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Prioritization of Watershed Using Remote Sensing and Geographic Information System

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Abstract: Soil erosion is becoming a major concern at the watershed scale for the environment, natural resources, and sustainable resource management. Therefore, the estimation of soil loss through this phenomenon and the identification of critical soil erosion-prone areas are considered to be key tasks in the soil conservation programme for the design and implementation of best management practices for specific regions or areas. In the present study, revised universal soil loss equation (RUSLE) modelling is combined with remote sensing (RS) and geographical information system (GIS) techniques and used to predict soil erosion and the prioritization of watersheds in Nainital district Uttarakhand, India. For the estimation of soil loss, different factors, namely, rainfall-runoff erosivity (R) factor, soil erodability (K) factor, slope length steepness (LS) factor, cover management (C) factor, and the erosion control practices (P) factor were computed. The data on various other aspects such as land use/land cover (LU/LC), the digital elevation model (DEM), slope, contours, drainage network, soil texture, organic matter, and rainfall were integrated to prepare a database for the RUSLE equation by employing ENVI & QGIS software. The results showed that a major portion (70.26%) of Nainital district is covered with forest, followed by area under fallow and agricultural land. Annual average soil loss ranged between 20 to 80 t ha^{-1} yr^{-1} in the study area. Out of 50 watersheds in the study area, 7 watersheds were given top priority for conserving natural resources, while 11 watersheds, mostly in the east-central part of Nainital, were kept under the next priority category. Only 4 watersheds of the total were given lowest priority. Moreover, it was concluded that major portions of Nainital district were in a severely prone category of soil erosion, and therefore required immediate action plans to check soil erosion and evade the possibility of landslides.

Keywords: GIS; prioritization; remote sensing; RUSLE; soil erosion

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1. Introduction

India supports 16 percent of the world's population on 2.42 percent of the world's land area, and global population growth has led us to make effective use of diminishing natural resources, particularly for livelihood needs and agricultural practices. Natural resource development programs are generally applied at a water level, because catchments and sub-catchments are the basic units for land and water resource management [1]. An estimated 147 million hectares (M ha) of land comprising approximately 45% of India's total geographical area suffers from soil erosion and land degradation problems [2]. Water and wind alone account for the degradation of 150 M ha of land in the form of active erosion, resulting in losses of approximately 5300 million tons of top soil; in addition, 25 M ha of land has been eroded due to ravines and gullies, shifting crops, salinity/alkalinity, water logging, etc. [3,4].

Nainital, a popular hill station in the Uttarakhand state of India, has mountains with a height of 2615 m and a sub-tropical to sub-humid climate with annual average rainfall of 1500 mm with high intensity. For the prevention of soil erosion, better practices and prioritization will be necessary for natural resources management.

Watershed management planning highlights the management techniques to control erosion in the catchment/watershed area [3,5]. Land and water resources are scarce and their widespread use is imperative, especially in developing countries such as India, where population pressure is steadily increasing while natural resources are dwindling day after day [6,7]. In addition to industrial expansion and the consequent need for infrastructure services, this trend will eventually lead to increased pressure on land for grain, fibre, and fodder while land is being converted for urbanization/settlement [8]. The watershed is an ideal unit for the planning and management of land and water resources [9,10]; however, realistic assessments of the hydrological behaviour of a watershed [6,7] and recognition of the inter-relationships among the linkages between soil, slope, uplands, lowlands, land use, and geomorphology [11] are important to the development of an effective management plan.

Remote sensing technology deals with the requirements of reliability and speed, and is an ideal tool for generating spatial information that is considered to be a prerequisite for planned and balanced development at the watershed level [12]. The geographical information systems (GIS) technology provides suitable alternatives for efficient management of large databases whereas the drainage characteristics of basins and sub-basins have been studied using conventional methods [13–15]. Morphometric analysis using remote sensing and GIS techniques has been attempted by a number of researchers [16,17]; the results of their studies concluded that remote sensing and geographical information systems are powerful tools for the study of basin morphometry [18–20]. Additionally, the integration of remote sensing data and GIS technologies has proved to be an efficient tool for water resources development and management projects as well as for watershed characterization and prioritization [21–24].

The integration of the RUSLE model with GIS enables detailed analysis of soil erosion because the mechanism has a spatially distributed character. GIS and remote sensing (RS) provide the model with spatial input data, whereas the RUSLE can be used to estimate watershed soil erosion [25,26].

Nevertheless, management interventions from the highest priority micro-watershed available should always be initiated [27]. Watershed prioritization is the ranking of different micro-watersheds of a watershed according to the order in which they have to be addressed with treatment and soil conservation measures [28]. The lowest-ranking micro-basin has the highest erosion risk and is urgently recommended for conservation measures [29]. Keeping in view the above concerns, the present study examined the utility of RS and GIS in the prioritization of natural resources in a hilly catchment using the RUSLE model inputs related to land use/land cover, soil etc.

2. Materials and Methods

2.1. Study Area

Nainital is a popular hill station in the Indian state of Uttarakhand in, and a sparkling jewel in the Himalayan necklace, blessed with scenic natural splendour and varied natural resources. The study area extended from 29°05′ N to 29°05′ N and 80°14′ E to 78°80′ E with an altitude of 2084 m above mean sea level. Figure 1 shows the location map of the study area. It is surrounded by mountains, the highest of which are Naina on the north (2615 m), Deopatha on the west (2438 m), and Ayarpatha on the south. The district's total geographic area is 4064.33 km^2. The study area has sub-tropical to sub-humid climate. The maximum temperature in the plain areas ranges from 42 °C to 46 °C and the minimum between 1 °C and 9 °C. In the hilly areas, the minimum temperature falls below the freezing point during winter. The rainfall rate usually increases from north to south. Quite steep to steep hills and glaciofluvial valleys are dominated by very shallow to moderately shallow, heavily drained, sandy-skeletal to loamy skeletal, neutral to slightly acidic soil with low water-holding capacity. Major crops grown in the study area are rice, maize, mandua, wheat, soybean, lentil, peas, and tomato.

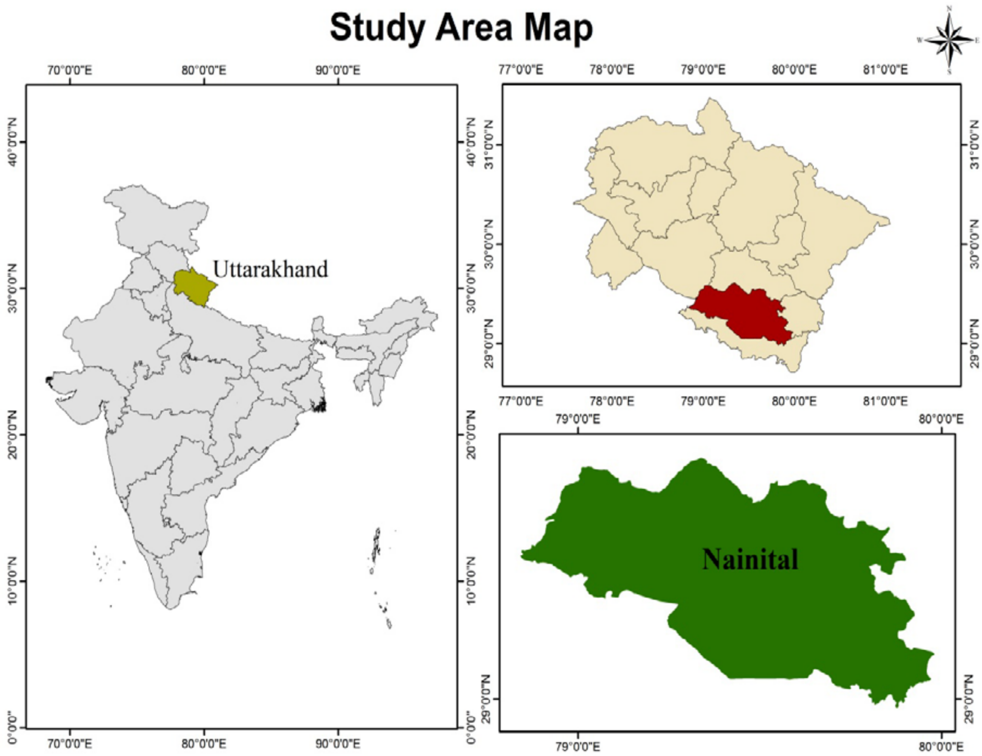

Figure 1. Location map of study area.

2.2. Data Use

The 14-year rainfall data (2001–2014) were obtained from the Department of Meteorology, GBPUA&T, Pantnagar with location 29°24′00.0″ N 79°28′00.1″ E. The data for soil such as silt, sand and clay in soil, percentage of organic matter, soil structure code, and permeability code were collected from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) Nagpur. Satellite imagery from LANDSAT 8 (30 m Resolution) was taken on 3 October 2015; the path and row of the satellite were 145 and 40, respectively, from https://landsat.usgs.gov/ site. ENVI and QGIS were used to create specific thematic layers such as contour, drainage, LU/LC, and other study area data sets.

2.3. Methodology

The RUSLE model quantifies soil erosion using five factors [30]

$$A = R\,K\,LS\,C\,P \tag{1}$$

where A is the average annual soil loss per unit area (t/ha/y)

R is the rainfall and runoff factor (MJ mm/ha/h/y)

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5\,\log 10\left(\frac{Pi}{P}\right) - 0.08188\right)} \tag{2}$$

where Pi is the monthly rainfall (mm), P is the annual rainfall (mm).

K is the soil erodibility factor (t.ha.h/ha/MJ/mm)

$$K = [2.766 \times M^{1.14} \times 10^{-7} \times 12 - OM) + 4.28 \times 10^{-3} \times (S - 2) + 3.28 \times 10^{-3}(P - 3)] \times 0.1317 \tag{3}$$

where M = particle size parameter (% silt + % very fine sand) × (100—% clay)

OM = organic matter (%), S = soil structure code
P = soil permeability class and 0.1317 is used for the conversion to SI units.
LS is the combined slope length and slope steepness factor (dimensionless)

$$LS = \left(\text{Flow accumulation} \times \frac{\text{Cell size}}{22.13}\right)^{0.4} \times \left(\text{Sin}\frac{\text{slope}}{0.0896}\right)^{1.3} \quad (4)$$

where cell size = size of grid cell (for this study 30 m)
sin slope = Z slope degree value in sin
C is the cover and management factor (dimensionless, ranging between 0 and 1.5)

$$C = \exp\left[-\propto \times \frac{\text{NDVI}}{(\beta - \text{NDVI})}\right] \quad (5)$$

where α and β are parameters that determine the shape of the NDVI–C curve.
Values of α = 2 and β = 1
P is the support practice factor (dimensionless, ranging between 0 and 1)

$$P = 0.2394 \times (\text{Slope}) \times 0.4061 \quad (6)$$

where slope is in percent, slope more than 30% will have the value 1. The range of P is 0–1.

The details of the above-mentioned factors and their effect on soil erosion processes are discussed below. The methodology flowchart is shown in Figure 2. For the estimation of soil erosion, the rainfall data for a 14-year period (2001–2014) were obtained from the Meteorological Department, GBPUA&T, Pantnagar, and used to estimate the rainfall runoff erosivity factor (R-factor). The soil map was procured from the National Bureau of Soil Survey & Land Use Planning and converted to digital format on 1:50,000 scale. The soil erodibility factor (K-factor) map was then digitized and prepared in QGIS using the soil map procured from NBSS&LUP; the values of K-factor were then assigned to the different soil types in the region according to U.S. customary units.

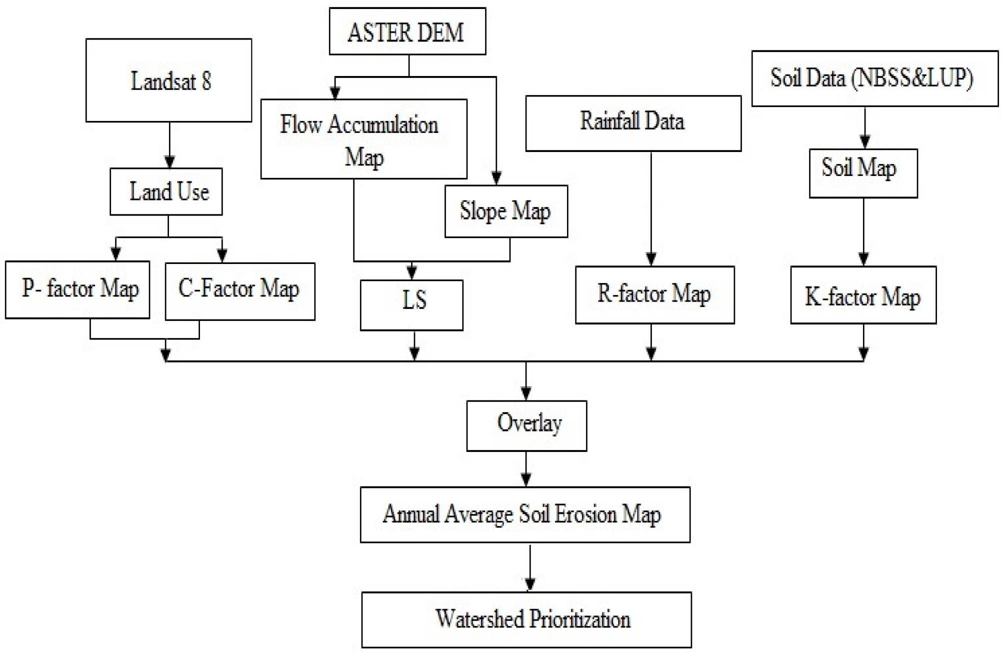

Figure 2. Methodology flow chart.

The ASTER data were used to draw up the slope map and the study field flow accumulation map, which were then used to prepare the LS factor map in QGIS. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument on-board the National Aeronautics and Space Administration's Terra spacecraft has an along-track stereoscopic capability using a near-infrared spectral band to acquire the stereo data. With a base-to-height ratio of 0.6, ASTER has two telescopes, one for nadir viewing and the other for backward viewing. In the horizontal plane, the spatial resolution is 15 m. During the initial operation time, parameters such as the line-of-sight vectors and the pointing axis were adjusted to generate Level-1 data products with high-quality stereo system performance. Both Japanese and American science teams independently evaluated the digital elevation model (DEM) data, using different DEM generation tools and reference databases. Without ground control point (GCP) correction, the vertical accuracy of the DEM data produced from Level-1A data is 20 m with 95 percent confidence for individual scenes. The essential geolocation accuracy for DEM datasets is better than 50 m. This tends to be constrained by the precision of the spacecraft's location. Furthermore, using GCPs to produce the stereo data results in a small improvement in accuracy. The DEM was utilized to deduce the flow direction to prepare the flow accumulation map. The LS factor map was then prepared using the slope and flow accumulation map in the raster calculator in QGIS. The drainage of the study area was delineated from the Survey of India topographical map in 1:50,000 scale and was updated by using higher resolution Landsat 8 satellite images. Radiometric and geometric corrections were made to remove errors and distortions during image pre-processing. The land-use/land-cover (LU/LC) map was developed from Landsat 8 satellite data, which, due to their high spatial resolution, provided accurate mapping of various LU/LC categories. The accuracy was assessed by computing the Kappa coefficient using ground truth data. The LU/LC map was used to prepare the land cover and management factor (C-factor) map. The values of C-factor were assigned to the different land-use/land-cover classes in the study area. The P-factor map was also prepared using the land-use/land-cover map of the watershed, and the values of P-factor were assigned to the different features based on the soil conservation practices addressed in the study area with reference to previous studies.

All five parameter maps (having the same coordinate system) were used to predict soil erosion and the spatial distribution of different soil erosion zones in the Nainital district. Raster Calculator was used to build the expression ($R \times K \times LS \times C \times P$), which, when applied to all cells in a raster coverage of the watershed, produced a map of average annual soil erosion.

2.4. Prioritization of Resources

The prioritization of natural resources is limited and their wide utilization is imperative and essential. The resource-based approach is considered to be practical for watershed prioritizations as it requires an integrated approach. In the present study, the knowledge-based weighting method was adopted for sub-watershed prioritization on the basis of study variables and after careful observation of field conditions. The basis for assigning weightage to different themes was according to the relative importance assigned to each parameter in the study area as depicted in Table 1.

Table 1. Priority classes and the criteria adopted for watershed prioritization.

Sr. No	Priority Class	Soil Loss (t ha^{-1}yr^{-1})	Class
1	6	<5	Slight
2	5	5–10	Moderate
3	4	10–20	High
4	3	20–40	Very High
5	2	40–80	Severe
6	1	>80	Very Severe

The weightage system adopted here depends entirely on the local terrain and can vary from place to place. The water-holding capacity or porosity and permeability of the formation in the area were also considered while assigning weightage.

3. Results and Discussion

The prioritization of the watersheds of the Nainital district was carried out using remote sensing and GIS technique by assessing potential soil losses arising due to the rainfall, slope, and soil factors and reduced by land cover and management practices. This technique is quite robust in evaluating the influence of different land covers and soil management factors on quantitative estimations of soil loss. The remotely sensed data plays an important role in delineating the land cover with greater accuracy of form and extent and in assessing the related annual cover factors. Implementing the revised universal soil loss equation using the GIS integration procedures enabled soil loss predictions at the sub-water level. The estimation of spatially varying soil losses requires the generation of the thematic layers such as land use and land cover, land slope, soil characteristics, land cover, and management practices.

3.1. Land Use and Land Cover

The supervised classification technique was used to produce maps of Nainital district land use and land cover (LU/LC). The minimum distance algorithm was employed to achieve the task. The ground truth was performed for verification of objects at different locations. A perusal of data presented in Table 2 indicated that a major portion of the Nainital district is under forest cover (70.26%), while agriculture is over a small region (9.32%). The other major land uses include fallow land (14.72%), water bodies (0.12%), rivers (3.92%), rocks (0.67%), and built-up (1.01%), respectively. Data clearly indicated that a major portion (70.26%) of Nainital is covered with forest, followed by agriculture at only 9.32% of total area, while the smallest percentage of area was occupied by water bodies accounting for only 0.12% of the total area. The value of the Kappa coefficient was found to be 0.9926, or 99.26%, which indicated that the accuracy of the classification is very high. The classified images of the Nainital district are presented in Figure 3. The classified results are listed in Table 2. Nainital has its highest area under forest cover, much than others features, and the probable reason behind this is that Nainital has totally undulating topography; therefore, land cannot be used for other purposes or particularly for agricultural or settlement purposes. Secondly, the weather conditions and especially the high rainfall also favour higher vegetation growth, which results in thick forest cover. Moreover, the southern region of Nainital has relatively more area in plain; therefore, most agricultural and built-up lands are found in this region. High concentrations of built-up land are found in the southern region as it is considered a gateway to the Kumaon region. Most of the facilities and installations whether industrial, educational or health related, have been developed in this region. As the region is topographically undulated, a significant amount of water is drained off, creating many seasonal and perennial water streams. Therefore, approximately 3.92 percent of Nainital's total area is occupied by water channels, although no reservoirs have been constructed.

Table 2. Area of different land use and land cover features during Kharif season.

Sr. No.	Feature	Area in (ha) of Nainital	Area in (%) of Nainital
1	Water bodies	452.07	0.12
2	Forest	285,472.17	70.26
3	Rocks	2714.04	0.67
4	Builtup Land	4084.47	1.01
5	Fallow Land	59,795.82	14.72
6	Agricultural Land	37,849.50	9.32
7	River	15,918.12	3.92
8	Total	406,286.2	100

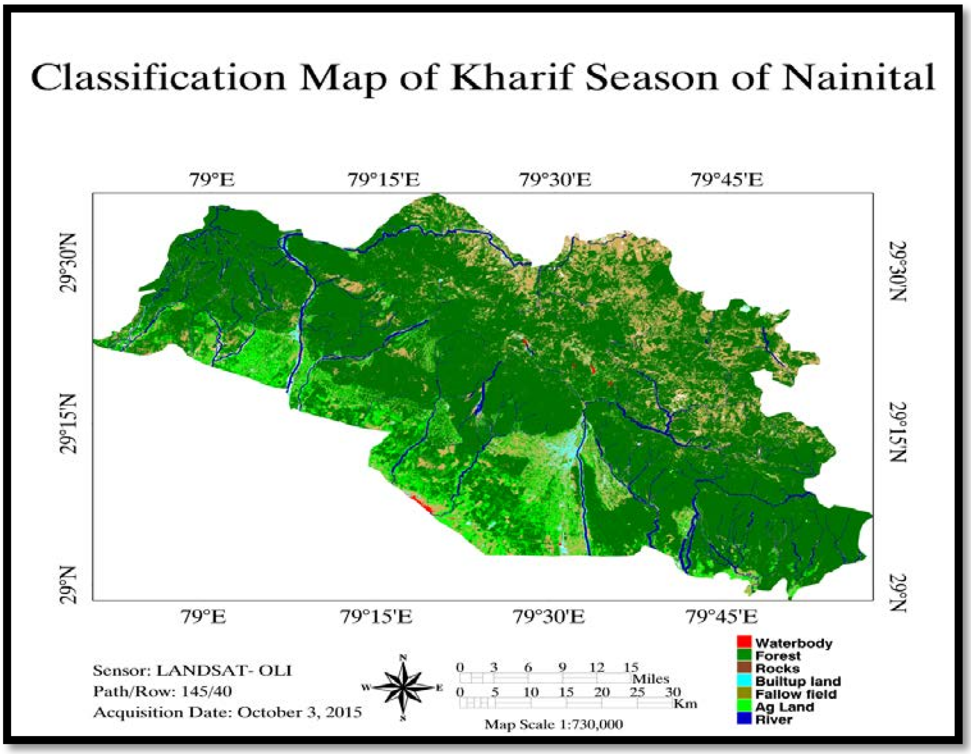

Figure 3. LU/LC map of Nainital district.

3.2. NDVI Map of Study Region

The NDVI image was generated using a combination of the NIR band and Red band. NDVI is a direct indication of vegetation cover in the region. The value of NDVI increased with the increase in vegetation cover. The NDVI image of Nainital district is shown in Figure 4. The value of NDVI was at its maximum in the lower and middle regions of Nainital, but gradually decreased with increasing elevations toward the northern part of the district. The region of higher vegetation in the lower part of Nainital district has comparatively less slope, whereas the lower density of vegetation in the higher regions of Nainital is due to the steep slopes. Water flow down the steep slopes is fast, which contributes to heavy soil loss. Therefore, the topsoil depth is very shallow, which does not allow root penetration into the deeper soil layers. Other major factors behind the higher density of vegetation in the lower regions of Nainital include the higher soil water-retaining capacity, higher nutrient accumulations, etc.

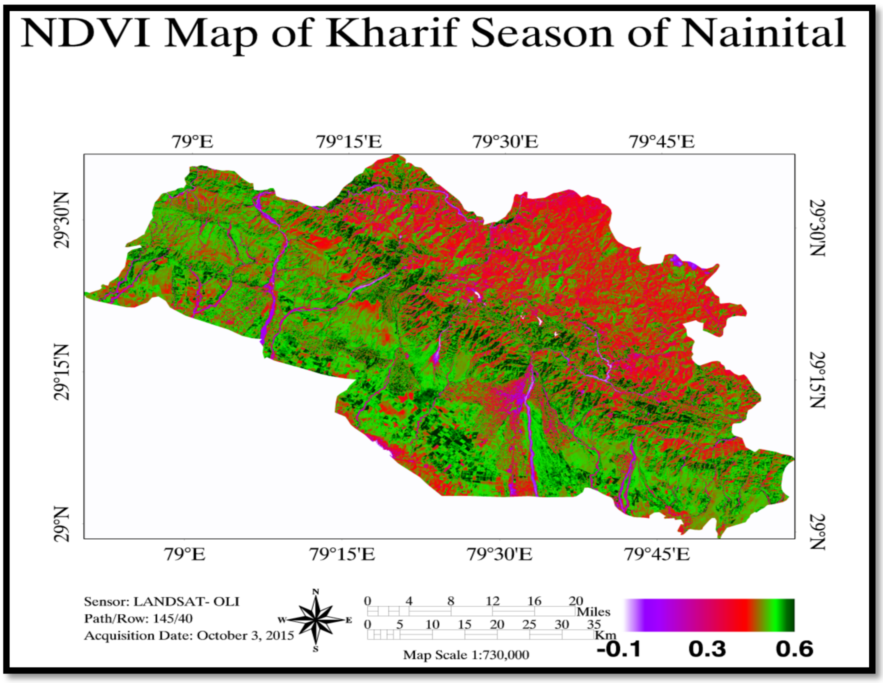

Figure 4. NDVI map of Nainital district.

3.3. Land Slope Layer

The slope features of the land are one of the most important parameters that strongly influences soil losses. Therefore, we generated a slope layer map of the Nainital district using ASTER data. A digital elevation map of the region was created, and the slope was then derived using the hydrological module available in Quantum GIS. The slope layer map of Nainital is shown in Figure 5. The figure indicated that the Nainital district has varying degrees of slope, from 1° to more than 40°. The lower areas of Nainital exhibit gradual sloping land with slopes of less than 10°; however, upper areas of the district (northern Nainital) exhibit steep slopes mostly of more than 40°. The elevation of the Nainital district gradually increases toward the northern region and the change in slope exhibits a similar trend.

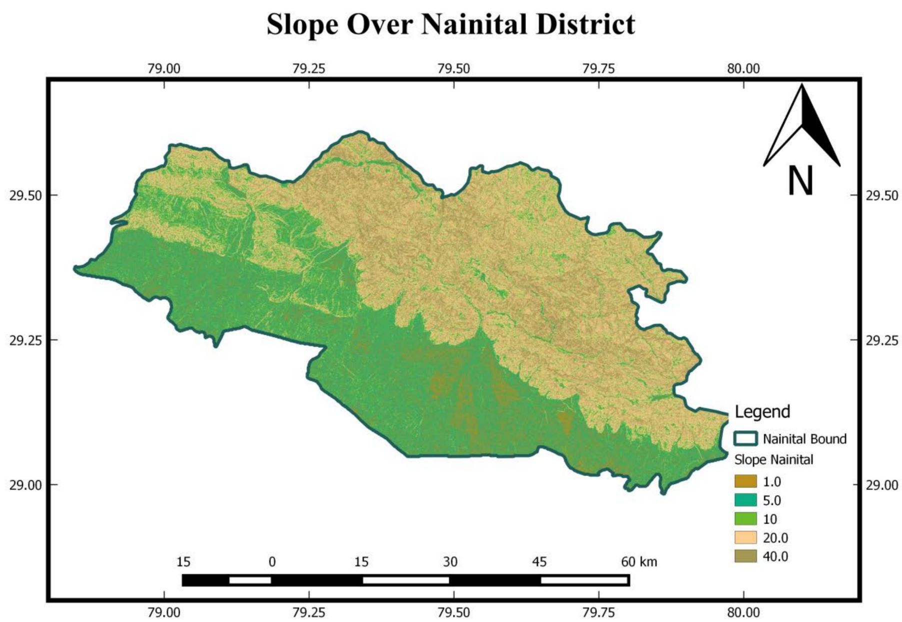

Figure 5. Slope map of Nainital district.

3.4. Average Annual Rainfall

The rainfall layer was generated by interpolating point weather data from various stations, primarily in Nainital, which served as the interpolation centre with location 29°24′00.0″ N 79°28′00.1″ E. the inverse distance weightage (IDW) method embedded in QGIS software was employed to transform point data into the spatial layer of rainfall. The rainfall layer of Nainital district is shown in Figure 6. Average annual rainfall in Nainital is very high, almost 1500 mm in most parts of the district, and around 2000 mm in some areas of the central part of the district. The higher rainfall in the north-central region of Nainital is due to the steep slopes in this region [31]. The steep slopes induce orographic effects that lead to higher rainfall [20].

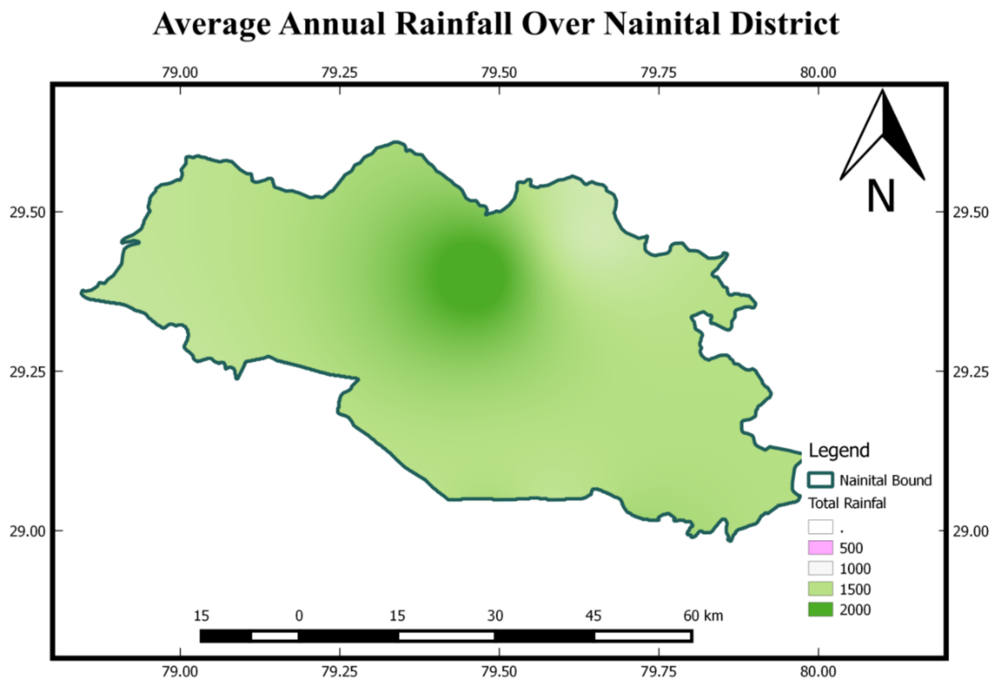

Figure 6. Average annual rainfall map of Nainital district.

4. Soil Layers

4.1. Organic Matter

An organic matter map of Nainital district was extracted from the database created by NBSSLUP, Nagpur. The hardcopy maps created by NBSSLUP were digitized in the QGIS environment, and the attributes were assigned as given in the legend. The map originally contained values for organic carbon, which were converted into organic matter. Organic matter is higher throughout the district of Nainital, except in some pockets of southern and western Nainital. The fairly high values for organic matter in the district are probably due to the higher amounts of forest cover. The forest trees shed leaves that ultimately are mixed into the soil and maintain the higher values for organic matter [32]. The organic matter layer of Nainital district is presented in Figure 7.

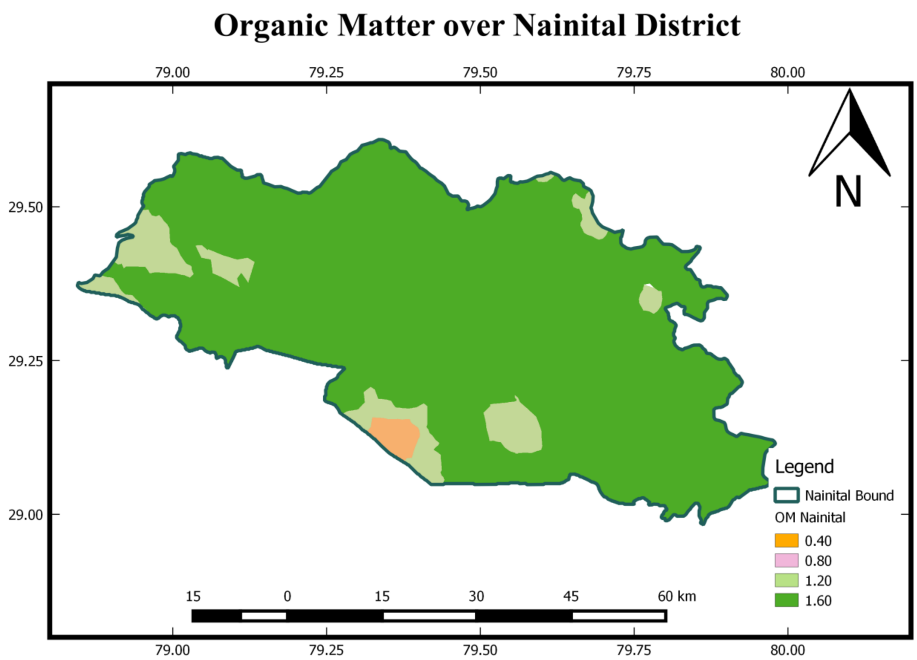

Figure 7. Organic matter map of Nainital district.

4.2. Soil Structure Class

The soil structure codes were extracted from the soil database of NBSSLUP, Nagpur. The legend of the map shows the information on soil texture. The soil textural classes were derived with the help of soil texture triangles, and the structure codes were accordingly assigned. The values of the soil textural codes were their lowest in the case of sandy soil, whereas the maximum was observed for fine silty and fine loamy soils. The sandy soil exhibits less adhesive properties and is more prone to soil erosion, while silty and loamy soils exhibit a higher soil structural class values and are therefore more effective in reducing soil erosion [32]. The soil structural classes for Nainital are shown in Figure 8. A major portion of the Nainital district shows soil structure codes of 2 or less, which suggests that the soils of Nainital district are more prone to soil erosion.

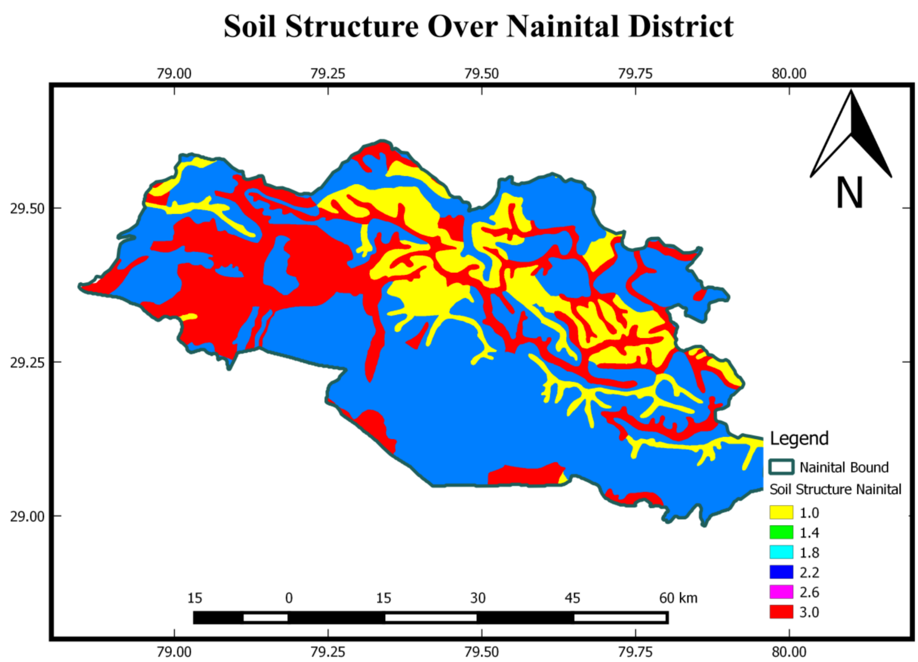

Figure 8. Soil structure map of Nainital district.

4.3. Particle Size Parameter

The particle size parameter is a function of the texture of the soil and mostly depends on the silt, fine sand, and sand content. Higher values for the particle size parameter lead to heavier soil losses. The spatial distribution of the particle size parameter over the district of Nainital is shown in Figure 9. Closer scrutiny of the map revealed that the values for the particle size parameter over most of the district of Nainital are quite high. Some areas of Nainital district, especially western Nainital, have lower parameter values attributable to thicker forest cover. The distribution of particle size parameters over two districts showed that Nainital district is more prone to soil losses.

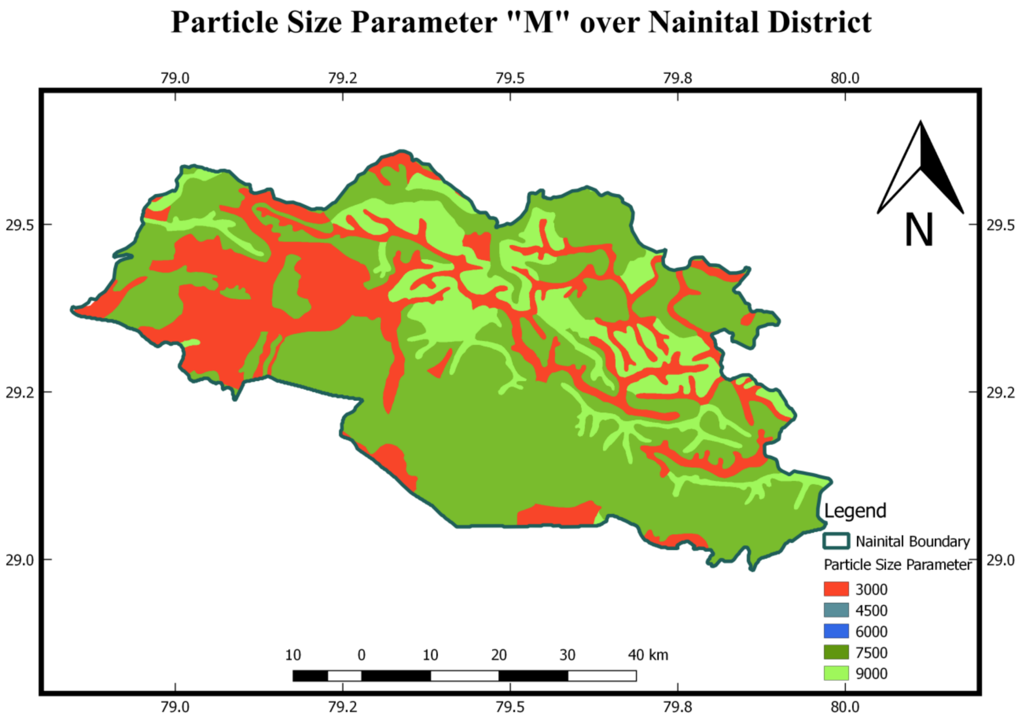

Figure 9. Soil particle size parameter map of Nainital district.

5. Hydrological Modelling

5.1. Flow Accumulation

The water from precipitation flows over land masses from the upper to lower regions in a gradual manner. It accumulates as it flows from one region to another. The water flow from regional points of origin is of low velocity, but gradually increases velocity as it passes through lower regions. The flow gradually increases not only in velocity but also in volume. Therefore, the lower regions of the topographical space are more prone to soil losses than relatively higher regions [33]. The flow accumulation over the district of Nainital is shown in Figure 10 and exhibits fairly extensive spatial distribution.

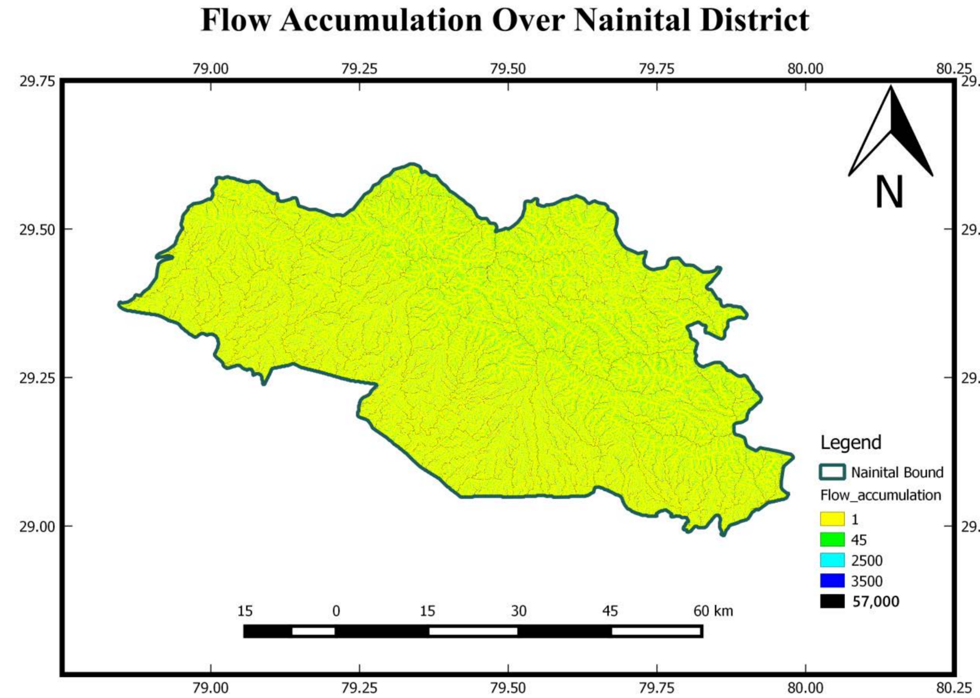

Figure 10. Flow accumulation map of Nainital district.

5.2. Delineation of Watershed Boundaries and Identification of Water Channel

The watershed boundaries in the district of Nainital were delineated using a digital elevation map (DEM) prepared with ASTER data as shown in Figure 11. ASTER-DEM is available at 30 m resolution and is widely acclaimed for its three-dimensional accuracy. The Grass module embedded in Quantum GIS was used to delineate the watershed boundaries. Grass computes the direction of water flow from each cell and thereafter summarizes the accumulated water flow. Based on the accumulated water flow, major water streams were also identified. Grass produces its results in a raster data model, which was transformed into a vector data model using the raster-to-vector conversion module available in Grass.

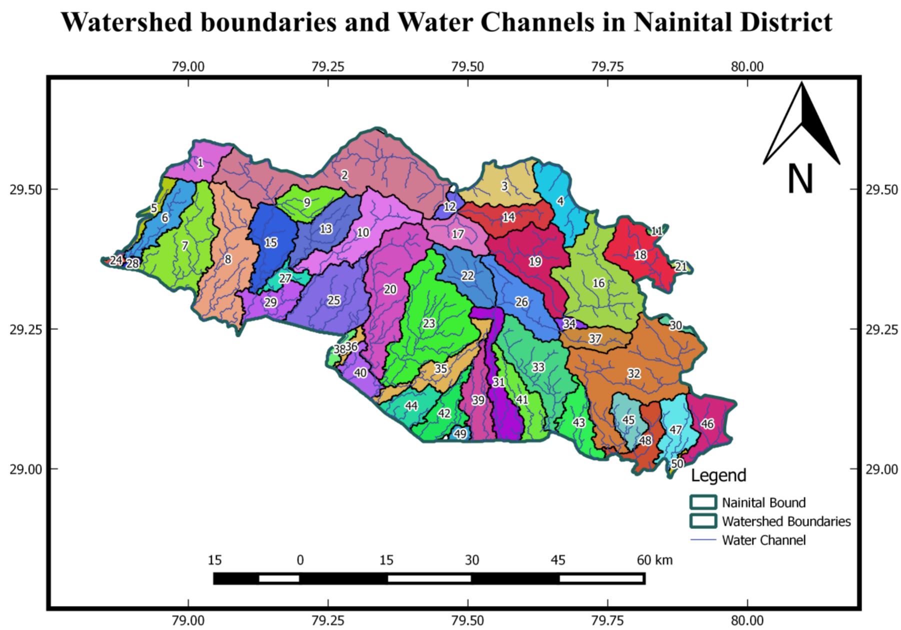

Figure 11. Watershed boundaries and water channel map of Nainital district.

5.3. Estimation of Soil Loss Using RUSLE Model

Soil loss assessment was carried out using the revised soil loss equation (RUSLE) for Nainital district. Various factors as discussed below are required to compute soil losses using the RUSLE model.

5.4. Rainfall-Runoff Erosivity Factor (R)

The quantitative expression of the rainfall-runoff parameter causing soil erosion is the R factor. It is greatly influenced by the intensity and duration of precipitation events and by the amount of resulting runoff [34]. The R value incorporates the total precipitation intensity and duration pattern of rainfall. The annual value of the R factor related to annual precipitation was computed. The value of the R factor for Nainital varies from 1000 to 5000 MJ mm/ha/h/year, as shown in Figure 12.

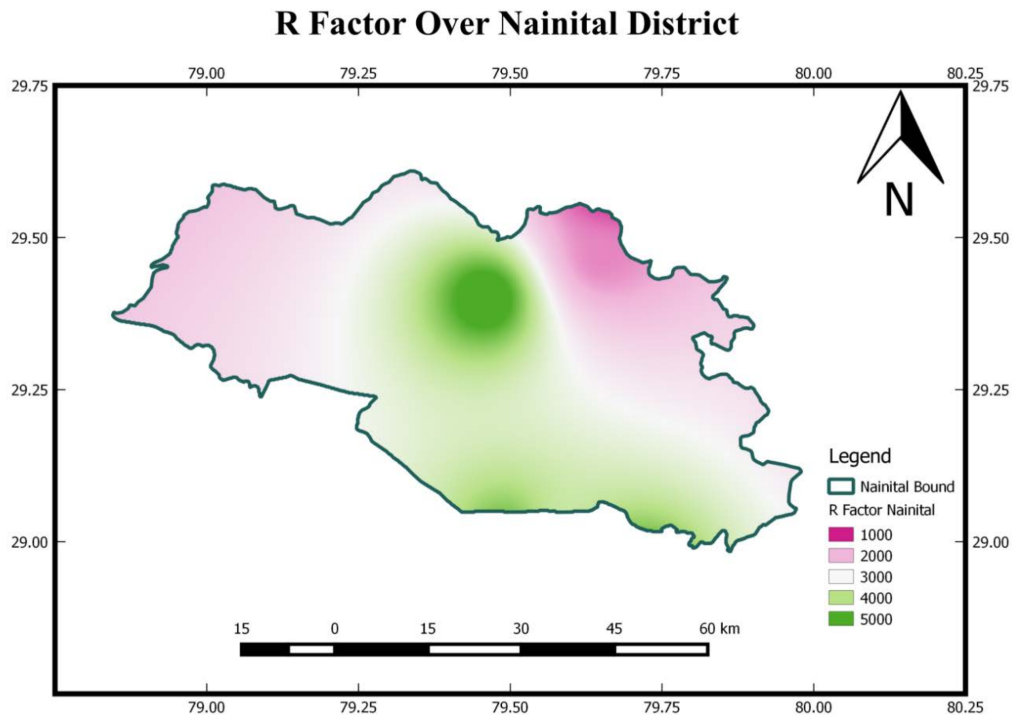

Figure 12. R factor map of Nainital district.

5.5. Soil Erodibility Factor (K)

Factors such as texture, structure, organic matter content, and permeability are highly significant determinants of soil erodibility. Soil erodibility is regulated by a complex set of physical and chemical properties and is usually determined empirically [32]. Soil analysis data were available for all soil types found in Nainital. Using K factor values, a K factor map was prepared in QGIS, and is shown in Figure 13. The value of the K factor was found to range between 0.002 and 0.012 t ha h/ha/MJ/mm for Nainital district.

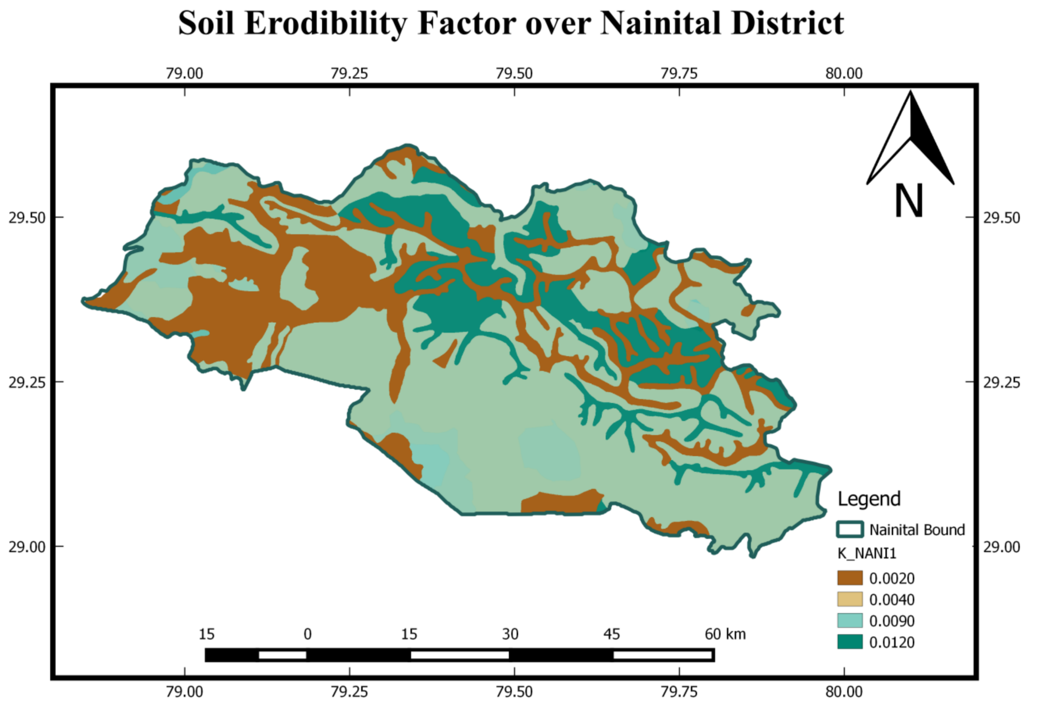

Figure 13. K factor map of Nainital district.

5.6. Slope Length Steepness Factor (LS)

The slope length created by DEM is based on the assumption that each slope plane consists of a homogeneous type of slope and vegetation cover, which may not be the case in practice. GIS techniques tend to predict very long slope lengths on flat to very gentle slopes while deriving topographic factors, which can result in overestimations of soil loss. As a result, the LS factor does not fully account for the hydrological processes that influence runoff and erosion, compromising its significance as a measure of the landscape's sediment carrying capacity [20]. The slope map shown in Figure 5 was derived from ASTER DEM in percentages and degrees. The LS factor map was prepared using QGIS and is shown in Figure 14. The value of the LS factor for the study area ranged from 0 to 60 for Nainital district.

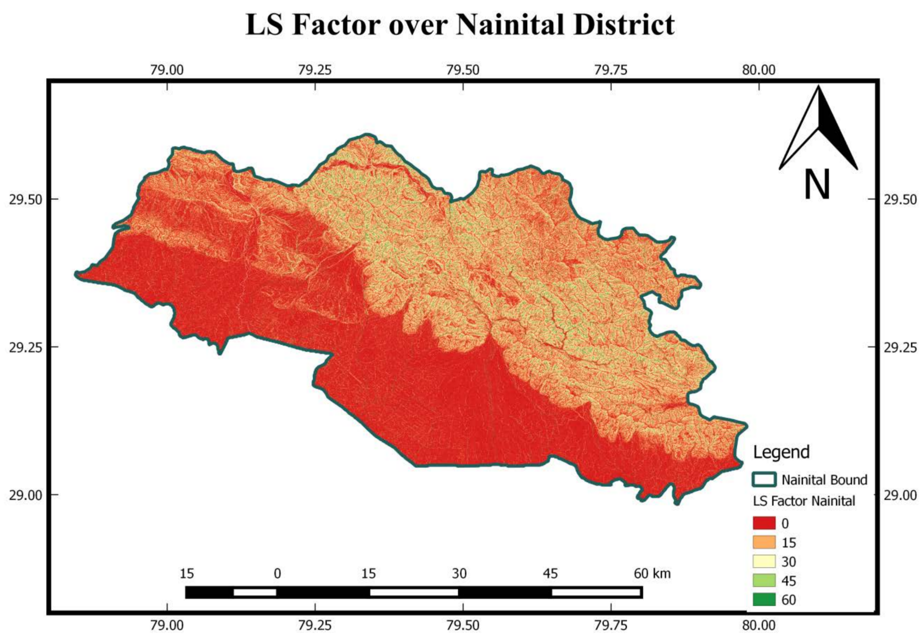

Figure 14. LS factor map of Nainital district.

5.7. Cover Management Factor (C)

Remote sensing and GIS technologies are capable of generating a region's LU/LC thematic layer [35]. The study area was classified into seven land use classes shown in Figure 3. The factor of crop management was assigned to various patterns of land use using the values given in Table 2. The C factor map was prepared in QGIS using an LU/LC map and C factor values and is shown in Figure 15. It was found that the crop management factor ranges between 0.2 and 1.00. The conservation practice factor for micro watersheds was assigned on the basis of percent slope. Its P factor map was prepared in QGIS and is shown in Figure 16.

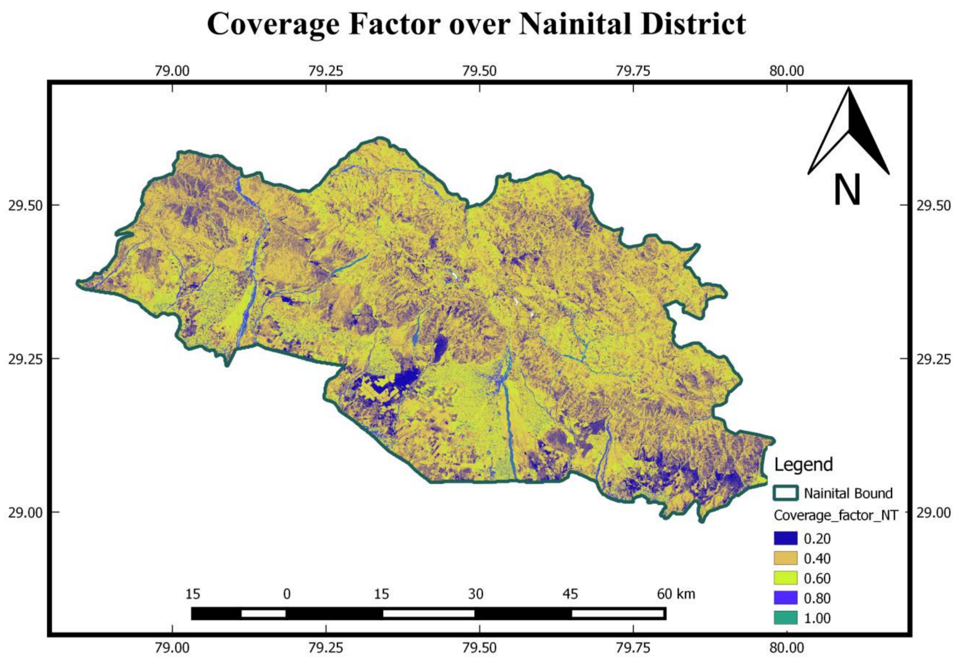

Figure 15. C factor map of Nainital district.

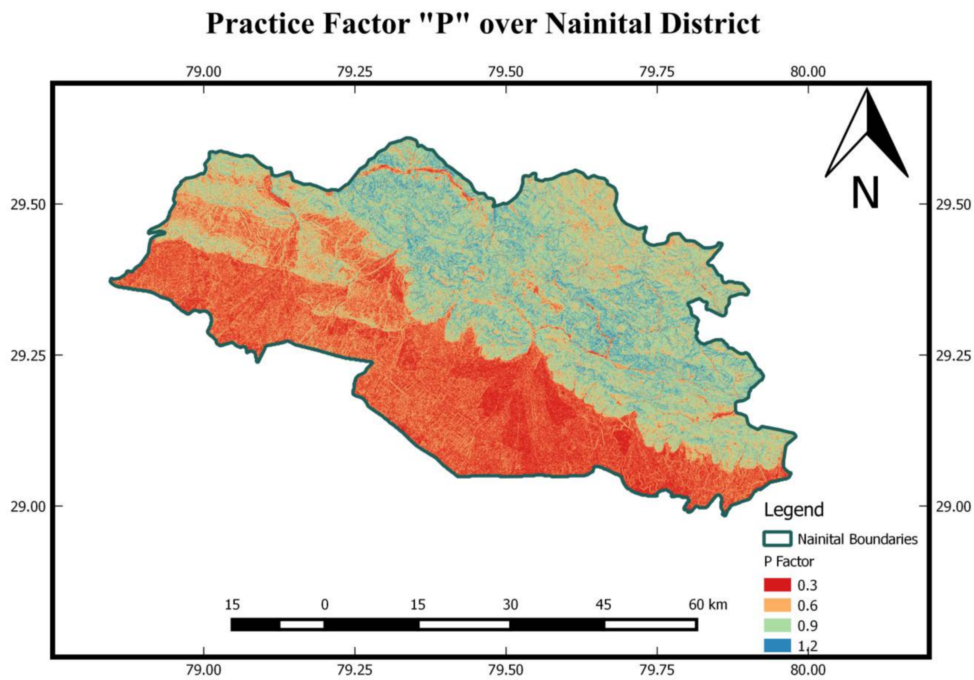

Figure 16. P factor map of Nainital district.

5.8. Erosion Control Practices Factor (P)

The P factor value ranges from 0.3 to 1.2 and it is clear from Figure 16 that the higher the value of slope, the higher the value of the P factor. It was found to be more than 1 when the slope is above 30%. The contribution of the P factor is highly significant in Nainital district.

5.9. Soil Losses

Annual soil loss for micro-watersheds was estimated using the annual average R (based on data from daily rainfall), K, LS, C, and P variables. All the different layers, namely, R, K, LS, C, and P, were generated in GIS and overlays to obtain the product that produces the Nainital annual soil erosion map (Figure 17). The soil erosion rate (t/ha/yr) for a given watershed was measured as total soil loss. Micro watersheds in each basin were prioritized on the basis of soil erosion risk.

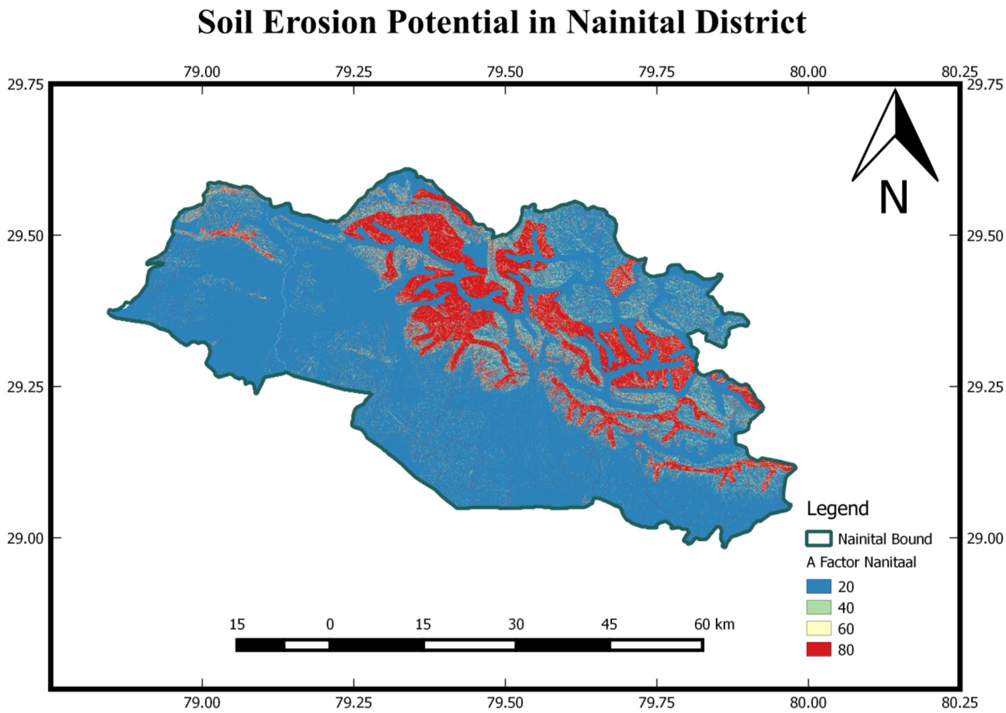

Figure 17. Soil erosion potential map of Nainital district.

5.10. Watershed Level Soil Losses

The watershed erosion maps show the ranges of erosion in different watersheds and thus illustrate the nature of the watersheds based on the severity of soil erosion within them. According to the soil erosion-prone rankings, various watersheds in Nainital fall into the severely prone range. Watershed boundaries were overlaid on raster-based soil loss erosion images for computation of average soil loss from each watershed, as depicted in Figure 18. Watershed-level soil erosion in Nainital ranges from 0 to 80 tonnes per year (Figure 17). Soil erosion is strongly influenced by the slope of the land and soil organic matter. Higher levels of soil erosion are found in regions with steeper slopes. Steeper slopes not only cause higher runoff but also add more momentum to flowing water, which erodes the soil almost every year [36]. The continuous erosion of soil does not allow accumulation of organic matter; the bonding power of the soil therefore deteriorates, which again leads to higher soil erosion. The northern hills of the Nainital district exhibit steep slopes and therefore high soil erosion, i.e., 60–80 ton/ha/year. High soil erosion is also responsible for landslides, thereby making this area highly prone to natural disasters. Moving toward the southern part of Nainital, the slope gradually decreases, and soil erosion is therefore at its minimum. In most parts of southern Nainital, soil erosion varies from 0 to 20 ton/ha/year.

Human settlements around the southern fringes of the district have further lowered the risk of soil erosion. Higher forest cover and agricultural lands intersecting the soil slopes in the southern region of the district also reduce the impact of rainwater.

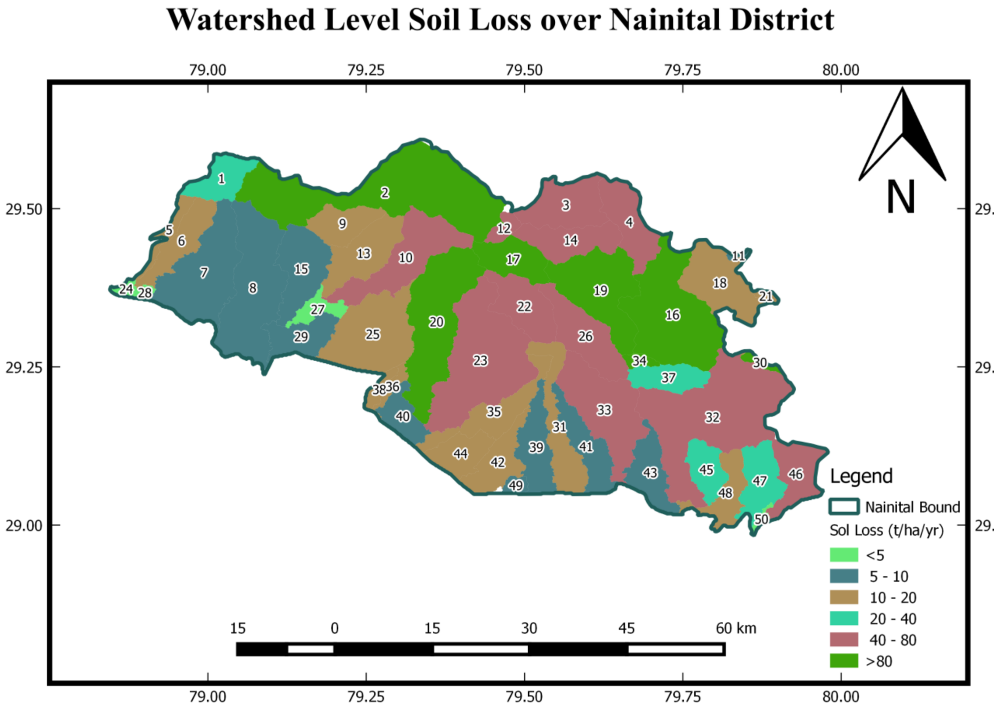

Figure 18. Watershed-level soil loss map of Nainital district.

The cropping intensity of the district is close to 200. That means farmers usually harvest two crops per year. Therefore, agricultural fields remain occupied by crops throughout the year, which helps reduce the risk of erosion. Thick forest cover, human settlements, and waterbodies further contribute to reduced soil erosion.

5.11. Prioritization of Watersheds for Sustainable Development

The watersheds identified in Figure 11 were prioritized on the basis of their potential for soil losses. Soil is assumed to be one of the most important natural resources due to its importance in providing support to vegetation, nutrients to plants, water retention capacity, and many other functions. Water is another important natural resource that should be conserved and judiciously used for sustainable development. However, water in the study region is sufficiently available in terms of precipitation; therefore, prioritization based on soil losses assumed prime importance [37]. The geospatial database was created as mentioned above in different sections. Soil erosion risk was calculated using the revised universal soil loss equation (RUSLE). Pixel-level soil erosion was averaged at the watershed boundaries so that watersheds could be prioritized. The critical level of the sub-watersheds was then determined using the criteria suggested by the authors of [38]. Each sub-watershed was ranked according to its soil erosion risk. The Nainital district was divided into 50 watersheds for prioritization. The watersheds were prioritized as listed in Tables 3 and 4 and as shown in Figure 19. Six different categories for potential soil losses—of less than 5 t/ha/yr (slight), 5–10 (moderate), 10–20 (high), 20–40 (very high), 40–80 (severe), and more than 80 (very severe)—were defined for watershed prioritization and were assigned priority rankings of sixth, fifth, fourth, third, second, and first, respectively. That means watersheds with higher potential soil losses were assigned higher priority for the conservation of precious soil resources, while those with lower soil loss potential received less priority, in descending order. The map of prioritized watersheds in Figure 19 for Nainital district shows that the top-priority watersheds (those ranked first or second)) were in the northern part of Nainital district. Extensive soil losses triggered by steep slopes, high rainfall, and low vegetation cover are the reason for the top priority given to the watersheds in the northern region. The watersheds in the southern part of Nainital district take low priority due to lower soil losses. Seven watersheds out of a total of 50 took top priority, while 11 mostly in the east-central part of Nainital received second priority.

Table 3. Quantitative analysis of watersheds with priority value.

Watershed No.	Soil Loss (t/h/year)	Perimeter (m)	Area (m^2)	Slope (Degree)	Priority
1	29.22	39,887	6396	17.99	3
2	87.40	132,497	37,376	23.70	1
3	60.05	52,084	10,613	24.15	2
4	42.66	56,320	9217	20.12	2
5	13.88	50,141	2727	10.53	4
6	13.40	65,385	7324	10.04	4
7	7.67	86,070	18,454	7.61	5
8	8.00	107,051	22,404	7.37	5
9	16.02	40,417	6226	16.96	4
10	46.78	89,209	14,729	19.87	2
11	9.19	21,174	467	22.88	5
12	61.79	21,752	1874	26.60	2
13	13.16	59,451	10,032	15.58	4
14	74.79	52,217	8614	26.00	2
15	5.67	63,669	10,763	9.81	5
16	84.76	89,954	24,125	26.65	1
17	155.20	41,906	7254	27.53	1
18	19.45	68,559	11,944	22.24	4
19	81.73	75,330	16,598	25.82	1
20	96.56	102,650	22,252	16.35	1
21	18.92	12,672	692	19.63	4
22	67.32	52,268	9169	24.81	2
23	68.07	105,178	27,686	13.33	2
24	0.87	14,846	905	5.26	6
25	12.98	72,648	17,339	6.86	4
26	67.54	59,520	10,879	23.93	2
27	3.05	41,913	2799	6.33	6
28	3.26	15,405	680	5.80	6
29	6.70	58,072	6765	6.61	5
30	88.48	22,273	924	21.89	1
31	14.18	94,552	9675	7.64	4
32	44.53	127,014	34,215	21.87	2
33	54.97	87,048	17,140	14.32	2
34	100.88	17,030	1170	29.52	1
35	14.98	92,628	8887	5.39	4
36	11.63	38,797	1373	5.57	4
37	37.47	38,575	5603	28.77	3
38	14.67	26,499	1687	5.79	4
39	5.10	69,266	8322	3.41	5
40	7.55	43,433	4925	5.37	5
41	5.93	71,241	7981	3.57	5
42	10.31	62,285	7257	4.56	4
43	5.36	58,435	7386	4.28	5
44	11.52	44,861	6102	5.13	4
45	37.60	39,633	5405	11.93	3
46	42.86	51,585	8065	15.85	2
47	34.69	56,825	7743	14.05	3
48	15.63	67,220	6154	8.67	4
49	8.48	16,003	1201	4.30	5
50	4.50	19,327	653	4.69	6

Table 4. Priority classes, criteria adopted for watershed prioritization, and the total number of watersheds in each category.

Sr. No	Priority Class	Soil Loss (t/ha/yr)	Class	No. of Watersheds
1	6	<5	Slight	4
2	5	5–10	Moderate	10
3	4	10–20	High	14
4	3	20–40	Very High	4
5	2	40–80	Severe	11
6	1	>80	Very Severe	7

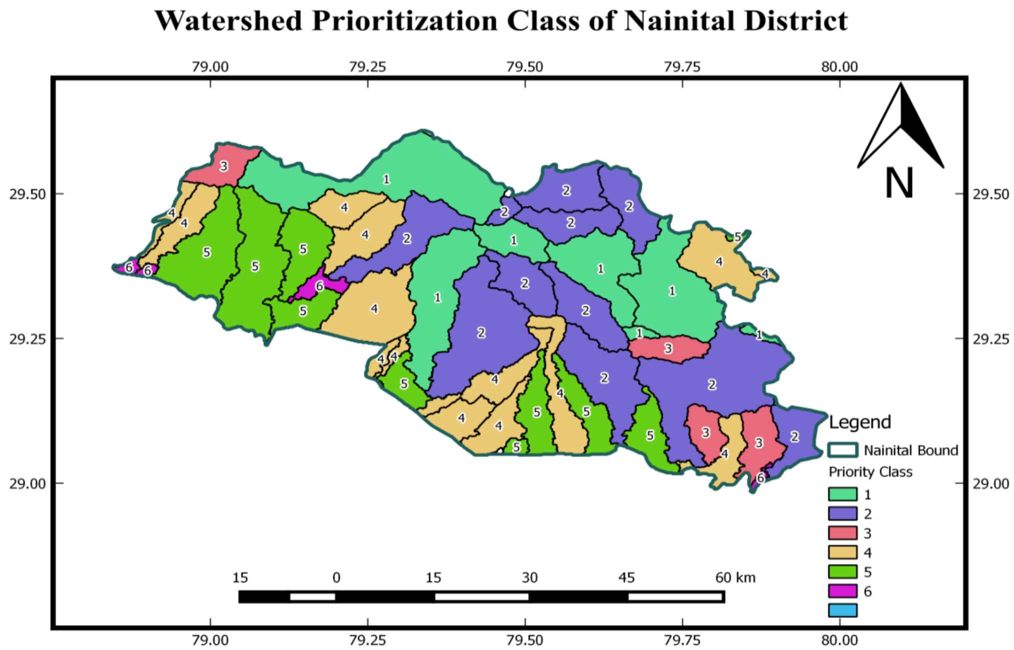

Figure 19. Watershed prioritization map of Nainital district.

These watersheds should be supported with the development of physical structures to reduce soil losses. The slope gradient should be pieced into relatively low sloping zones to reduce water-induced soil losses. Massive plantations of fast-growing tree species should be extended to enhance vegetation cover and root-based soil retention capacity. Four watersheds, three in the eastern part and one in the western part of Nainital, take third priority. Fourteen watersheds were given fourth priority. In the third and fourth priority categories, contouring, terracing, and bund formation should be adopted for agricultural lands to check large-scale soil erosion. Plantations should be developed on non-agricultural lands. Ten watersheds were assigned fifth priority, while the remaining four watersheds were assigned last priority. These watersheds should be targeted for contour farming, proper bunding, etc. Additional applications of organic matter in agricultural fields will not only increase the water retention capacity of the soil, but also the percolation rate and particle adhesiveness. These practices together with persistent plant cover that helps control soil losses will be crucial for sustainable development [39]. Therefore, controlling large amounts of runoff and enhancing organic matter buildup in the soil will suffice for the purpose [32,38].

6. Conclusions

The creation of a geo-database on land use and land cover, slope, soil properties, climatic variables, and hydrological characterization was found to be very effective and useful for estimating soil losses. Landsat 8 (OLI) optical data of the 145/40 path and row were used to create a land use and land cover map of the Nainital district. According to the findings of the prioritization analyses, 32 watersheds had very high priority and

28 had high priority. These watersheds should be thoroughly investigated for soil and water conservation, water resource conservation, and proper land-use planning. This will aid in the development of a comprehensive database for each natural resource theme, which is essential for successful and efficient watershed management and the protection of deteriorating watersheds.

The proposed action plans are based on the prioritization outcomes. We recommend the construction of major check dams in high-priority watersheds and minor check dams in low-priority watersheds. Additionally, percolation tanks and recharge wells should be built and forest and grassland expansion and improvement projects should also be implemented in these watersheds. Water harvesting techniques are being implemented to prevent rainwater from being wasted in the watersheds. In addition to providing supplementary irrigation, this will increase groundwater recharge. Farmers should be encouraged to use soil conservation techniques and build farm ponds. Contour bunding is a good example of a soil and water conservation measure. Fodder, silvo pasture, and social forestry can be used to cultivate lands with low productivity and severe soil erosion. These growth activities aid in soil erosion reduction, moisture conservation, and enhanced soil productivity. The study area mostly comprised hard rock terrain. Water harvesting and artificial recharge sites would raise the water table level and meet water demand for crop irrigation during the summer season, thus meeting the needs of both urban and rural areas.

Based on the results of our study, it may be concluded that a major portion of Nainital district comes under the severely prone category of soil erosion, and therefore demands immediate attention as well as appropriate measures by government agencies and civil society to control soil erosion and avert the possibility of landslides.

7. Future Scope of Research

In the future, a segments and sub-watershed study will be carried out to further investigate the area's infiltration potential in extensive detail.

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