Watershed prioritization for soil erosion mapping for the Lesser Himalayan Indian basin using PCA, WSA method in conjunction with morphometric parameters and GIS-based approach

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Watershed prioritization for soil erosion mapping for the Lesser Himalayan Indian basin using PCA, WSA method in conjunction with morphometric parameters and GIS-based approach

Highlights:

1. Watershed prioritization using morphometric parameters is the best technique for soil erosion mapping.
2. Soil erodibility assessment using GIS-RS integrated with PCA, WSA models.
3. Evaluation of sub-watershed hydro-geomorphological parameters are the most influential parameters for soil erodibility assessment.
4. The most rugged high altitude sub-watersheds are the most susceptible to soil erosion in the basin.
5. Both model results showing outlet watersheds are high priority, and the sub-watersheds in the north-eastern part having the lowest priority.
6. The assessment can help the sustainable development and management of soil and natural resources in the region.

Abstract:

Watersheds in the subtropical Himalayan basins are highly prone to land degradation due to deforestation, landslides, intensive agriculture, population pressure, and overgrazing, in particular, where various fluvial and denudation processes occur. It is important to assess the magnitude of problem and to understand the erosion process under normal conditions, so that effective measures can be implemented. Therefore, the study selected Kalsa watershed from the Lesser Himalayan region, where soil erosion is more prominent. Regarding this issue, to identify the hotspot of soil erosion of the basin, watershed prioritization methods using advanced geographical information system and remote sensing techniques integrated with weighted sum analysis (WSA) and principal component analysis (PCA). In addition, a comparison has been made to evaluate the performance of these models. The study considered sixteen different morphometric parameters, including linear (Rho coefficient, stream frequency, drainage density, length of overland flow, drainage texture, and constant of channel maintenance); landscape (relative relief, relief ratio, basin slope, and ruggedness number); and shape (elongation ratio, form factor, circulatory ratio, and compactness coefficient). Both the method PCA and WSA indicate the same results showing high priority, meaning the outlet watersheds have high priority. The sub-watersheds in the north-eastern part have the lowest priority. The results also show that the length overland flow, relative relief, basin relief ratio and hypsometric integral are the most important indicators. The sub-watersheds prioritize high ranks, medium ranks, and low ranks out of 10 sub-watersheds covering about 45.32%, 27.78% and 26.90% area of the Kalsa River watershed, respectively. This study will help regional planners, farmers, and governments take more detailed decisions to propose efficient soil erosion control measures and conservation priorities of the watershed. The study findings have implications for sustainable land management and conservation goal targets (target 2.3 and 2.4; target 3.9; target 13.1, 13.2 and 13.3; target 15.3 and 15.4), which finally helps to achieve the United Nation’s 2030 Agenda for Sustainable Development.

Keywords: Soil erosion; Kalsa River; Lesser Himalayan basin; watershed prioritization; Principal Component Analysis; Weighted Sum Analysis.

1. Introduction

Soil erosion is a significant ecological and agricultural issue worldwide and has broad economic, political and social implications. It has a significant influence on the lives, livelihood, and resources of many individuals and requirements to find solutions (Keesstra et al., 2016). It involves removing, carrying, and depositing soil particles, separating and aggregate matter of rock, and replacing them in new areas by water flow (Masselink et al., 2017). This has long-term effects since fertile topsoil is degraded, and the soil's productivity potentials decrease, and global food security threats increase (Mosbahi et al., 2013). The current global erosion rate was estimated at 35.9 pg. yr^{-1} petagrams yr^{-1} (pg) (1 Pg = 10" grams [g]) using global potential soil erosion model in 2012. There is a slightly higher observed in India (~0.45%), and about 0.20 million km^2 area is suffering with soil erosion (Borrelli et al., 2017). There is a slightly higher rate of erosion observed in India (~0.45%) and about 0.20 million km^2 area is suffering from soil erosion. On the other hand, while densely inhabited areas, there is a decline in soil erosion forecasted (Borrelli et al., 2017).

In addition, about 175 mha of land in India is suffered by severe soil erosion and other forms of land deterioration, accounting for about 53% of the total geographical area (Narayan and Babu, 1983). The active erosion is caused due to ravines, gully erosion, shifting cropping pattern, salinity, alkalinity, continuous waterlogging, and about 25 mha of land actively affected by wind and water (Mandal and Sharda, 2011; Pramanik, 2017). Rivers carry the estimated annual loss of soil about 5,334 Mt (16.4 t ha-1) from India and 29 percent into the sea. About 10 percent is deposited in reservoirs indicating a lack of storage capacity in the country (Singh and Singh, 2018). It is also estimated that the soil nutrients loss varies from 5.37 to 8.40 million tons, resulting in a supply reduction of 30-40 million tons of food grain per year (Das, 2014). Arable land per head is projected to decrease to 0.09 hectares in India by 2075 and now to around 0.17 hectares, varying from region to region (Sujata et al., 2002). This dilemma is sufficiently important because India supports about 16% of the world's population in 2% of the world's land area.

In many developing countries, where human resources, financial budgets are limited, and these activities are costly and time-consuming, the decision-making process for watershed strategy and management is challenging (Rahmati et al., 2016; Ameri et al., 2018; Rahmati et al., 2019). In recent research on soil erosion focuses on the different hilly regions, i.e. Deccan plateau (Gaikwad and Bhagat, 2017; Telore, 2020); northern plateau (Yadav et al., 2018); Western Ghats (Thomas and Thrivikramji 2018; Choudhari et al., 2018; Kadam et al., 2019a); Eastern Ghats (Markose and Jayappa, 2016; Hembram and Saha, 2020); north-eastern parts (Ahmed et al., 2017; Mandal and Mandal, 2018); and northwestern parts (Chauhan et al., 2016; Singh and Singh, 2018; Siddiqui et al., 2020) of India. Most parts of the Himalayan region is made up of fragile rocks, such as sandstone, grits, shale, conglomerates. The terrains are in a constant tension state as the north advances. Active tectonic structures accommodate the continuous collision of the Indian and Eurasian Plate, i.e. thrusts and faults reflected in similar geomorphologic configurations of the region (Kumar and Negi, 2016; Singh and Singh, 2018; Kumar et al., 2020; Sati et al. 2007). The huge topographic ruggedness in the terrain is the erudite testimony of active tectonics in the region. The Kalsa river basin terrain is sandwiched between Main Boundary Thrust (MBT) and South Almora Thrust (SAT). These formations are very vulnerable to soil degradation and may need further investigation. The youngest mountain ranges also distinguish the area with folded slopes, rocky outcrops, degraded forest cover, extensive road development, steep tillage farming, and erratic rainfall pattern, poor water retention and severe soil losses (Rawat and Rawat, 1994; Jain et al., 2003; Singh and Singh, 2018).

An evaluation of Himalayan erosion-prone areas can help assess land erosion as the main challenge to sustainable agricultural production (Jasrotia and Singh, 2006; Mandal and Sharda, 2013; Pramanik et al., 2015, 2018; Kumar et al. 2020). The evaluation of soil erosion and erosion-prone area mapping function as soil conservation awareness, land protection and, in particular, agricultural sustainability (Montgomery, 2007; Sharma et al., 2012; Pramanik et al., 2020b). Formulating effective and sustainable agricultural land management systems includes knowledge about soil erosion (Montgomery, 2007; Bagherzadeh, 2014; Pramanik, 2016a; Singh and Singh, 2018). Soil erosion can also be critical for all dynamics in developing policies to sustain the soils and anything in tandem with soil productivity. Therefore, an evaluation of soil erosion is unavoidable. Moreover, the database with spatial distribution of various soil and land attributes is a pre-requisite for development of strategic planning of any land development programme and the rehabilitation planning of degraded lands.

One of the essential principles for effective and productive watershed protection is sub-watersheds prioritization, which protects, restores, and promotes the sustainable use of the region's terrestrial ecosystems. Morphometric analysis the measurement and mathematical analysis include various hydrological, topographic and areal aspects that earth's surface, shape and dimension of its landforms at various regional scales. The cornerstone for quantitative analysis of basin morphometry has been laid by Horton (1932), followed by Miller (1953); Schumm (1956); Strahler (1957, 1964), Hadley (1961); Leopold (1964) and Morisawa (1985). Many researchers have been suggested that this helps in tracking soil erosion, flooding, and sediment load identification and sustainable development of critically endangered sub-watersheds (Chowdhary et al., 2013). Sustainable forest and soil support combating desertification and reverse and halt land degradation, and control biodiversity loss (Fan and Shibata, 2014). These principles of sustainable soil management are critical to ensure soil degradation neutrality at all scales: local, regional, national and global. Adopting these principles is essential because if soil resources degrade and dwindle, ecosystem services provisioned by soil (i.e., food, feed, fibre, fuel, water, biodiversity, climate, medicinal products) are weakened and become inadequate for the human population that continues to grow and become increasingly affluent on a planet of finite and ever-decreasing natural resources (Lal, 2018; Pramanik et al., 2020a).

Numerous studies have been attempted using geo-morphometric multivariate analysis in conjunction with several weight deriving methods to prioritize sub-watersheds in different levels (Rahmati et al., 2016;

Chandniha and Kansal, 2017; Malik et al., 2019; Arefin et al., 2020); Principal Component Analysis (PCA) (Gopinath et al., 2016; Singh and Singh, 2018; Malik et al., 2019); and Weighted Sum Analysis (WSA) (Adhami and Sadeghi, 2016; Ayele et al., 2017; Naqvi et al., 2019). Moreover, several approaches have been developed to determine soil degradation and resulting prioritization of watersheds, ranging from basic analytical models to process-oriented physical-based models. Such analytical and process-oriented models are difficult, data-driven and nuanced for watershed prioritization. Still, they can be restored using morphometric variables of watersheds with fewer data requirements and efficient techniques. Besides, the prioritization of the catchments in order to assess soil erodibility was not carried out at the sub-watershed level due to the lack of regular monitoring and data pertaining to factors responsible for land erosion (Pramanik et al., 2015; 2016; 2021). Moreover, the region is highly prone to land degradation due to deforestation, landslides, intensive agriculture, population pressure, and overgrazing, in particular, where various fluvial and denudation processes occur (Biswas et al., 2015; Pramanik, 2016; Pal et al., 2016a; b; Pramanik et al., 2021). Continuous deterioration of soils and increasing dependency on agriculture for food production became imperative to assess, plan and manage the soil for sustainable development of agriculture and all the biotic resources in the region. Hence, it requires a comprehensive watershed management plan to conserve soil health, especially physical properties, by watershed prioritization in soil erodibility based on the morphometric analysis. Moreover, it is also important to assess the magnitude of problem and to understand the erosion process under normal conditions, so that effective measures can be implemented. Therefore, the study's objective is to analyse the areal, linear and relief morphometric parameters of all sub-watersheds of the Kalsa Basin, incorporating geospatial and statistical technique to prioritize the watershed in terms of their erosional potential for the sustainability of agriculture, natural resource management and livelihood activities. It also establishes an integrated approach based on a wide variety of evaluation criteria, PCA and compound factor method to determine the watersheds' erosional potential. This study's findings can help ecologists, hydrologists, geomorphologists, conservationists, regional planners, farmers, and government make more precise decisions for the watershed management to the conservation of soils, natural resource management, and restoration of livelihood resources in such high mountainous region. The results also provide implications for developing a sustainable integrated watershed management plan to mitigate soil erosion risk, improve soil fertility, improve land productivity, restore and protect land-related ecosystems in the region. The methods presented in this study can also provide tools for watershed prioritization in land resource conservation and various other applications for different mountainous areas worldwide.

2. Material and methods

2.1 Study area

Kalsa River originates from the southern hills of the lesser Himalayan region in different tributaries. It is known as Kalsa River after conferencing Tandi Gad and Ghat Gad tributaries nearby Padampuri village. After flowing southward, it eventually meets with the Gola River. Kalsa River watershed lies between latitude 29° 21' 18.3" N to 29° 20' 14.25" N latitude and 79° 39' 04.38" E longitude to 79° 40' 19.50" longitude E. The area extended over 145.98 km^2 and NNW to SSE elongated in shape, having an aerial length of about 19.36 km from north to south and width approximately 14.89 km from east to west fall in Nainital district (Kumaun Region). The altitude of its catchment extends from 723 to 2475m asml (Fig. 1). The region is sandwiched between the Main boundary thrust (MBT) and South Almora thrust (SAT) from south to north, and the Ramgarh thrust passes from the middle part of the catchment. The hypsometric curve of all the catchments indicates maturity to the young stage of the watershed. The area is characterised by sub-tropical climatic conditions, where maximum rainfall (3016.5 to 1147.2mm) received during the monsoon period (July to October) (Fig. 2). June and January are generally hottest (22.9°C) and coldest (5.2°C) months, respectively; winter is severe because of temperature declines some time below minus (Fig. 2). Elevation plays a major role in defining the climate variability of the region.

2.2 Data Source

Survey of India (SOI) (https://soinakshe.uk.gov.in/) open series topographical sheets on the scale of 1:50,000 have been used to extract and verify various spatial information such as the extent of the basin and hydrological characteristics. In addition to this, Carto-DEM with 30m spatial resolution obtained from Bhuvan portal (Table 1) (https://bhuvan-app3.nrsc.gov.in/data/download/index.php) used for hydrological analysis (drainage system), relief, slope aspects and other topographical parameters. For assessing various spatial morphometric parameters, relative relief, slope, drainage density, stream frequency, drainage texture, the zonal analysis was carried out using 1km*1km pixel size. For extraction, calibration, processing and mapping the data, ArcGIS 10.4 software was used. For lithological formations and structures, the Geological Survey of India (GSI) at 1:150000 scale digital layer was obtained from Bhukosh GSI web portal (http://bhukosh.gsi.gov.in/Bhukosh/Public) (Table 1). LISS III (April 2018) was used for land use and land cover mapping.

2.3. Tools, techniques and software used

GIS can be described as a system that makes geographical (land and water resources) data and human activities easier to store and intelligent utilization (Srivastava, 2003). To extract, digitize and estimate attribute and spatial database in the drainage analysis, Arc-GIS and Q-GIS were used in the present study. These software's are designed for spatial query analysis, integrated database generation, visualisation, and basic modelling. Additionally, the digital elevation model (DEM) used for extracting for drainage network verified through SOI toposheet in GIS through overlaying techniques, in which the stream drainage system was modified. ERDAS Imagine was used in toposheet geo-registration and for the composition and classification of digital FCC images from the LISS-III satellite data. It is a visualization tool that combines various types of geographic data with spatial modelling and remote sensing images. ERDAS IMAGINE essential modules include a set of tools of geo-correction, image processing, and so on. Moreover, it consists of several other tools such as mosaic, surface interpolation, and ortho-rectification for data analysis.

2.4. Extraction of morphometric parameters of watershed

The following measurements were carried out for the morphological characterization of the watershed geometry: (i) linear aspect, (ii) landscape aspect, and (iii) shape aspect. The linear aspect incorporates Rho coefficient (ρ), drainage density (Dd), stream frequency (Fs), drainage texture (Rt), constant channel maintenance (C), and length of overland flow (Lg) (Table 2). The landscape parameter includes relative relief (Rh), relief ratio and sub-basin slope (Bh), and ruggedness number (Rn); and shape aspect embrace elongation ratio (Re), form factor (Rf), circulatory ratio (Rc), and compactness coefficient (Cc) (Table 2). These three sets of parameters were utilized to prioritise soil erosion control of the study watershed. A digital elevation model of the study area with a pixel size of 30m was used, from which the linear, landscape, and shape morphometric parameters were estimated for each sub-watershed. The Arc-GIS hydrology toolbox automatically conducted the extraction of these parameters.

2.5. Sub-watershed prioritization:

The morphometric parameters in the linear, relief/landscape, and shape aspects were termed as risk factors for assessing soil erosion and prioritising sub-watersheds. The linear and landscape parameters are directly proportionate to the factors of erodibility (Ratnam et al., 2005). The morphometric parameter with the highest value was assigned the first rank and so on. On the other hand, the shape parameters of sub-watersheds are inversely proportional to soil erosion, so the morphometric parameter with minimal value was assigned the first rank. Likewise, further ordering was carried out (Ratnam et al., 2005). The significance of all input constraints cannot be equivalent in deciding the potential area for risk assessment and management, as each watershed has some uniform characteristics. In other words, approaches such as Weighted Sum Analysis (WSA) and Principal Component Analysis (PCA) should be formulated in conjunction with the above parameters to prioritize sub-watersheds. A correlation analysis was employed to evaluate the influence of many morphometric parameters to eliminate the bias of the individual morphometric parameters in a precise ranking to be involved in the final combination for the analysis. Thereby, WSA and PCA methods were used in this research to estimate the relative importance of each constraint by evaluating the correlation analysis between the individual variable and assigning due importance to each input constraint. Priority scaling for all ten sub-watersheds of the Kalsa River was achieved using WSA and PCA approaches estimation of the compound parameter values. The minimum value of the WSA and the PCA was given top priority in the sub-watershed. The approaches (WSA and PCA) used in the present study, described in the following sections.

2.5.1 Principal Component Analysis (PCA)

The morphometric parameters extracted from a river basin usually several times associated with each other several times a single parameter characterized several of the basin's characteristics. The PCA method comprises a rotation of the coordinate axes' whole vector space into a new reference point. Orthogonal transformation or unassociated conversion in which the new major components are represented by one of the initial variables. One most effective parameter of the current modules is that the overall variance is considered in turn. The principal component analysis is used on all geomorphic parameters to calculate the correlation matrix and the primary components and find the most influential parameter. The PCA examines the matrix of correlation and even the significant elements and finds the most appropriate parameter out of all geo-morphometric parameters. The same method of parameter ranking is adopted by Kadam et al. (2019) and Meshram and Sharma (2017).

PCA is a multivariable computational method used to reduce the complexity of a dataset by preserving the initial data reliability. Trimming is accomplished by transforming the original information into two or more key components unrelated, orthogonal, and relatively significant. The updated orthogonal elements maintain the absolute maximum variation of the variables as a key function. The first PC contains one or more parameters that make up the highest variance in the data set, while subsequent components reflect a low or marginal variance that does not correspond to either component. The most suitable approach is to calculate all factors on the same scale. PCA can be used to identify the most critical parameters for nearly all morphometric parameters in the PC. The four basic steps were taken to enact the PCA is discussed below.

In the first step, the data set was standardized to enhance the performance of PCA. Standardization has been performed by subtracting each data value from the total average and by dividing the data set by standard deviation. This method turns all data into zero mean and standard unit deviation. The process was achieved as follows:

$$\boldsymbol{Z} = \frac{\boldsymbol{C_{ij}} - \boldsymbol{C_j}}{\boldsymbol{S_j}} \tag{1}$$

Where Z denotes the standardized matrix of parameters, C_{ij} stands for ith observation on the jth parameter, i ranges from 1, 2…n (number of observation), j ranges from 1, 2…p (number of parameters), C_j mean of the jth parameters, and S_j the standard deviation of the jth parameter.

The second step involved the computation of the covariance matrix to identify any possible correlation between the data set variables. Let us assume Z matrix of n observations, and p number of PCs may be represented in the matrix notation as:

$$\boldsymbol{Z} = \boldsymbol{X} \times \boldsymbol{P} \tag{2}$$

Where Z and X are the $n \times p$ matrices and P indicates coefficient matrix with $p \times p$ dimension, jth PC Z_j is generally expressed as

$$\boldsymbol{Z_j = X_{aj} \quad for\, j = 1, 2 \ldots \ldots p} \tag{3}$$

Where Z_j is n×1 (column) vector, and aj is p ×1 (column) vector of coefficients.
In general, the covariance matrix is represented as:

$$\boldsymbol{C = \frac{X'X}{n-1} = \begin{bmatrix} c_{11} & \cdots & c_{1p} \\ \vdots & \ddots & \vdots \\ C_{p1} & \cdots & C_{pp} \end{bmatrix}} \tag{4}$$

Where X' denotes the transpose of the standardized matrix of X predictor variables.
Every covariance matrix element is evaluated as:

$$\boldsymbol{C = \frac{1}{n-1} \sum_{k-1}^{n} X_{kj} X_{ki}} \tag{5}$$

In step three, the eigenvalues and eigenvectors for the covariance matrix were calculated to determine the PCs of the data. If λ' is an eigenvalue for covariance matrix C, the solution can be explained through the characteristic equation as:

$$\boldsymbol{|(C - \lambda' I)| = 0} \tag{6}$$

Where I is the identity matrix of the same dimension (i.e., $p \times p$) as C and is regarded as a necessary condition for matrix subtraction. For every eigenvalue λ', the corresponding eigenvector, v can be solved as:

$$\boldsymbol{|(C - \lambda' I) \times v| = 0} \tag{7}$$

If the eigenvalues are ranked in decreasing order, we get $\lambda' 1 > \lambda' 2$, suggesting that the eigenvector corresponding to the first PC (PC1) is *v1,* and the one that corresponds to the second PC (PC2) is *v2*.

The fourth and last move was to develop the function vector and PCs. The function vector is a matrix of eigenvectors, corresponding to the largest eigenvalue (i.e., PC1) or simply both PC1 and PC2 if there are two PCs. The final PC loading matrix was formed by taking the transpose of the feature vector and left-multiplying it with the transpose of a scaled version of the original data set and represents a degree of correlation between the X variables and the different F factors that is equivalent to the correlation between the X variables and the Z PCs. As a result, the PC loading matrix was obtained by pre-multiplying the square roots of the eigenvalues of the C matrix with the characteristics values of the correlation matrix (P). The PC loading matrix (R) can be written as:

$$\boldsymbol{R = PD^{\frac{1}{2}}} \tag{8}$$

where $PD^{\frac{1}{2}}$ represents the diagonal matrix featuring nonzero elements as reciprocals of the square roots of the eigenvalues of the C matrix expressed by Eq. 4. In this study, the eigenvalues and eigenvectors were calculated using Eqs. 6 and 7. A rotated loading matrix of the available variables was obtained to identify the most significant morphometric parameters for prioritising the Kalsa River sub-watersheds.

2.5.2 Weighted Sum Analysis (WSA)

Weighted sum analysis is a well-known method that offers consistency in addressing complicated problems to compare land surface processes between related entities such as watersheds. For this purpose, numerous researchers have been widely used this method to assess the sustainable planning and management of sub-watersheds in data scarcity regions (Altaf et al., 2014).

WSA represents the preferences of decision-makers in a linear additive function (MacCrimmon, 1968). Triantaphyllou and Mann (1989) have investigated the usefulness of decision-making methods and pointed WSM is one of the simplest strategies to overcome MCDM problems. The best alternative is the one with the maximum score satisfying after transforming all evaluation criteria to a single dimension (equation 9):

$$\boldsymbol{WSA_{Cp} = Pr_{p1} * W_{p1} + Pr_n + W_n} \tag{9}$$

Where, WSA Cp is the compound parameter used for weighted Sum Analysis, Pr is the preliminary priority rank of each morphometric parameter (p1, p2…n), and W indicates the weight of morphometric parameters obtained using cross-correlation analysis, which can be expressed as:

$$\boldsymbol{Weights\ of\ parameter\ (W) = \frac{\textbf{Sum of correlation coefficient}}{\textbf{Grand total of correlations}}} \tag{10}$$

3. Results

3.1 Morphometric analysis

The morphometric analysis using advanced GIS and remote sensing is a helpful technique for surface hydrological assessment of the watersheds (Banerjee et al., 2017; Pramanik, 2016b). It thoroughly discusses how the Planet's various surface processes apply to the different earth system components, including geomorphology, hydrology and geology (Paul and Bayode, 2012). Furthermore, the drainage system's properties of the watershed basin significantly affect its infiltration and runoff potential (Sharma et al., 1986). Some morphometric parameters are referred to as the indicator of soil erodibility measure and designated as an indicator for soil erosion risk evaluation that includes basic, linear, shape and landscape parameters of the watersheds. In this study, quantitative analysis of the morphometric parameters of drainage network characteristics and their role in soil erosion in the Kalsa River basin and its ten sub-watersheds (Fig. 1). In this context, 16 different morphometric parameters, which indicate linear (ρ-Rho coefficient, Fs-stream frequency, Dd-drainage density, Lg-length of overland flow, Rt-drainage texture, and C-constant of channel maintenance); landscape (Rh-relative relief in meters, Bh-relief ratio, sub-basin slope in degree, and Rn-ruggedness number); and shape (Rf-form factor, Re-elongation ratio, Cc-compactness coefficient, and Rc-circulatory ratio) characteristics of the sub-watersheds. These parameters were extracted and analysed using quantitative statistical techniques following the formula mentioned in table 2.

3.1.1 Basic parameters

The parameters pertaining to the dimensional estimation of the sub-watersheds indicate the basic morphometric parameters of the basin shown in Table 2. Stream order of the drainage basin is the successive assimilation of streams within a drainage basin (Jadhav, 2014). Kalsa River is listed as the 6th order river basin based on the stream order rule propounded by Strahler (1957). It was computed that the basin is extended over 147.98 sq. km area with a 66.7 km perimeter. The cumulative number of streams in the aforementioned basin is 1645 with a 702.80 km length. The dimensional measurement such as basin length, width, the channel length is given in table 3 and basic drainage characteristics, i.e., stream order, stream number, stream length, bifurcation ratio, stream length ratio, mean bifurcation ratio etc. of all the sub-watersheds given in table 4 and 5. The drainage network was extracted using the hydrological tool in Arc-GIS software and verified overlaying SOI toposheet (Fig. 3). A continuum that indicates a gradual decrease in stream number with the higher-order exists in the watersheds. This change in the rank of streams occurred due to the watershed's structural and morphological characteristics.

3.1.2 Linear parameters

(a) Rho coefficient (ρ)

The Rho coefficient is an essential parameter relating drainage density to a watershed's physiographical growth that facilitates the estimation of the drainage network's storage potential and, thus, a determinant of the ultimate degree of drainage growth a given watershed (Horton, 1945). The Rho coefficient in sub-watersheds is ranging from 0.09 (SW6 and SW7) to 0.31 (SW1); the higher Rho coefficient value suggests increased flood storage and thus ameliorates the erosion effect (Table 5).

(b) Drainage density (D_d)

Drainage density is defined as the total stream's segments length per unit area. It mainly depends on surface relief, runoff, distance, fluid viscosity, gravity acceleration and proportional factor (Kumar and Negi, 2016). Resistance to weathering, permeability, rock composition, landscape and vegetation are factors that influence Dd. Generally, Dd has a low benefit in regions of high-resistance permeable content and vegetative cover and poor relief. A high density of drainage seen in regions with weaker and impermeable subsurface soil, sparse vegetation and mountainous terrain. Drainage density indicates that sub-watershed SW1 and SW8 have low Dd ranging from 3.76 to 4.14 per sq. km (Table 5) designated very coarse Dd class (Fig. 4d), whereas SW7 and SW6 fall under high Dd ranging from 7.12 to 6.30/km^2 (Table 5). Fig. 4d indicates the Dd's spatial distribution and suggests that the north-western part of the catchment has high density. In the whole river catchment, sub-watersheds with low to moderate drainage density indicate that they are composed of permeable subsurface materials, low relief to strong vegetation cover resulting in more infiltration capacity and a better groundwater recharge relative to high drainage density watersheds.

(c) Stream frequency (Fu)

The stream's frequency has an inverse relation to the permeability and direct relation to the roughness of the watershed (Montgomery and Dietrich, 1992). Fu mainly depends on the lithological, physiographical conditions of the surface and precipitation of the particular area. High stream frequency suggests the rocky surface, complex lithological conditions, and low permeability capacity, contributing to further erosion and vice versa. High Density of drainage seen in regions with weaker and impermeable subsurface soil, sparse vegetation and mountainous terrain. In the present analysis, the stream frequency ranged from 3 to 14 stream segments/km^2 (Fig. 5b), and high stream segments exist in the northwestern part of the catchment. The SW7 and SW6 have the lowest, and SW1 and SW8 have the highest Fu.

(d) Drainage texture (Rt)

Horton (1945) described the drainage texture, meaning the number of total stream segments in any order of the basin's perimeter. The higher the texture of the runoff, the greater dissection, and the more erosion are suggested. Therefore, Rt is taken as the most crucial factor in land resource assessment in all ten sub-watersheds given in table 5 in sequence 7.92, 4.66, 9.74, 7.34, 12.37, 14.19. 12.68, 7.39, 6.39 and 7.34 from SW1 to SW10, respectively (Table 5). The highest Rt found in SW6 and SW7 indicates the higher intensity of erosion caused due to the low relative spacing of streams in the watersheds, whereas SW2 and WS9 have the lowest Rt. It prominently depends on climate, precipitation and rock type, relief, and development (Horton, 1945; Smith, 1950).

(e) Length of overland flow (Lo)

The Lo shows the water flow duration across the ground because it is accumulated in a particular stream (Horton, 1945). This indicates one of the most significant independent variables influencing the drainage basin's physiographic and hydrological development (Waikar and Nilawar, 2014). In the present study, the length of overland flow for all 10 sub-watersheds are shown in table 5 in chronological order 0.53, 0.45, 0.43, 0.48, 0.32, 0.32, 0.28, 0.48, 0.41 and 0.44 respectively.

(f) Mean bifurcation ratio (Rbm)

Bifurcation ratio can be defined by the ratio, which is denoted by R_b (Horton, 1945), of the streams number of a given order (N_u), to the streams number of the higher-order (N_{u+1}). The Bifurcation ratio developed by Horton (1945) is also called a relief and dissection index. For watersheds in which a geological structure does not distort the drainage pattern, the bifurcation ratio typically ranges between 2.00 and 4.94 (Strahler, 1964). This indicates a minimal variation in the few locations in different environmental conditions, even where there is a robust geological control in the area. In the present case, the bifurcation ratio is not the same from one order to the next due to the difference in the basin's configuration and its lithological conditions.

The Rbm for all the ten sub-watersheds are 1.91, 2.23, 2.98, 2.69, 3.54, 3.82, 3.76, 1.86, 2.75, and 3.23 from SW1 to SW10, respectively (Table 5). The maximum Rbm is found in SW6 and SW7 indicates that the early hydrograph peak with a tough surface and strong structural control on drainage patterns and their potential for flash floods during the flood hazards. The minimum value of Rbm is obtained for sub-watersheds SW8 and SW1 shows delayed hydrograph peak and less strong structural surface control on the drainage patterns.

(g) Constant of channel maintenance (C)

The importance of the ratio is that it reflects, in square km area needed to maintain 1 km of the stream channel, which means that a minimum area of required for the development of the drainage channel (Schumm, 1956). It is very similar or equal to the inverse of density drainage. It is also very useful for measuring the terrain's erodibility or other factors influencing the erosion of the land and development of the drainage network. Hence, the value of C is taken to compare the erosional intensity in all the watersheds given in table 5 in chronological order 0.27, 0.22, 0.22, 0.24, 0.16, 0.16, 0.14, 0.24, 0.21 and 0.22. It was found that maximum C is confined in SW1, SW4 and SW8 sub-watersheds ranging from 0.27 to 0.24, indicating the highest soil erosion susceptibility.

3.1.3 Shape parameters

(h) Elongation ratio (Re)

For deciding the shape of the basin, the elongation ratio is used. The basin circle ratio to the total basin length is known as the relation of the circular diameter (Schumm, 1956). The elongation ratio (Re) over a wide range of climatic and geological conditions generally varies between 0.6-1. When the value is 1, it indicates that the drainage basin is spherical. A circular basin is more productive in the river runoff than an elongated river basin (Singh and Singh, 1997). Thus, the regions with a very low terrain are near 1 and vary from 0.6 to 0.8 to high relief and a steep road (Strahler, 1964). These values can be classified into three categories, namely, less elongated (< 0.7), oval (0.9–0.7), and circular (> 0.9) (Altaf et al., 2013).

The elongation ratio for all ten sub-watersheds ranges between 0.52-0.79, indicating that watersheds are moderately elongated. The sub-watersheds SW1, SW2, SW5, SW6, SW7 and W10 have a Re value less than 0.70 (Table 5), indicating that these watersheds are elongated steep slope and high relief. Only SW3, SW4, and SW9 sub-watersheds have ranged from 0.74 to 0.79 seem to be oval (Table 5), while no watershed falls in the circular category.

(i) Circularity ratio (Rc)

The Rc is the ratio between the basin and the circular area of the basin perimeter (Miller, 1953). Significant characteristics influence Rc, including frequency and stream length, land use/land cover, geological composition, relief, slope and the climate condition in the basin (Altaf et al., 2013; Pramanik, 2017). The value of the circulatory ratio varies from 0 (a line) to 1 (a circle) (Singh and Upadhyay, 1982).

In the present study, circulatory ratio (R_c) for sub-watersheds SW1, SW2, SW3, SW4, SW5, SW8 and SW10 ranges from 0.50 to 0.67, which indicating the terrain of the watershed is characterised by an elongated, high relief and permeable surface resulting in increased basin lag times. The sub-watershed SW6, SW7 and SW9 have Rc <0.50, indicating impermeable surface and low relief, resulting in lower lag values of the basin (Table 5).

(j) Form factor (Rf)

The form factor may be defined as the watershed area's ratio to the square of the maximum length of the basin (Horton, 1945). The Rf value should always be less than 0.78 (the value corresponding to a perfectly circular basin) (Waikar and Nilawar, 2014). The lower the value of the Rf, the elongated the basin would be. Basins with a high Rf value encounter more increased peak flow with a shorter duration. In contrast, extended watersheds in terms of length with low form factors experience more negligible water runoff of a more extended period. In the study area, the form factor value for all ten sub-watersheds is less than 0.48 (Table 5); this implies that the form of the basin is prolonged by a longer pick flow than the normal.

(k) Compactness coefficient (Cc)

The coefficient of compactness (Cc) of the watershed is the ratio of the sub-watershed perimeter to the circumference of the circular area (Gravelius, 1914). The Cc is independent of the size of the watershed and depends only on the gradient. The constant compactness is the relationship between the shape of the catchment and the circle having the same area and depending on the slope. Cc=1 means that the basin appears completely like a circular basin. Cc > 1 suggests a more divergence from the circular existence of the basin. It is intrinsically linked to the watershed's infiltration potential (Altaf et al., 2014; Kadam et al., 2019). The highest Cc was found in WS21, WS22, WS23, WS2 and WS11, ranging from 1.23 to 1.71, indicating the highest infiltration capacity. The Cc values of all the sub-watersheds are differential to 1, showing the land's erosional potential (Table 5).

3.1.4 Landscape parameters

(l) Basin relief (Bh)

Basin Relief is defined as the drainage basin's topography, which affects the quality and speed of drainage in the river catchment. The altitude difference between the highest and lowest point of any given area as relief and the total basin relief is defined as the altitude difference between the highest point at the source and the river mouth in a basin. The Kalsa River basin is lies between 723m to 2475m (Fig. 1).

(m) Relative relief (Rh)

The difference between the minimum height and maximum height within the area unit can be defined as the Rh. Rh may also reflect the relief property, excluding considerations of sea level (Singh 1992). It is also known as local relief. Maximum Rh found in the northern upper part of the study area; it ranges from 88 to 562.43m (Fig. 1). Relative relief of the Kalsa river basin has been classified into five relief class categories (Fig. 4c).

Fig.4c reveals that the 3/4th part of the catchment having Rh frequency occurs under the moderate relative relief class of 201 - 300m and the minimum area, i.e. 2.73% under very high local relief class >400m. The distribution of relative relief is shown in Fig. 4c, and it reveals that more than 200m relative relief is common in the watersheds.

(n) Slope (Sb)

Slopes are interdependent with stream channels and the drainage basin geometry, but slope in geomorphology is a combined effort of form and processes, which are operative on the slope themselves (Leopold, 1964). There are many processes responsible for forming hillslopes such as endogenetic forces (tectonic movement, earthquake, etc.), orogenic forces (weathering and erosion), and climate elements for the development of different types of slope in the region. Slope analysis is the subject matter of geomorphology since the beginning of geomorphological studies. In the previous era (past), slope analysis was done with the manual methods of Rich (1916), Wentworth (1930), Smith (1938), Raisz and Henery

(1937), Calef and Newcombe (1953), Strahler (1956), and Miller and Summerson (1960). Still, all these methods are time-consuming, and despite these nowadays, the average slope is done with the help of DEM in Arc-GIS software. The GIS generated mean slope data reveals that slope angles vary from 9.5° to 41.65° in the study area. This shows that high variations in the terrain configuration in the Kalsa River basin. The southern slope receives direct sunrays compared to the northern part of the study area, and the southern part has maximum vegetation compared to others (Fig 7a). Slope angle is classified into five generalized classes, as suggested by Young (1972). From the above fig. 4a, maximum 42.16 % area is under the category of very steep slope followed by moderate slope, i.e. 28.86%. Gentle to moderately steep slope occupied only 27.38% of the total area.

(o) Ruggedness number (Rn)

Rn plays a significant role in amplifying river streams' flooding because it directly correlates with the parameters that affect erodibility (Patton and Baker, 1976). Rh and Dd's product of the same unit and the increasing value indicates the basin's higher erosional intensity. The Rn value of all the sub-watersheds ranging from 2.65 to 9.17. The highest Rn value found in SW6 and SW7 is most sensitive to erosion, whereas the lowest value is found in SW4 and SW3. Rn's extremely high value exists when all variables are high and the slope is steep (Strahler, 1964).

(p) Hypsometric integral (HI)

This was initially introduced to produce an area-altitude relationship by Langbein (1947) and then updated by Strahler (1952) to understand relative heights and areas of a watershed for evaluating the developmental stage with each unit. Strahler has suggested that the hypsometric dimensional integral can be used as a measure of landscape evolution. It was computed that the Kalsa watershed has HI 0.54 indicate early youth stage; whereas, only sub-watershed SW9 in late mature stage (< 0.40); six sub-watersheds, i.e. SW1, SW3, SW5, SW6, SW8 and SW10 in the early mature stage (>0.40 to 0.45 HI). The remaining three sub-watersheds, i.e. SW2, SW4 and SW7 of the river basin, indicates its early youth stage (> 0.50) (Fig. 5b and Table 5).

3.2 Inter-correlation among all the selected morphometric parameters

A correlation matrix is estimated using to extract the interrelation between the different morphometric parameters (Table 6). The values of ρ, Dd, Fu, Rt, Lo, Rbm, C, Rh, Bh, HI, Sb, Rn have direct relationship to land erodibility, i.e. higher the values; the more will be the erodibility and vice versa. The sub-watershed having the highest value in respect of the aforementioned parameters was assigned the highest rank 10 and so on. Likewise, Re, Rf, Rc, K, Cc have an inverse relationship to soil erosion, i.e. higher the value, less will be the erosion susceptibility and vice versa. The sub-watershed having the highest value in respect of these parameters was assigned rank 1, and so on (Table 7).

The organization of the parameters into components and the physical meaning are very complicated at this stage. The principal component analysis's main aim has then been extended in the next step to the correlation matrix. In the next step, the PCA was then introduced. The correlation matrix is subjected to evaluation by factor analysis.

3.3 Sub-watershed prioritization for the land and water resource management using PCA and WSA methods

The PCA approach was taken into account to achieve the first-factor loading matrix and, afterwards, the rotated loading matrix by the orthogonal transformation. The findings are depicted in the following sections.

3.3.1 First factor-loading matrix

The PCA points forth the priority erosional parameters for land and water protection by demonstrating the correlation among the criteria. The study produces a PCA loading matrix that shows the intensity of the relationship or association among the morphometric parameters and the associated variable. PCA analysed the most significant components, and the 16 parameters were reduced to four PCs. PCA generates, then by orthogonal transformations, the first element loading matrix and the rotated loading matrix. A matrix with 16 geomorphometric parameters is extracted from the first unrotated factor-loading matrix. Table 7 shows that about 94.74% of the total variance of the Kalsa River is made up of the first four components with values greater than 1. Table 8 shows that the first variable of PC1 is highly correlated (> 0.90) with Dd, Fu, Lo, C and Rn and moderately correlated (> 0.75) with Re, Rf, Rc, Cc, Rt and Rho. The second component is highly correlated with Sb and somewhat associated with Rh; the PC3 is moderately (>0.75) with Bh whereas, the PC4 is low (<0.72) correlated with all variables for the Kalsa River watershed.

3.3.2 Rotation of first factor-loading matrix

When a few factors are strongly correlated with other variables, some are moderately or insignificantly correlated with other variables. It, however, becomes difficult at this point to define a substantially significant component. Therefore, the first element-loading matrix was then rotated for a better interpretation to overcome the difficulty of identifying a significant variable.

After multiplying the transformation matrix with the first-factor loading matrix's selected component, the rotated factor-loading matrix is generated. The first component (>0.90) is highly correlated with Lo, C, Rho, Dd, Fu and Rbm and moderately associated with Rt, according to table 9. Table 9 shows a strong (>0.90) correlation between the first component and Lo, C, Rho, Dd, Fu and Rbm and that the only component which is moderately correlated with Rt is the first-stage component. The second component is strongly correlated with Rh and Sb and moderately correlated with Rn, Re and Rf. The third and fourth component is only moderately correlated with only single parameter Bh and HI respectively and insignificant correlation with rest variables. It may be termed as an organization-processes component for the Kalsa river watershed. As shown (Table 9), the most relevant four parameters, i.e., Lo (length overland flow), Rh (relative relief), Bh (basin relief ratio) and HI (hypsometric integral), have finally been used for sub-watershed prioritisation because they are not interrelated with each other (Fig. 6). For final prioritisation, the weighted sum method was adopted considering the most significant factors from PCA (Eq. 11). Table 10 reveals that SW10 maintains an overall Cp rating of 9.0 (1), while SW3 receives a maximum CP of 17.33 and thus the lowest priority (10) (Fig. 8a). The difference between soil degradation and the prospective soil conservative interventions for the same sub-watershed is of the utmost importance. The last priority map of the catchment of the Kalsa River displayed in fig. 8a. It shows that soil conservation initiatives can be extended to SW2 and other sub-watersheds based on the priority rating.

$$\boldsymbol{PCA\ C_p = (L_o + R_h + B_h + HI)/4} \tag{11}$$

3.3.3 Sub-watershed prioritisation using WSA method and computation of compound parameter (Cp) score

The WSA approach is a well-known way to address very complex problems to compare land surface systems with similar entities such as watersheds. For this reason, various researchers in the sustainable maintenance and monitoring of sub-watersheds in data deficiency regions have been commonly used (Altaf et al., 2014). In the present study, the compound parameter (Cp) values for each sub-watershed are obtained by adding all the rankings of different parameters indicating linear (ρ, Dd, Fs, Rt, Lg and C) landscape (Rh, Bh, Sb and Rn) and shape (Re, Rf, Rc and Cc) and multiplying with weights calculated of each parameter. Each parameter's weight values were obtained, employing a total of correlations determined by the number of each parameter's (table) correlation coefficient. After that, CP values of each parameter were used for the ultimate preferences score of the 10 sub-watersheds by taking into account Eq. 9 and results shown in Table 11. According to the matrix (see table 6), Lo, C, Rn and Rc have moderate to very high positive correlation (0.50 to 1.00) with most morphometric parameters. In contrast, Rho, Dd, Fu, Rt, Rbm and Cc has moderate to high negative correlation (-0.50 to -1.00) with some of the parameters. The Cp value ranging from high to low ranked ascendingly in order to prioritize the watersheds environmental vulnerability into account. Higher the Cp value receive lower propriety and lower the Cp value assigned a higher priority. Figure 8b showing the spatial ranking of the sub-watersheds in the Kalsa river catchment. The sub-watershed achieving high Cp is ranked greater in terms of importance and has a higher erosion risk and ecological sensitivity. Eventually, final rankings were assigned to each sub-watershed and output are depicted in both visual (Fig. 8b) and numerical (Table 11) fashions indicated that SW3, SW4 and SW9 have the highest Cp value have low priority. In contrast, the sub-watersheds SW6, SW2 and SW5 having the lowest Cp value designated the highest priority from 8 to 10, respectively. The results signify that the major part of the basin is highly susceptible to erosional vulnerability. WS-10, WS-8, WS-2, and WS-1 sub-watersheds prioritize high ranks; sub-watersheds WS-4, WS-6, WS-7 prioritize medium ranks sub-watersheds WS-3, WS-5, WS-9 prioritize low ranks covering about 45.32%, 27.78% and 26.90% area of the Kalsa River watershed, respectively (Table 11 and Table 12). As far as the comparison of performance and output of the both PCA and WSA method is concerned, PCA is found to be most effective methods that enables decision maker to select the most effective parameters for the accurate sub-watershed prioritization evaluation process. The results output of the both methods are very similar but WSA is much time taking and it is not easy to identify the most effective factors in terms of soil erosion.

4. Discussion

The protection of land as well as soil a dynamic biophysical, social and economic issue. There are Inceptisols, Entisols and Mollisols in order of their dominance (SLUSI) with moderately deep to shallow buried soils are found in the watershed. Shallow soils with less vegetative cover are more susceptible to erosion due to fluvial processes throughout the catchment. Both natural and anthropogenic activities affect the degradation of soils, either their bio-physiochemical properties. Soil erosion is due to improper cultivation practices, growth of infrastructure and adverse environmental conditions resulting in land clearance of forests and the conversion of fellow and wasteland in the region (Uddin et al., 2016). The Kalsa Basin suffers from a very high level of land degradation in soil erosion, affecting the soil and contributing to too many adverse effects from sedimentation. The formulation and implementation of erosion control practices for highly vulnerable areas are significant. Erosion prevention techniques should be planned for the most vulnerable areas with the most remarkable effects to maximize their performance. However, the spatial pattern of erosion processes at the sub-watershed level is first to be considered. Field-based monitoring can provide valuable information at a sub-watershed level, but many such studies will be required to cover the basin. However, several studies have been carried out (Malik et al., 2012; Rawat et al., 2015; Khare et al., 2017; Mahapatra et al., 2018) concerning land degradation at various spatial scale. No study has been carried out at the sub-watershed level in Kalsa Basin that can be used to identify priority areas for land conservation practices.

Despite the constraints, the approach provides an advantageous alternate method for recognising areas that are more prone to erosion and less problematic. This area is continuously facing climate change due to anthropogenic pressure in deforestation, intensification of inappropriate agricultural activities and uncontrolled urbanization (Batar et al., 2017). These activities have, in turns, resulting in the depletion of biotic and abiotic resources of the basin. In light of this evidence, the present study's purpose was to prioritise sub-watersheds of the Kalsa River basin, located in the lesser Himalayas, based on various hydro-geomorphological characteristics. Recognition of sensitive areas vulnerable to soil erosion is essential if appropriate land and water management strategies are established and enforced. This task's morphological features were calculated using a more realistic geospatial technique and analysed using the most appropriate PCA and WSA techniques incorporating linear, areal, form and relief aspects. This is the first time in the region that this technique has been used to measure soil erosion at the sub-watershed level in this river catchment, and the framework has certain limitations. Still, it offers a valuable way of defining the priority areas to be identified for intervention to mitigate soil erosion. It also provides a dynamic, cost-effective and sustainable alternative to conventional watershed prioritisation approaches, in which the importance of several characterization parameters was assumed the same. It can be shown that both PCA and WSA are suggesting the same result substantially. A major portion of the catchment is suffering from high to very high soil erosion, and thus urgent attention needs to be paid to restoration and management of it. This problem would become worse under such areas under changing climatic conditions without taking the appropriate steps. Thus, there is an immediate need for integrated watershed management for vegetative and structural controlling measures to minimize the menace of soil erosion (Khare et al., 2017).

The Kalsa basin is extended in the southern Lesser Himalayan region, where Proterozoic (Almora, Ramgarh Groups), Mesoproterozoic (Ramgarh Group), Neoproterozoic (Jaunsar Groups), Paleozoic (Almora Group) and Shiwalik Group is located in the south of Jaunsar Groups are exposed over the basin area and near Kalsa river basin. For precise understanding about the lithological formations and rock, groups are as follows: (a) Almora Group (fine to medium leucocratic granite and granodiorite, mica and chlorite schist); (b) Jaunsar Group (leucocratic to mesocratic biotite granite; medium-grained, leucocratic granite); (c) Ramnagar Group (biotite schist, chlorite schist, quartzite and gneiss); and (d) Shiwalik Group (sandy clay and sandstone, siltstone, claystone) etc. (Fig. 7b). In addition to this, the terrain is sandwiched between Main Boundary Thrust (MBT) and South Almora Thrust (SAT) and rugged due to continuous compression of active tectonics. These formations are highly susceptible to soil erosion and require further study (Kumar et al., 2020). Moreover, geological texture plays a vital role in controlling denudational processes, whereas the tectonic activities and thrusts, faults, and fractures highly create havoc and caused soil erosion. The HI 0.54 indicate early youth stage of the whole basin, which means various fluvial and denudational processes affect the terrain at different scale and extent.

This basin is highly forested, about 1/3rd part of the basin under forest cover and only minimal areas, about 24% of the basin under agriculture, where traditional subsistence agriculture is practised (Fig. 7a). Due to agricultural land abandonment, a large portion of the land is converting land and wasteland, which is highly susceptible to soil erosion (Kumar et al., 2019). Moreover, the economy of the study area mainly depends on agriculture activities, where land is a prerequisite to attain economic sustainability; hence the land management in the entire region, especially the agriculture region, has to be undertaken seriously by the authorities. It became imperative that hilly regions be more vulnerable in land resources due to significant soil erosion and degradation; hence, these areas should be taken up to manage soils by watershed prioritization of the watershed. If the governing bodies would like to restore the agriculture-based livelihood system, they will have forced the agencies to protect the land resources very carefully in these areas. Additionally, the spatial extent of regional land quality improvement has to be considered and integrated into policies ranging from sustainable urbanization to agricultural development.

Therefore, the sustainable management of land resources includes the productivity of land, control of soil degradation, protect soils from pollution and contamination, and combat desertification and restore degraded lands by establishing appropriate management strategies like watershed prioritization region. Soil erosion control measures through watershed prioritization would be very useful in improving groundwater in the long run. After the prioritization of the watershed and its vulnerability were successfully identified, the status of the sub-watershed was stressed at the watershed level. Furthermore, careful environmental preparation for the management of land resources often ensures the sustainability of this valuable resource. In particular, successful land management planning will lead to improved productivity of land, soil erosion controls, and regeneration of the degraded soil for watershed level. Moreover, the database with spatial distribution of various soil and land attributes is a pre-requisite for development of strategic planning of any land development programme. The database on the identification of erodible areas will not only help for rehabilitation planning of degraded lands but will be the vital base for monitoring purposes. The results could be updated to facilitate in identifying the changes being taken place due to dynamic processes that are operating on land.

Soil functions and risks of deterioration are manifold, and measures of soil are complex. For all these reasons, controlling soil erosion and land resources is a major challenge, which needs to be addressed. Current efforts in the direction of regional harmonization of measures to manage soil erosion by prioritizing watersheds suggest their potential fulfilment. The following steps are to completely align and help achieve the SDGs by incorporating this helpful information. In particular, the successful implementation of the sub-watershed prioritization can lead to better management of the land resources in the region (see Table 12).

Finally, it may help to the progress of United Nations (UNs) Sustainable Development Goals (SDGs) pertain to zero hunger (SDG2) by controlling the productivity of land for ensuring sustainable food production by reducing soil degradation and improving soil health for sustain food production in hilly regions (https://www.globalgoals.org/2-zero-hunger) (target 2.3 and 2.4) (UNSDG, 2015). Moreover, healthy soils will support in producing healthy food and protecting health hazards due to soil pollution and contamination. (https://www.globalgoals.org/3-good-health-and-well-being) (target 3.9). The Kalsa river catchment is located in the highly vulnerable and ecologically sensitive region therefore the current assessment will support in strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries ((SDG 13.1); integrating climate change measures into national policies, strategies and planning (SDG 13.2) (UNSDG, 2015).

Improving education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning (SDG 13.3) (https://www.globalgoals.org/13-climate-action). Integrating various hydrological, geological and ecological aspects in the assessment to prioritize the areas for mitigating soil erosion is evitable for combating desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world (SDG 15.3) (UNSDG, 2015). It also ensures the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development (SDG 15.4). (https://www.globalgoals.org/15-life-on-land) (UNSDG, 2015).

5. Conclusion

The present study prioritises ten sub-watershed to assess the erosional land potential based on the linear, areal, and landscape morphometric parameters derived from CartoDEM using advanced geospatial techniques. The basin is situated in the southern part of the Lesser Himalayan region, where diverse lithological and hydro-geomorphological characteristics affect the area's erosion of land and soil. To estimate and compute the erosional potential in all the sub-watersheds of the Kalsa River basin, 16 morphometric parameters comprise linear, areal, and landscape analyzed precisely and accurately by integrating quantitative and spatial techniques with the help of GIS techniques to enhance the reliability of the study. As a morphometric assessment helps demonstrate the salient features of sub-watersheds in hydrological and land erosional processes, areas experiencing severe soil erosion degradation have been recognized for adopting watershed management and soil conservation measures. To enhance the reliability of the study, a comparative study was carried out using PCA and WSA. It is found that both techniques are showing almost similar results with high erosion with some variation in sub-watersheds. Because of the increased vulnerability of the Kalsa basin to erosion, appropriate conservation measures are recommended to reduce soil erosion, minimize sediment production in main channels, and preserve steep slopes that prevent landslides and control future flood potential. The present morphological-analysis-based prioritization also focuses on geological and geomorphological field verification. It is also essential to take appropriate soil erosion control measures in these sub-watersheds to prevent further soil degradation. The study results could also be useful for the water management decision-makers, the rehabilitation planning of degraded lands by taking effective decisions to control soil erosion using the maps and outputs produced in the present study. Prioritization of sub-watersheds is considered a pragmatic approach that can be implemented to watershed management and land and water resources conservation. Moreover, it has significant implications for developing sustainable land management and conservation priorities, which is essential to achieving the societal goals of the United Nation's 2030 agenda for sustainable development.

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Figures

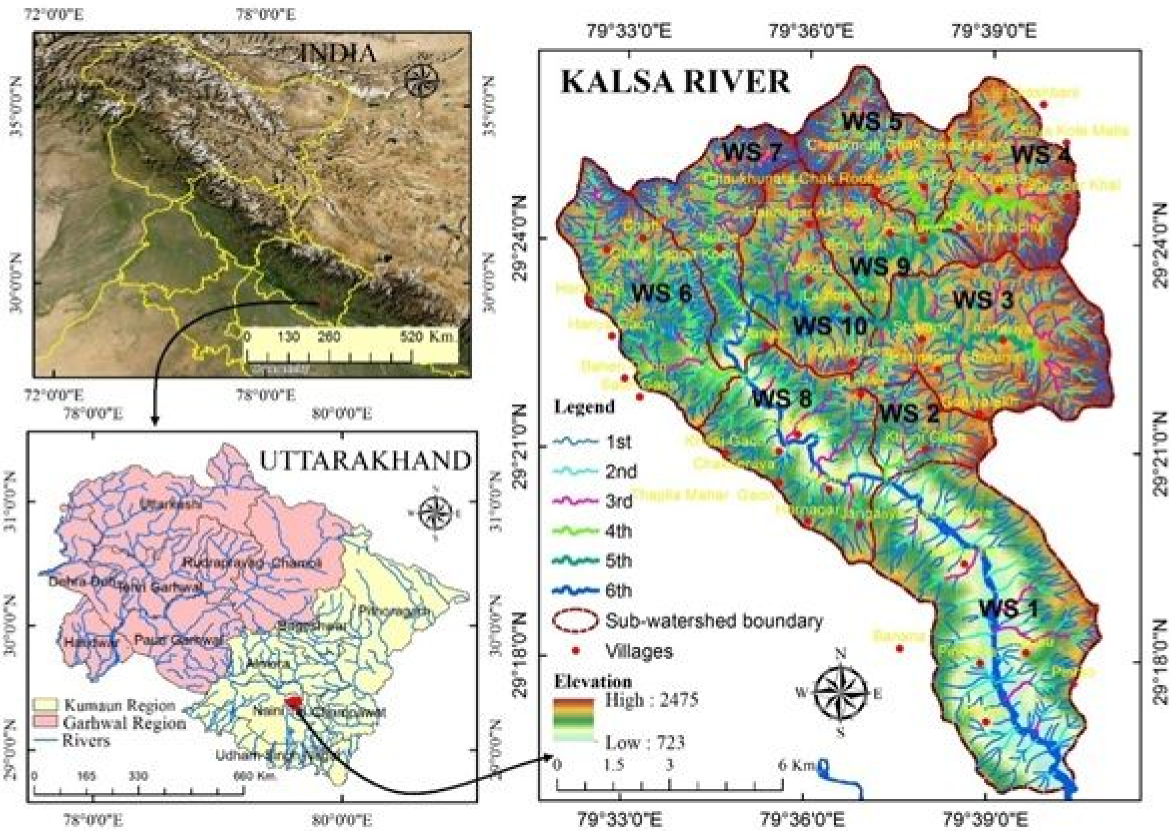

Figure 1

Location of Kalsa River watershed, Uttarakhand, India

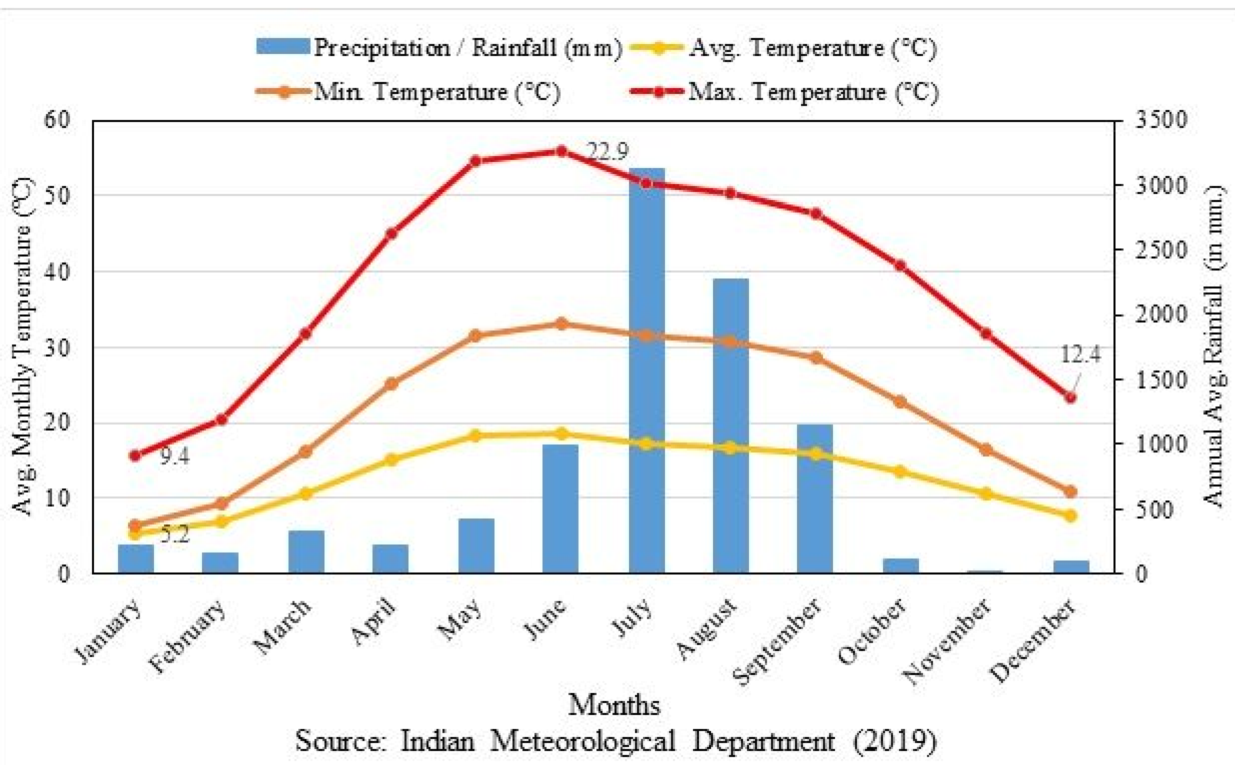

Figure 2

Showing climatic characteristics (e.g., average, maximum and minimum monthly temperature, and monthly rainfall) of the study watershed

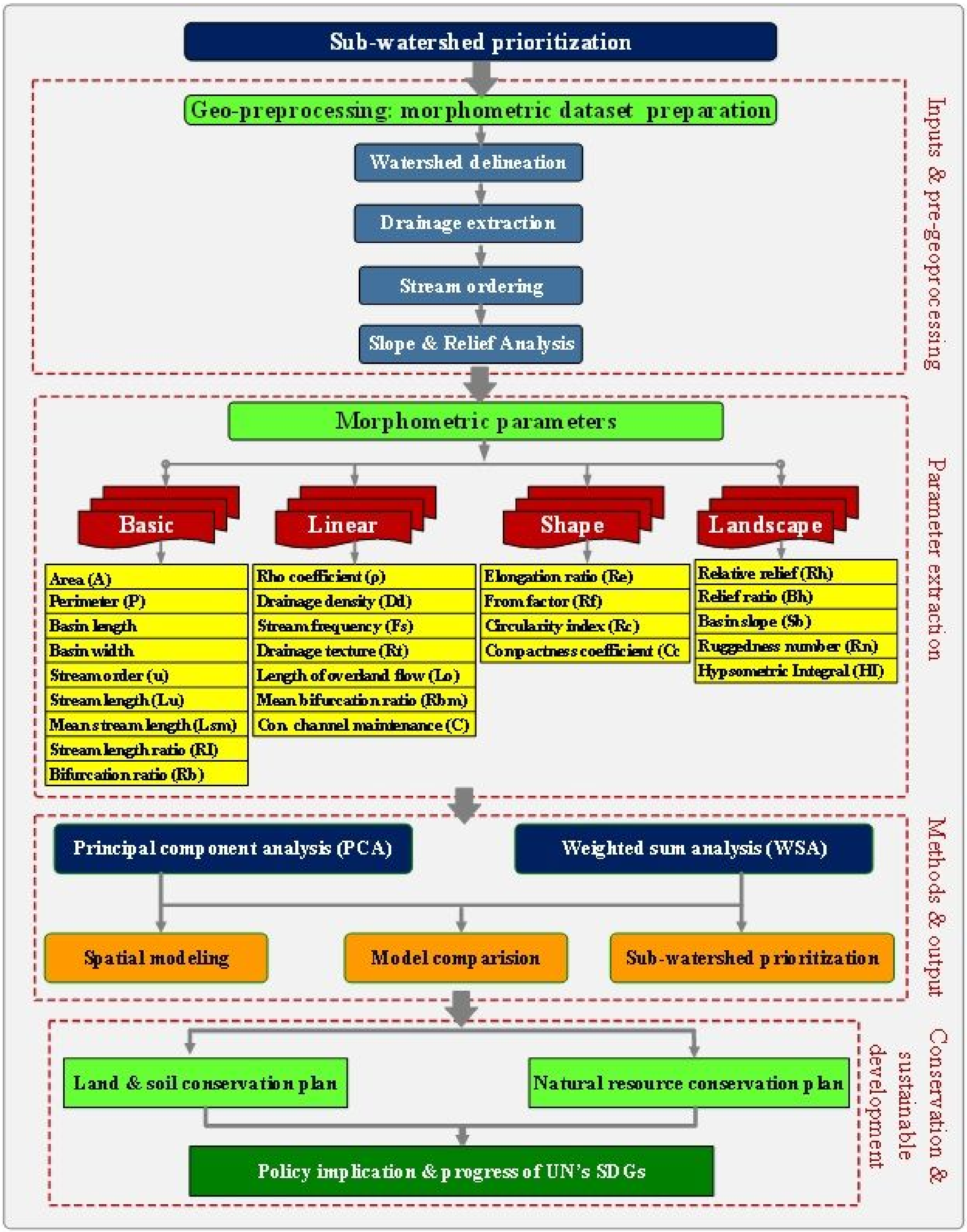

Figure 3

Showing methodological steps for the processing of sub-watershed prioritization

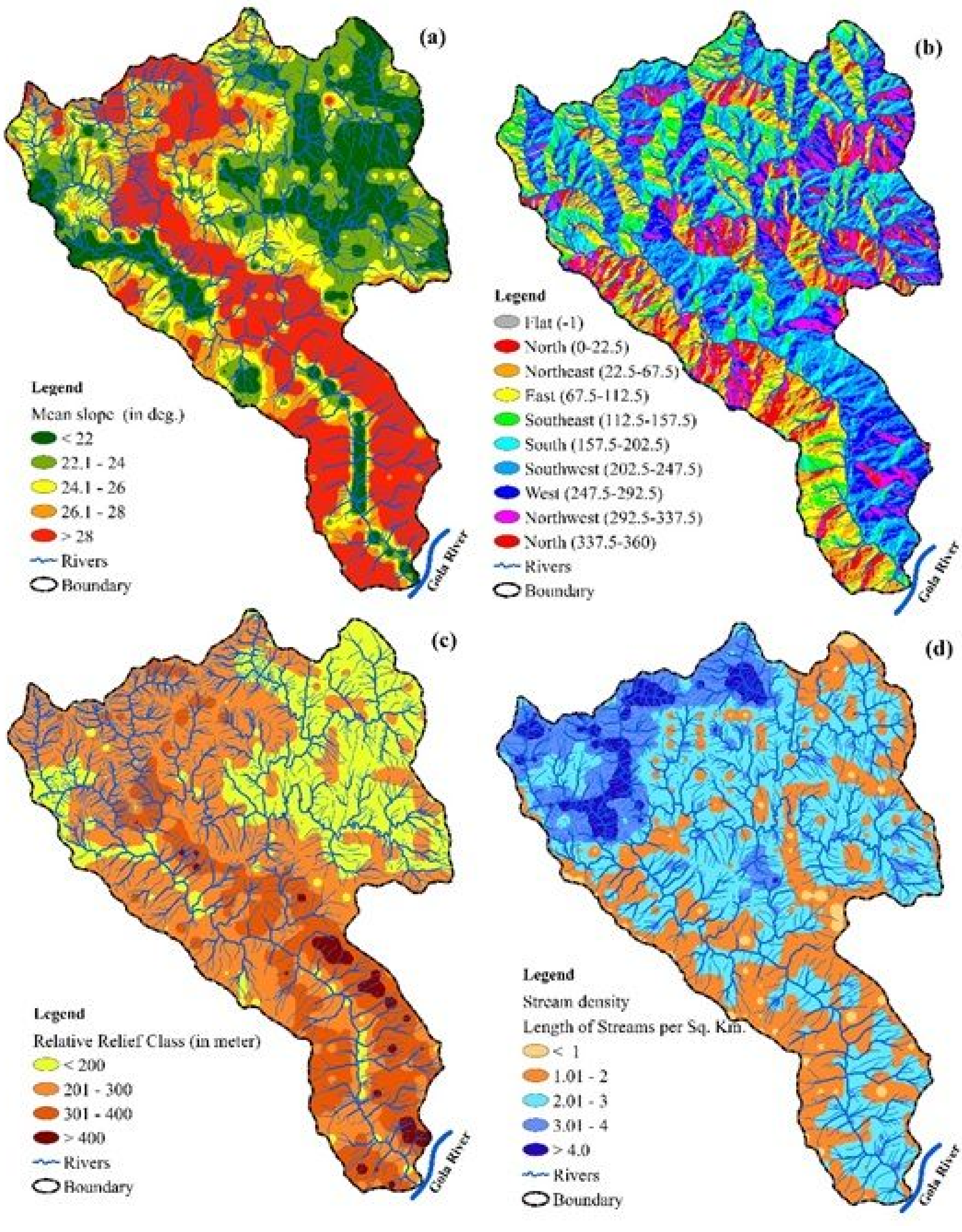

Figure 4

Maps showing (a) slope; (b) aspect; (c) relative relief; and (d) drainage density of the study watershed

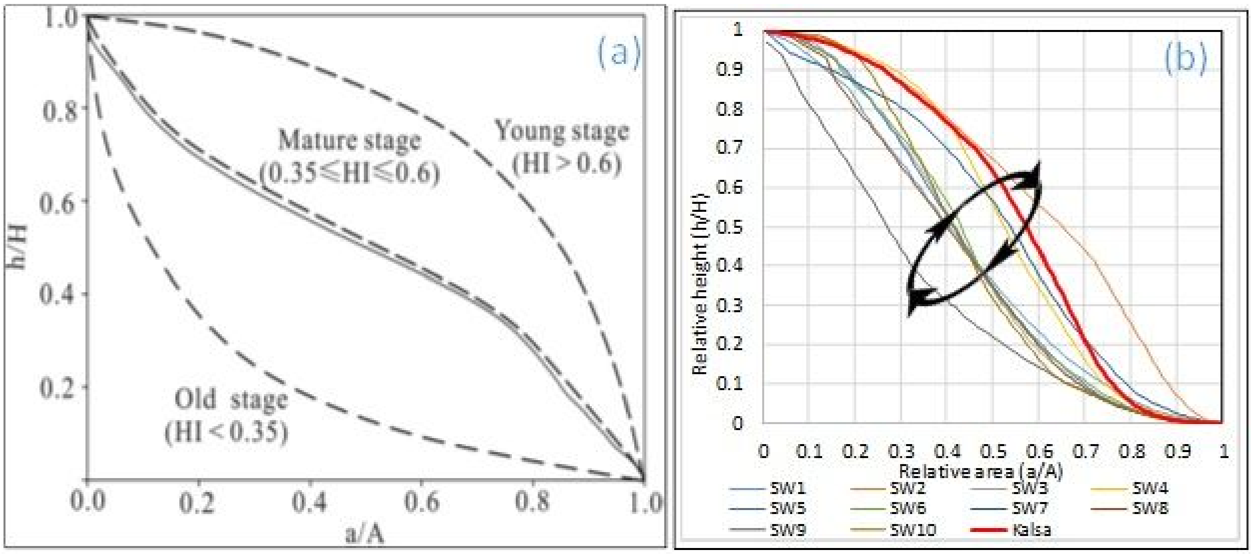

Figure 5

Hypsometric curve showing ideal stages of fluvial development (a); and stages of all sub-watersheds of the catchment (b)

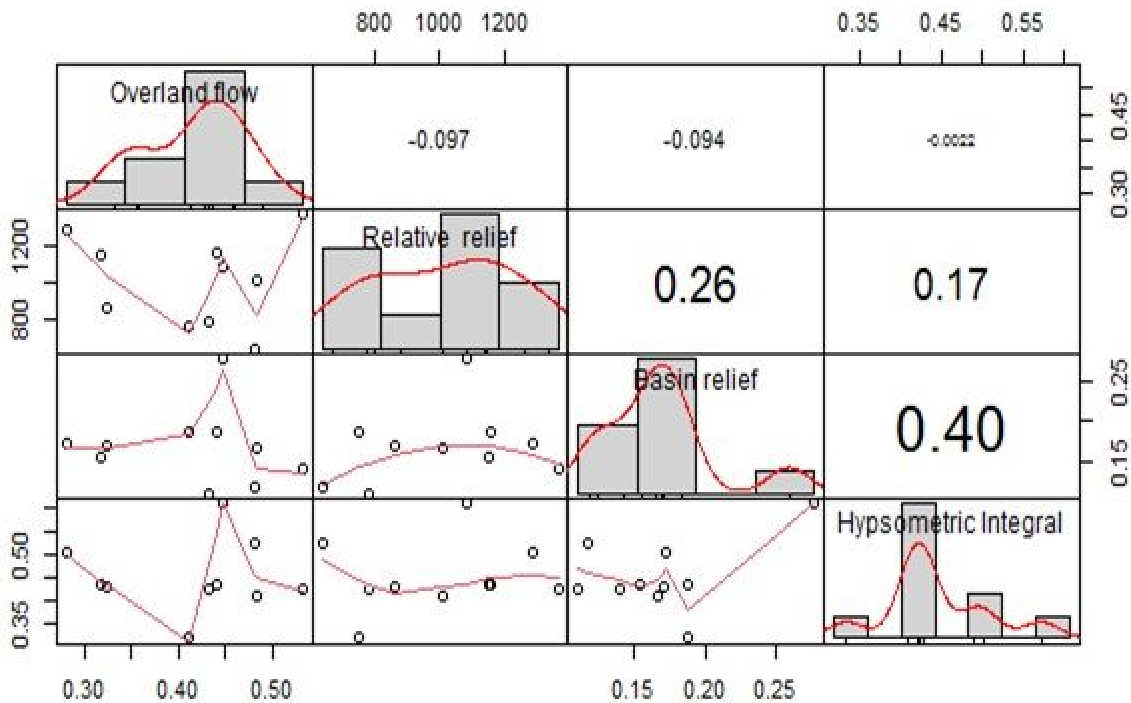

Figure 6

Showing inter-correlation between morphometric parameters used for the prioritization based on PCA method

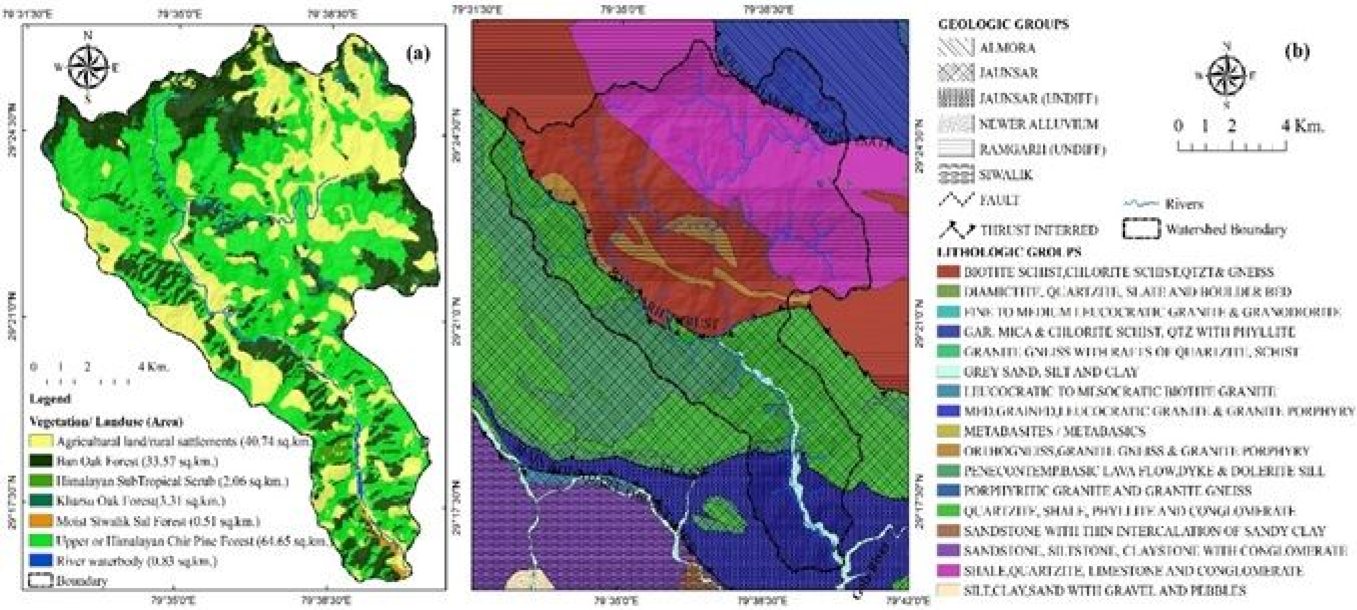

Figure 7

Maps showing land use land cover classification (a); and geological setup (b) of the Kalsa River basin

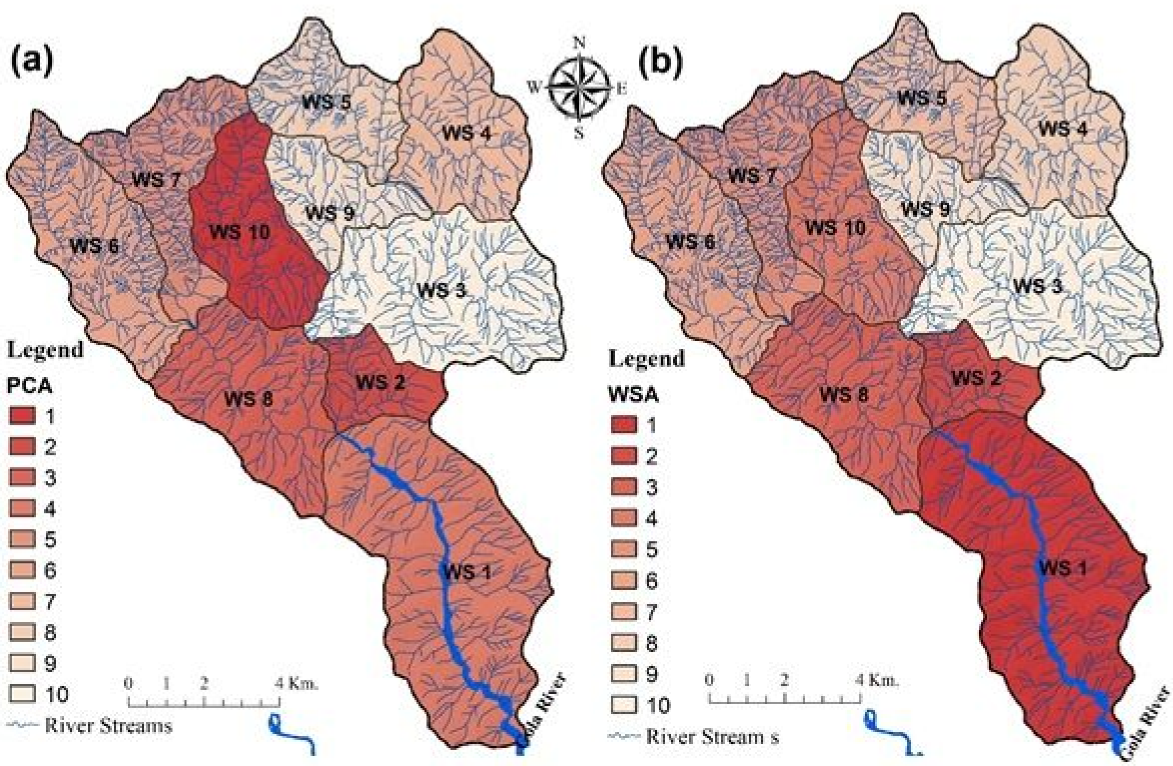

Figure 8

Maps showing prioritization of sub-watersheds in Kalsa river watershed using PCA (a); and WSA methods (b)

Supplementary Files