ANALYTICAL STUDY OF SEDIMENT YIELD CHARACTERISTICS OF TEHRI CATCHMENT IN UPPER HIMALAYAS

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ABSTRACT

Tehri Storage Dam built across Bhagirathi River with a catchment area of 7511 km² is located at Tehri which is 85 km from the famous holy place Rishikesh, Uttarakhand, India. Reservoir of the Tehri Dam spreads in an area of approx. 42 km² and possesses a live storage of 26.15 billion m³. The topography of the catchment area of Tehri reservoir is hilly and undulating, from where soil loss is more due to lack of conservation measures, therefore the erosion from the catchment and rate of sedimentation in the reservoir may be more than the designed rate. The process of sedimentation embodies the sequential process of erosion, entrainment, transportation, deposition and compaction of sediment. The steady erosion and sediment reduces the capacity of reservoir and affects the water availability for the designated use. Thus, a well-designed CAT plan is essential to ameliorate the above-mentioned adverse process of soil erosion and to enhance the life of reservoir live storage.

A study has been taken up for assessment of sediment yield from the reservoir catchment area, identification of sub basins which contribute maximum sediment to the drainage system feeding the reservoir and for understanding the erosion characteristics of the terrain required for design of a suitable catchment area treatment (CAT) plan. The processes of erosion of soil from earth surface is largely depends on topography, vegetation, soil and climate variables. These areas found to have pronounced spatial variability in a catchment due to the spatial variation of climate factors and catchment heterogeneity. Spatial prediction of a variable implies that estimates of this variable can be derived at any location or sub-areas. The USLE model applications in the grid environment with GIS allows to analyze soil erosion in much more detail since the process has a spatially distributed character. A recent and emerging technology represented by GIS provides the tools to generate, manipulate and spatially organize data for sediment yield modelling. The GIS and Remote Sensing (RS) provide spatial input data to the model, while the Universal Soil Loss Equation (USLE) can be used to predict the sediment yield from the watershed.

The cloud free digital data of Landsat imagery of 30 m spatial resolution was used in the study. ERDAS IMAGINE and Arc-GIS software's were used in the study to classify satellite and generation of various maps. The watershed boundary of the Tehri catchment was delineated using hydrology tool within GIS environment considering topographical parameters derived from Digital Elevation Model and Drainage network. SRTM DEM of 30 m resolution used for the delineation of watershed boundary which helped in prioritizing the sub-watersheds for CAT plan based on vulnerability to soil erosion.

This paper provides an insight of the methodology adopted in the analytical study for sediment yield characteristics of Tehri reservoir catchment area including the benefits expected from the study.

***Keywords** : Reservoir, Sediment Yield, USLE, SYI, HEC-RAS*

1. INTRODUCTION

Tehri Dam Project is a mega multipurpose river valley project which has been constructed on river Bhagirathi in north Himalayas. It is the first major storage scheme on this river that originates from Gomukh glacier in Himalayas and has large potential for Irrigation and Power benefits. The 260.5 m high clay core earth & rockfill dam is located about 1.5 km d/s of the confluence of river Bhagirathi and river Bhillangana, a major tributary of river Bhagirathi. The dam has been raised to a height of 239.5 m above the river bed which is at a general elevation of 600.0 m. The full reservoir level and minimum draw down level have been fixed at El 830.0 m & El 740.0 m respectively. The highest flood level may reach El 835.0 m while passing the estimated probable maximum flood of 15,540 cumecs. The reservoir at FRL of 830.0 m has a surface spread of 42 sq km extending about 44 km along river Bhagirathi and about 25 km along river Bhillangana. The gross and live storage capacities of the reservoir are 3540 MCM and 2615 MCM respectively.

The catchment area up to the dam site is about 7511 sq km stretched in a length of 187 km. An area of about 2323 sq km lying in range of El 6900 m to El 4480 m is perpetually snow bound. The rest of the catchment area comprises reserved forest land (2400 sq km), civil soyam land used for cattle grazing (1300 sq km) and private agricultural land (1240 sq. km.), all lying between El 4880 m to 600m. Location map of the study area is shown in Figure-1.

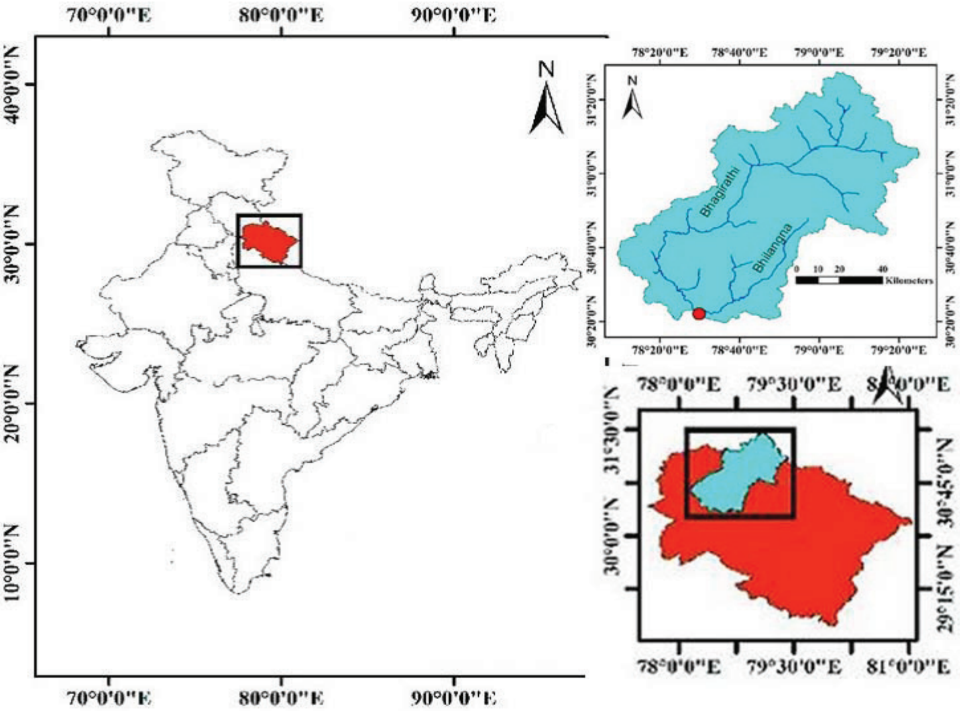

Figure 1 : Location map of the study area

2. BACKGROUND OF THE STUDY:

Erosion is a natural geomorphic process occurring continually over the earth surface. The processes of erosion of soil from earth surface largely depends on topography, vegetation, soil and climate variables. The USLE model applications in the grid environment with GIS would allow to analyze soil erosion in much more detail since the process has a spatially distributed character. The GIS and Remote Sensing (RS) provide spatial input data to the model, while the Universal Soil Loss Equation (USLE) can be used to predict the sediment yield from the watershed. The model stimulates the dynamics of event runoff, soil detachment and transport process.

3. OBJECTIVES OF THE STUDY

- Identification of vulnerable areas in the catchment of Tehri Reservoir using USLE, GIS and Remote Sensing data.
- Preparation of Catchment Area Treatment (CAT) plan for recommendation soil conservation measures in the vulnerable areas of the catchment of Tehri Reservoir.
- Develop an explicit relationship between runoff and sediment yield.

4. STUDY DATA

The daily precipitation data for the period of 1980 to 2012, was obtained from one rain gauge station located at Tehri. The cloud free digital data of Landsat imagery of 30 m spatial resolution was downloaded from http://glovis.usgs.gov. ERDAS IMAGINE and Arc-GIS software's were used in the study to classify satellite and generation of various maps.

4.1 Delineation of watershed boundary

The watershed boundary of the Tehri catchment was delineated using hydrology tool within GIS environment considering topographical parameters derived from Digital Elevation Model (SRTM DEM) and Drainage network.

4.2 Soils of the Tehri catchment

Soil map for the study area is prepared by using soil maps collected from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), ICAR, Nagpur. The soil map and description of soil is given in Figure 2.

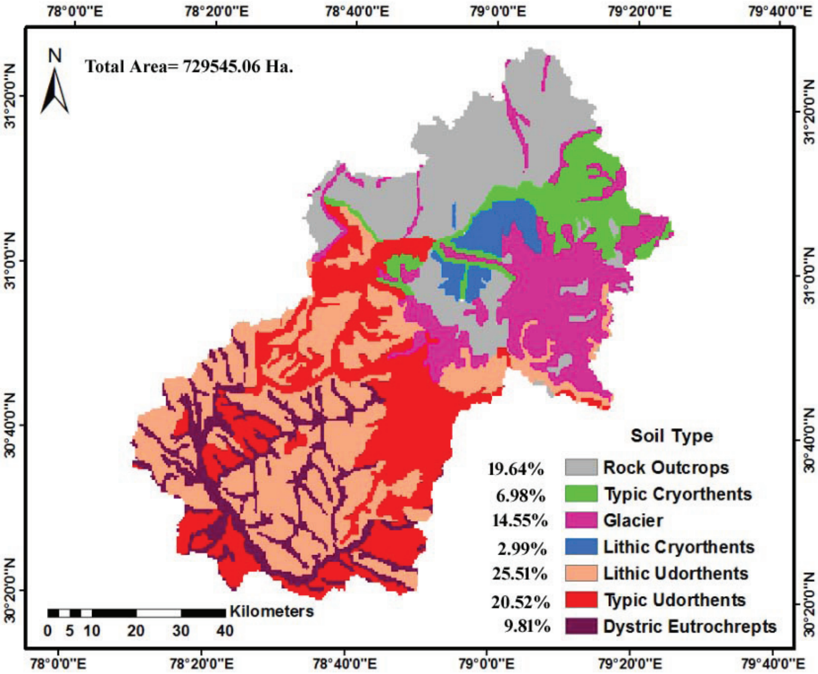

Figure 2 : Soil Map of the Tehri catchment

4.3 Generation of Slope Map

Slope map of the Tehri catchment has been generated using Digital Elevation Model (DEM). DEM is the raster representation of a continuous surface, usually referring to the surface of the earth. The DEMs have proved to be very efficient in extracting different topographical attributes (elevation, slope, aspect, relief, curvatures etc.). A Digital Terrain Model (DTM) of the area was then prepared, which was used to derive a slope map. The slope was divided into classes of slope percentages. This map is classified into five categories for estimation of soil erosion. Slope map of free draining catchment is shown in Figure 3.

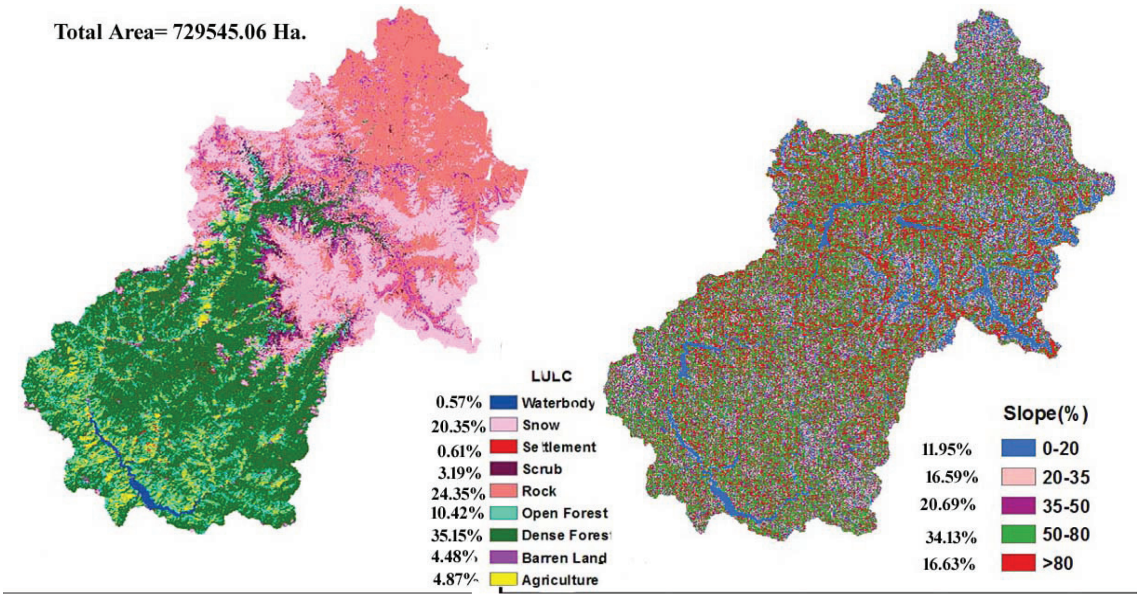

Figure 3 : Slope Map & Land use/Land cover Map of the Tehri catchment

4.4 Land Use /Land Cover

Land use and land cover mapping was carried out by standard methods of analysis of remotely sensed data following by ground truth collection and visual interpretation of satellite data. For this purpose, Landsat 8 data of September 2013 was used. Digital image processing of the satellite data and the analysis the analysis of interpreted maps were carried out using ERDAS Imagine and ArcGIS for GIS analysis. The classified land use/ land cover map of free draining catchment is shown in Figure-3. The digital vector layer for the entire catchment area was used as a mask to extract the required area from the image for further processing.

5. WTERSHEDS/ SUB-WATERSHEDS:

In this study, the catchment boundary of Tehri was delineated digitized and then watershed was divided into seventeen sub-watersheds considering topographical parameters derived from Digital elevation model (DEM) and drainage network. Finally, code numbers from SWS1 to SWS17 were allotted to these seventeen sub-watersheds.

The sub-watersheds and GPS locations during ground truth verification is shown in Figure 4.

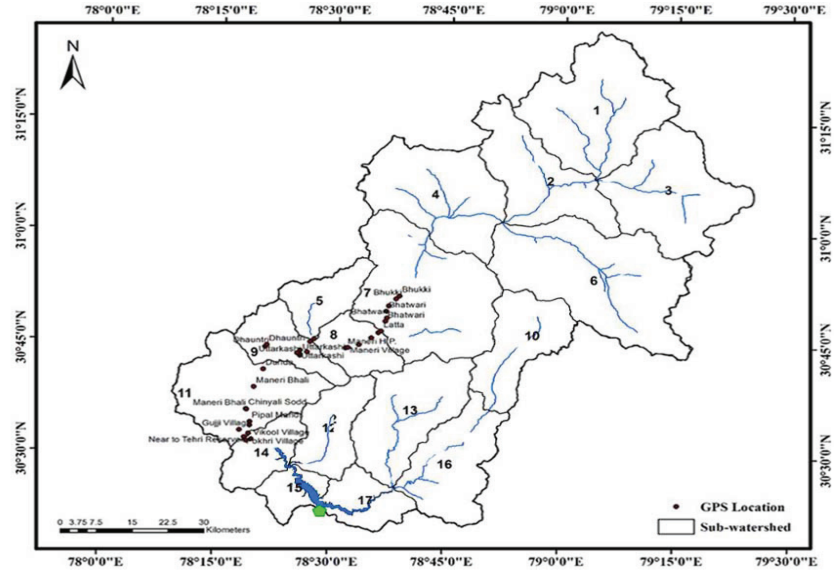

Figure 4 : Delineation of sub- watersheds of the Tehri catchment

6. ASSESSMENT OF SOIL EROSION FROM TEHRI CATCHMENT:

6.1 Estimation of USLE Parameters

6.1.1 *Rainfall Erosivity (R) factor (MJ mm ha-1 h-1yr-1)*

The Erosivity factor of rainfall (R) is a function of the falling rainfall intensity. Rainfall data of 20 years (1993-2012) were used for calculating R-factor. Annual rainfall data were used to calculate R- factor annually using the relationship R=0.5×P (Devatha, 2015); Where, R = Rainfall Erosivity factor (Mj mm ha-1 h-1 year-1) and P = Annual rainfall (mm). Based on the 20 years railfall data, the average annual rainfall erosivity factor comes out to be 659.49 Mj mm ha^{-1} h^{-1}.

6.1.2 *Soil Erodibility (K) factor*

The K-factor (in t ha h ha^{-1} Mj-1 mm^{-1}) adopted for this study for different types of soil as per Ahamed et al. (1991) and Wang et al. (2001) are as shown in the Figure 5.

6.1.3 *Topographic Factor (LS):*

The L-factor was calculated based on the relationship $L = (\lambda/22.13)^m$; Kinnell (2001).

Where, L=slope length factor; λ = field slope length (m); m=dimensionless exponent that depends on slope steepness, being 0.5 for slopes exceeding 5%, 0.4 for slope 3% to 5%, 0.3 for slopes 1% to 3% and 0.2 for slope upto 1%. The percent slope was determined from DEM, while a grid size of 90 m was used as field slope length (λ). Slope length factor values varies from 1.55 to 3.0 depending on the topography of the study area (Figure 5).

6.1.4 *Slope steepness factor (S):*

The S-factor was calculated based on the relationship given by McCool et al. (1987) for slope longer than 4 m as:

$S = 10.8 \sin\theta + 0.03$ for slopes < 9 % & $S = 16.8 \sin\theta - 0.03$ for slopes ≥ 9 %;

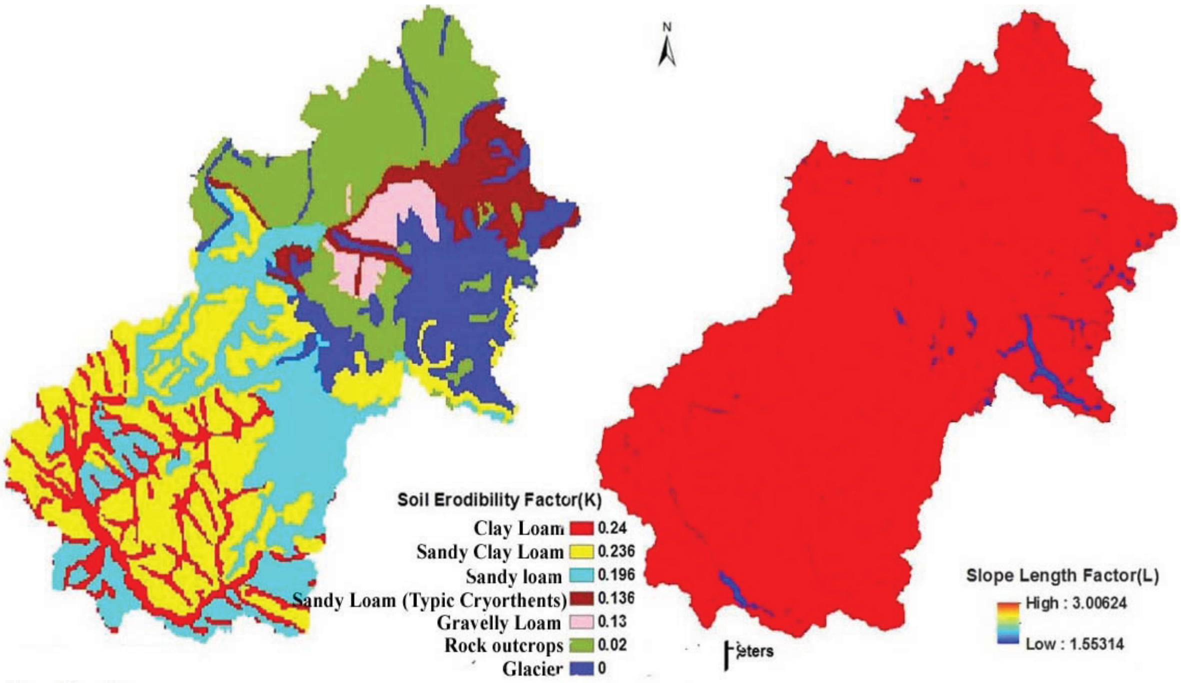

Figure 5 : Spatial distribution of soil erodibility factor & slope length factor

Where, S=slope steepness factor and θ=slope angle in degree. The slope steepness factor is dimensionless. Slope steepness factor varies from the 0.03 to 13.64 depends on the slope steepness of the study area. Spatial distribution of slope steepness factor is shown in Figure 6.

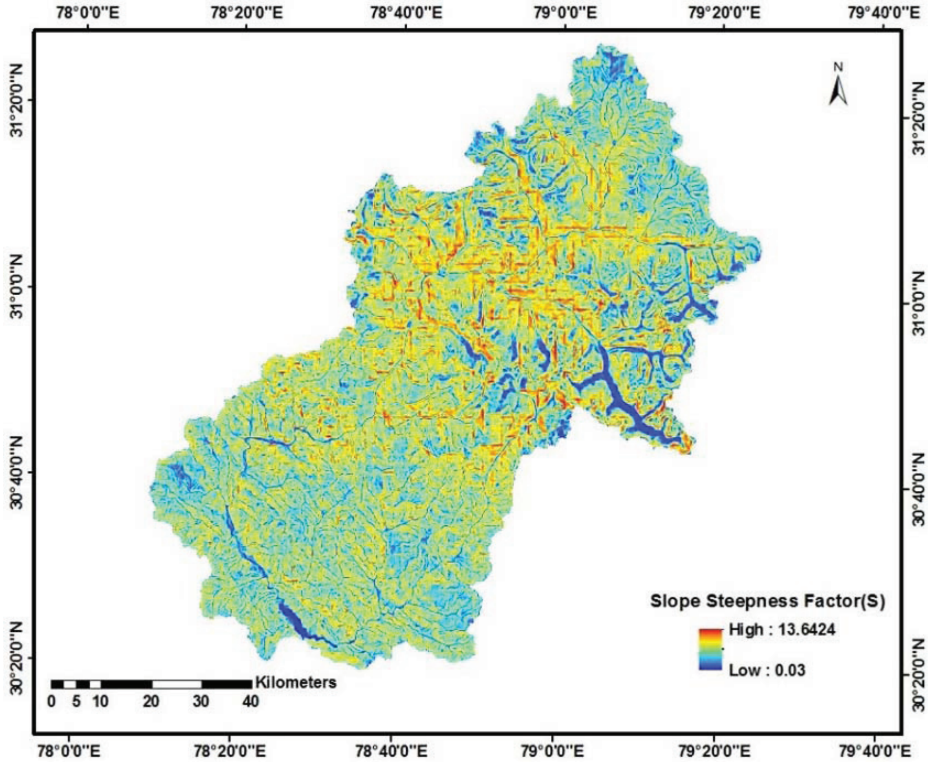

Figure 6 : Spatial distribution of slope steepness factor

6.1.5 *Crop Management Factor (C):*

Crop Management factor is the expected ratio of soil loss from a cropped land under specific condition to soil loss from clean tilled fallow on identical soil and slope under the same rainfall conditions. In the present study, the land use/land cover map was derived from the satellite images and the crop management factor varies from 0 to 0.45 depends on the land use/ land cover type. Spatial distribution of crop management factor is shown in Figure 7.

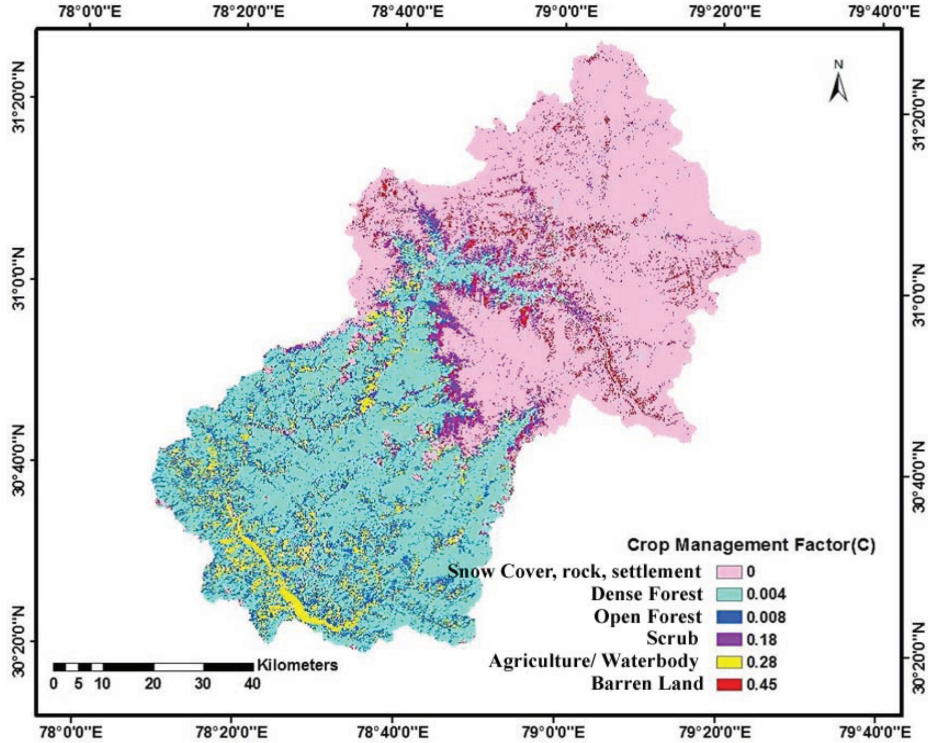

Figure 7 : Spatial distribution of crop management factor

6.1.6 *Conservation Practice Factor (P):*

Conservation practice factor (P) is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope cultivation. In the study area, no major conservation practices are followed. The values for P-factor were assigned to be 0.28 for area under cultivation and 1.0 for other area as suggested by Rao (1981). Spatial distribution of conservation practice factor is shown in Figure 8.

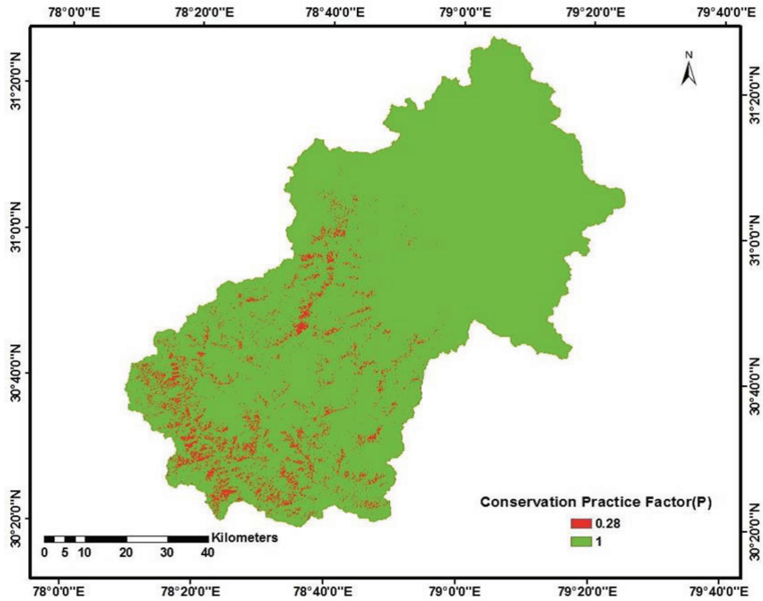

Figure 8 : Spatial distribution of conservation practice factor

6.2 Spatial distribution of annual soil loss

To determine the spatial distribution of average annual soil loss in the catchment, cell-based USLE parameters were multiplied in the specified 30×30 m cells. Average annual soil losses were grouped into different classes. About 66.94% of the catchment area is found out to be under slight erosion class. Areas covered by moderate, high, very high, severe, very severe erosion potential zones are 11.42%, 9.83%, 4.52%, 2.02%, 5.26% respectively. Average annual soil loss in the river basin is about 30.61 t/ha/yr. Spatial distribution of average annual soil loss is shown in Figure 9.

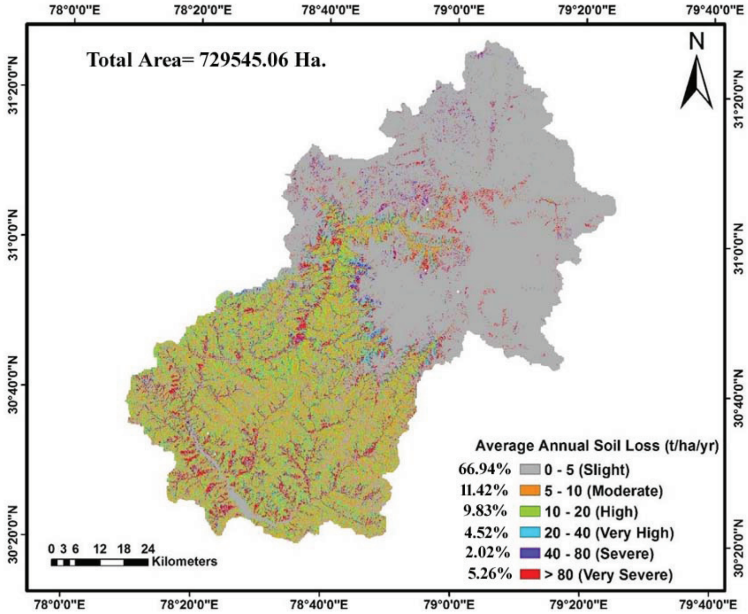

Figure 9 : Spatial distribution of average annual soil loss

7. CATCHMENT AREA TREATMENT PLAN FOR THE STUDY AREA:

7.1 Composite Erosion Intensity Mapping

The composite erosion intensity mapping units are assigned relative erosivity values adjudged to be indicative of the combined effect of dynamic interrelationship of the factors in terms of active erosivity of the units. After assigning appropriate weightages for land use, soil depth & erosion tendency and slope, all maps were superimposed to get composite erosion intensity map. Weightages assigned to each class of soil map, slope map and land use land cover map are added to get Composite Erosion Intensity Unit (CEIU) map. Composite Erosion Intensity Unit (CEIU) map of Tehri catchment area is shown in Figure 10.

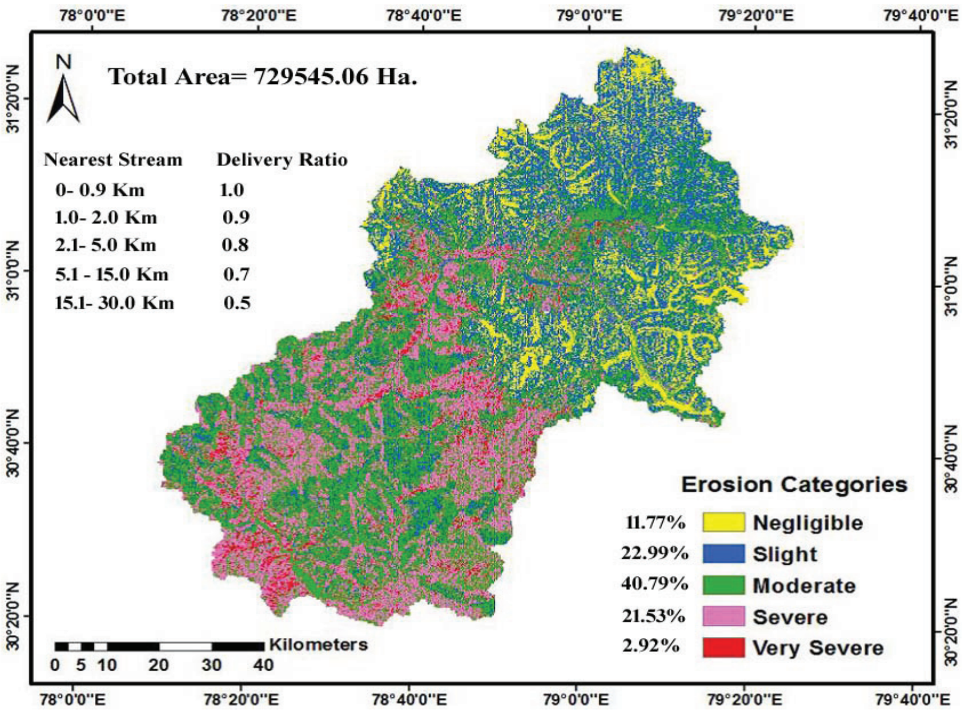

Figure 10 : Composite Erosion Intensity Unit(CEIU) map of catchment area

7.2 Computation of Sediment Yield Index (SYI)

The SYI sediment yield index was calculated using the methodology developed by All India Soil and Land Use Survey (AISLUS). Each erosion intensity unit is assigned a weightage. The range of weightage values assigned for CEIU in the study was from 12 to 20, depending upon the variables. The catchment area of the Tehri was divided into seventeen sub-watersheds for treatment (Figure 2). The area of each of the mapping units is computed and silt yield indices of individual sub-watersheds are calculated using the following equation:

Silt Yield Index (SYI) = $\Sigma(A_i \times W_i \times D_i) \times 100/A_w$ where, i = 1 to n

Where, A_i = Area of ith unit (EIMU); W_i = weightage value of ith mapping unit; n = No. of mapping units; A_w = Total area of sub-watershed; D_i = Adjusted delivery ratio assigned to the mapping unit.

7.3 Estimation of soil loss using Silt Yield Index (SYI) Method

Sediment delivery from a hydrologic unit to a reservoir is a multiplicative function of the potential soil detachment representing the erosive factor, transportability of the detached material (delivery ratio) and area of hydrologic entity. This can be expressed as

Sediment Yield = f × Delivery Ratio (DR) × Area.

The SYI values obtained thus are further adjusted by multiplication with a suitable factor to account for the erosion and deposition of the material at the site. The gradation and the assignment of priority ratings to the sub-watershed are based on the descending values of sediment yield index.

8. PRIORITIZATION OF WATERSHEDS/ SUB-WATERSHEDS

The prioritization of smaller hydrologic units within the vast catchments is based on the Silt Yield Index (SYI) of the smaller units. The **boundary** values or range of SYI values for different priority categories are arrived at by studying the frequency distribution of SYI values and locating the suitable breaking points. Watershed prioritization is the ranking of different critical sub-watersheds according to the order in which they have to be taken up for the treatment and soil and water conservation measures. Based on the SYI, prioritization of watersheds along with their respective SYI values is shown below in Figure 11.

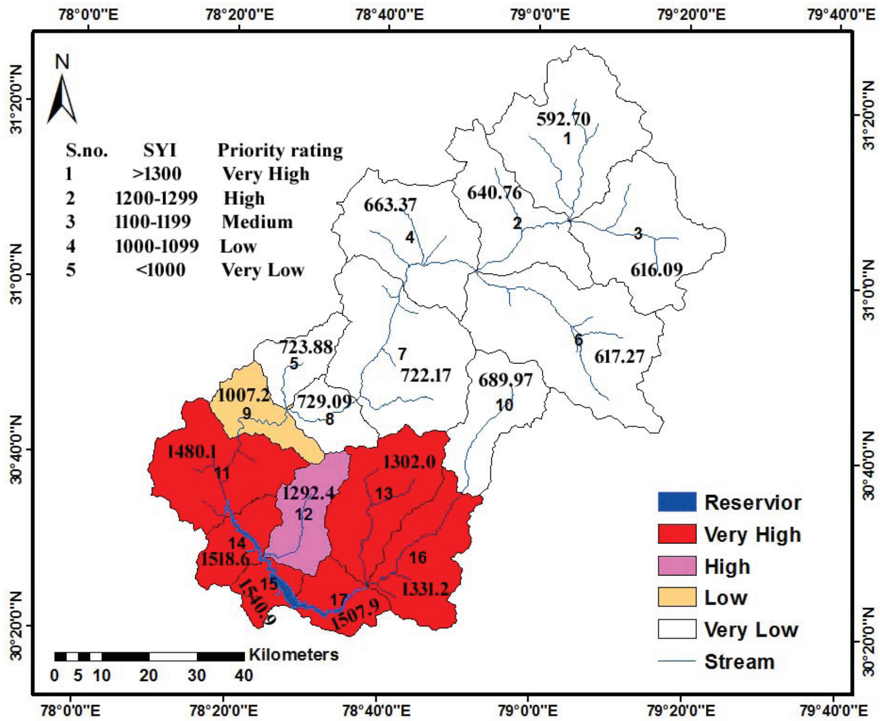

Figure 11 : Treatement priority of catchment of Tehri Reservoir

9. RAINFALL- SEDIMENT YIELD MODEL

A sediment yield model for Tehri Catchment has been developed by coupling the basic proportionality concept of the SCS-CN method with the universal soil loss equation (USLE). The coupling leads to an analytical method that uses a C = Sr = DR concept, where C is the runoff coefficient, Sr is the degree of saturation, and DR is the sediment delivery ratio, and requires data of storm rainfall and watershed characteristics. It also permits an interpretation of the SCS-CN parameter potential maximum retention (S) from USLE and describes the ratio of the potential erosion (A) to S as a constant for the watershed under dry conditions. The method is applied to rainfall-runoff-sediment data of four watersheds of urban, agricultural, and rangeland land uses.

10. CONCLUSIONS AND RECOMMENDATIONS:

10.1 Conclusions

- The priority category of sub-watersheds of Tehri catchment reveals that most part of the catchment area contributes very low sediment yield. However, sub-watersheds 11, 13, 14, 15, 16, 17 fall under very severe areas and main source of sedimentation, and therefore, require very high priority for conservation practices.

There exists a definite relationship between rainfall (P) and sediment yield (Y):

$$Y = \frac{4507 * (P - 46.35}{P + 185.4}$$

10.2 Recommendations

- The change in erosion effect be described considering 2006 as a bench mark.
- ASTER DEM may better be substituted by SRTM DEM.
- HEC-RAS model may be employed for determination of distributed sediment loading.
- The effect of velocity on soil erosion may be evaluated using a physically based model.

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