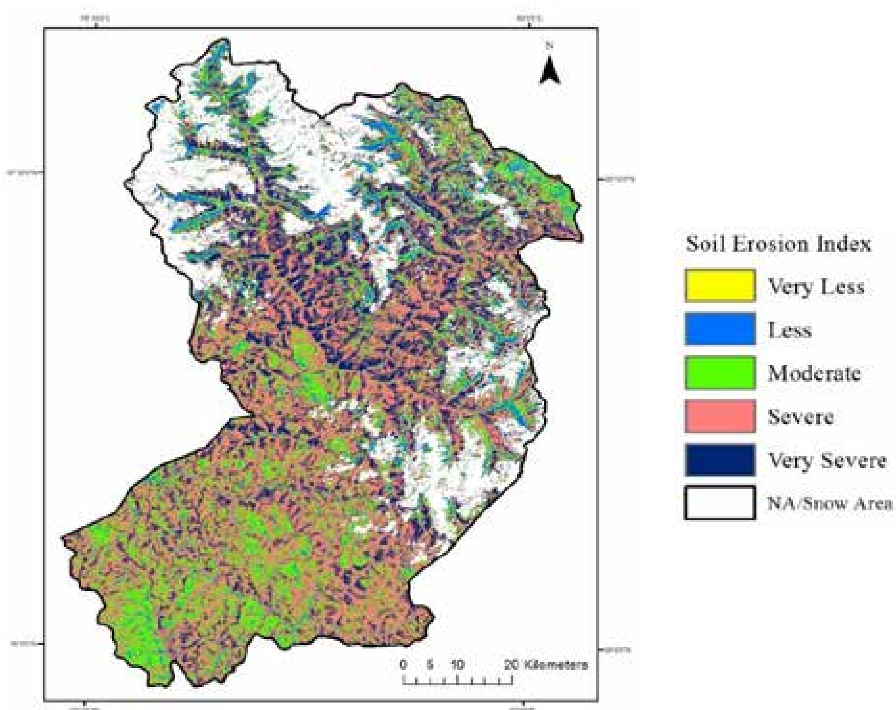

Fig. 8. Soil erosion risk prone areas of the study area

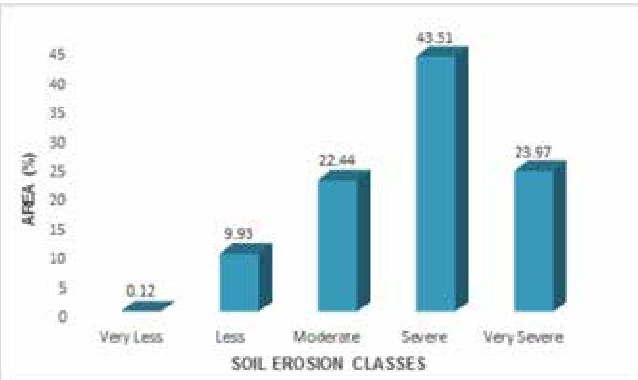

Fig. 9. Areal extent of different soil erosion classes

Conclusions

The Risk analysis conducted in this study was based on an efficient methodology with an objective to delineate the soil erosion area. The risk analysis of the study area represents terrain features which can be ultimately used for the delineation of the risk areas affected by the different parameters like Slope, Aspect, TWI, Landform, Land use / Land cover, and NDVI. Thematic maps were prepared that has finally focused on the identification of the factors that controls the soil erosion risk in the study area. It is accomplished by the AHP technique with the GIS based overlay analysis.

The analytical hierarchy process (AHP) provided a systematic approach for assessing and integrating the impacts of various parameters, involving several level of dependent and independent, qualitative as well as quantitative information. This study developed a logical weightage assigning based on relative soil erosion potential of different contributing parameters. ARC-GIS model builder is an efficient GIS based tool for overlay analysis of thematic layers for generating soil erosion zonation map. The point to be considered during overlay analysis is that all the thematic layers should have discrete values rather than continuous values for assigning weightage. The study demonstrated the potential of the methodology and estimated that major portion of the Chamoli district is prone to severe erosion influenced by the terrain parameters. Thus alteration of terrain parameters would results in accelerated erosion and further consequences.

Acknowledgements

I take this opportunity to express my gratitude to my guide, all the faculty members, as well as the non-teaching staff of ASD, IIRS for all the support, help and knowledge imparted to me during my stay at IIRS.

References

Carter, B.J. & Ciolkosz, E.J. (1991). Slope gradient and aspect effects on soils developed from sandstone in Pennsylvania. Geoderma 49:199-213.

Youfu, D., Guoan, T. & Ting, Z. (2008). A Systematic Classification Research of Topographic Descriptive Attribute Digital Terrain Analysis. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVII, Part B2, pp. 357-362.

Gallant, J.C. & Wilson, J.P. (2000). Primary topographic attributes. In: *Terrain Analysis: Principles and Applications*, Wilson, J.P. and Gallant, J.C., Eds. John Wiley and Sons: New York, NY, USA. pp. 51-85.

Jenson, S.K. (1991). Applications of hydrological information automatically extracted from digital elevation models. Hydrol. Process. 5:31-44.

Nekhay, O., Arriaza, M. & Boerboom, L. (2009). Evaluation of soil erosion risk using Analytic Network Process and GIS: A case study from Spanish mountain olive plantations. J. Environ. Mgt. 90:3091-3104.

Qiang, W. & Wang, M. (2007). A framework for risk assessment on soil erosion by water using integrated and systematic approach. Department of Resources and Earth science, China University of Mining and Technology, Beijing 100083, PR China.

Raina, A.K. & Gupta, M.K. (2006). Geology and geomorphology of Arnigad watershed in Lesser Himalayas, Missoorie Forest Division, Uttaranchal. Ann. Forest. 14:255-267.

Saaty, T.L. (1980). The Analytic Hierarchy Process. McGraw-Hill International, New York, USA.

Received: 15th October 2022 **Accepted: 18th November 2022**