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Ashwani Kumar Maurya
Research Scholar, Department of Geography, DSB Campus, Kumaun University, Nainital, Uttarakhand, India

Tripathi Manisha
Associate Professor, Department of Geography, DSB Campus, Kumaun University, Nainital Uttarakhand, India

Corresponding Author:
Ashwani Kumar Maurya
Research Scholar, Department of Geography, DSB Campus, Kumaun University, Nainital, Uttarakhand, India

An assessment of geo-ecological richness in the Kalsa river basin (Himalayan region) using RS and GIS techniques

Ashwani Kumar Maurya and Tripathi Manisha

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Abstract
This study evaluates the geo-ecological richness of the Kalsa River Basin, located in the Lesser Himalayas and known for its rich biodiversity and ecological significance. An assessment of geo-ecological richness in the Kalsa River basin in the Himalayas is a comprehensive study that takes into account various attributes related to the watershed's topography, geomorphology, geology, vegetation, and land use. The purpose of this assessment is to understand and quantify the ecological wealth and diversity within the specified geographical area. The study uses remote sensing (RS) and geographic information systems (GIS) along with a multicriteria decision-making (MCDM) method called the Analytic Hierarchy Process (AHP) to look at different aspects of the environment. The study finds four different geo-ecological richness zones. The "Very High Richness" zone covers 19.34% of the basin and has a lot of different types of plants and animals; the "High Richness" area has a lot of resources, mostly forests; the "Moderate Richness" region has a mix of resources and problems, like landslides; and the "Low Richness" region covers 18.34% of the basin and has few resources that are mostly used for farming. Integrating AHP and GIS provides a comprehensive assessment, highlighting areas with significant biodiversity and potential for resource development. These findings offer valuable insights for targeted conservation and sustainable land management practices in the Kalsa River basin.

Keywords: Geo-ecological richness, Kalsa River Basin., Remote Sensing (RS), Geographic Information System (GIS), Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Sustainable land management, Conservation

1. Introduction

Geo-ecology is an interdisciplinary field of study that examines the interactions between the Earth's physical environment (geosphere) and ecological systems (biosphere). It focuses on understanding the relationships and feedback mechanisms between geological, geomorphological, and ecological processes (Naveh, & Lieberman, 2013; Rispoli, 2023) [4, 7]. Vladimir Vernadsky (1926) [12], a Russian mineralogist, geochemist, and bio-geochemist, is widely regarded as the pioneer of geo-ecology. He is renowned for his groundbreaking research on the biosphere, which he defined as the "thin layer of life surrounding the Earth." Vernadsky asserted that the biosphere is a dynamic system constantly evolving, influenced by both the physical environment and the activities of living organisms.

This field of study investigates various aspects, including the distribution of organisms, nutrient cycling, biodiversity, ecosystem functioning, and the impacts of natural and human-induced disturbances on ecosystems. It also examines how ecological systems, in turn, can influence geological processes, such as weathering, sedimentation, and landform development. Geo-ecology plays a vital role in addressing environmental issues, land management, and conservation efforts. By understanding the complex interactions between geological and ecological systems, scientists and policymakers can develop strategies for sustainable land use, biodiversity conservation, and the restoration of degraded ecosystems.

Vernadsky's contributions laid the groundwork for the field of geoecology, which explores the interactions between the Earth's physical environment and living organisms. Geoecology encompasses a broad range of subjects, including the impact of geology, climate, and topography on the distribution of plants and animals, the role of organisms in processes such as weathering, soil formation, and nutrient cycling, and the environmental consequences of human activities.

Other notable figures in the development of geoecology include Frederic Clements, an American ecologist who introduced the concept of the plant community; Arthur Tansley, an English ecologist who coined the term "ecosystem"; Eugene Odum, an American ecologist who pioneered the study of energy flow in ecosystems; G. Evelyn Hutchinson, an American ecologist who focused on the limnology of lakes; and Howard T. Odum, an American ecologist who investigated energy flow in ecosystems.

This study aims to delve into the myriad factors impacting the ecological vibrancy of the Kalsa River basin by weaving together these factors into intricate geospatial layers, we seek to unveil the mosaic of geoecological richness zones within the basin. Employing the robust Analytical Hierarchical Processes (AHP) for Multicriteria Decision Making we endeavor (MCDM), we strive to assign precise weight values to every criterian and sub-criterian, ensuring a methodically standardized approach. Through this comprehensive methodology, we endeavor to illuminate the intricate tapestry of ecological dynamics shaping the Kalsa River basin.

2. Materials and Methods

2.1 Study Area

The Kalsa River originates in the southern slopes of the Lesser Himalayan region as many tributaries. It is known as Kalsa River by combining the Tandi Gad and Ghat Gad tributaries near Padampuri village (Kumar *et al*., 2022) [3]. After flowing south, it eventually enters the Gola River. The Kalsa River watershed is located between latitudes 29° 21' 18.3" N and 29° 20' 14.25" N, and longitudes 79° 39' 04.38" E and 79° 40' 19.50" E. The area spans 145.98 km² and is elongated from NNW to SSE, with an aerial length of 19.36 km from north to south and a width of 14.89 km from east to west, located in Nainital district (Kumaun Region). Its catchment ranges in altitude from 723 to 2475 meters above sea level (Fig. 1). The region is sandwiched between the Main boundary thrust (MBT) and the South Almora thrust (SAT) from south to north, with the Ramgarh thrust passing through the middle of the catchment (Valdia, 1979; Valdiya 2001) [10, 11]. The hypsometric curves of all catchments reflect the watershed's maturity at an early stage. The area has subtropical climatic conditions, with the highest rainfall 1243 mm occurring during the monsoon season (June-September) (Fig. 2). May and January are generally the hottest (23.2 °C) and coldest (1.1 °C) months, respectively; winter is severe since temperatures drop below zero (Fig. 2). Elevation significantly influences the region's climate fluctuation.

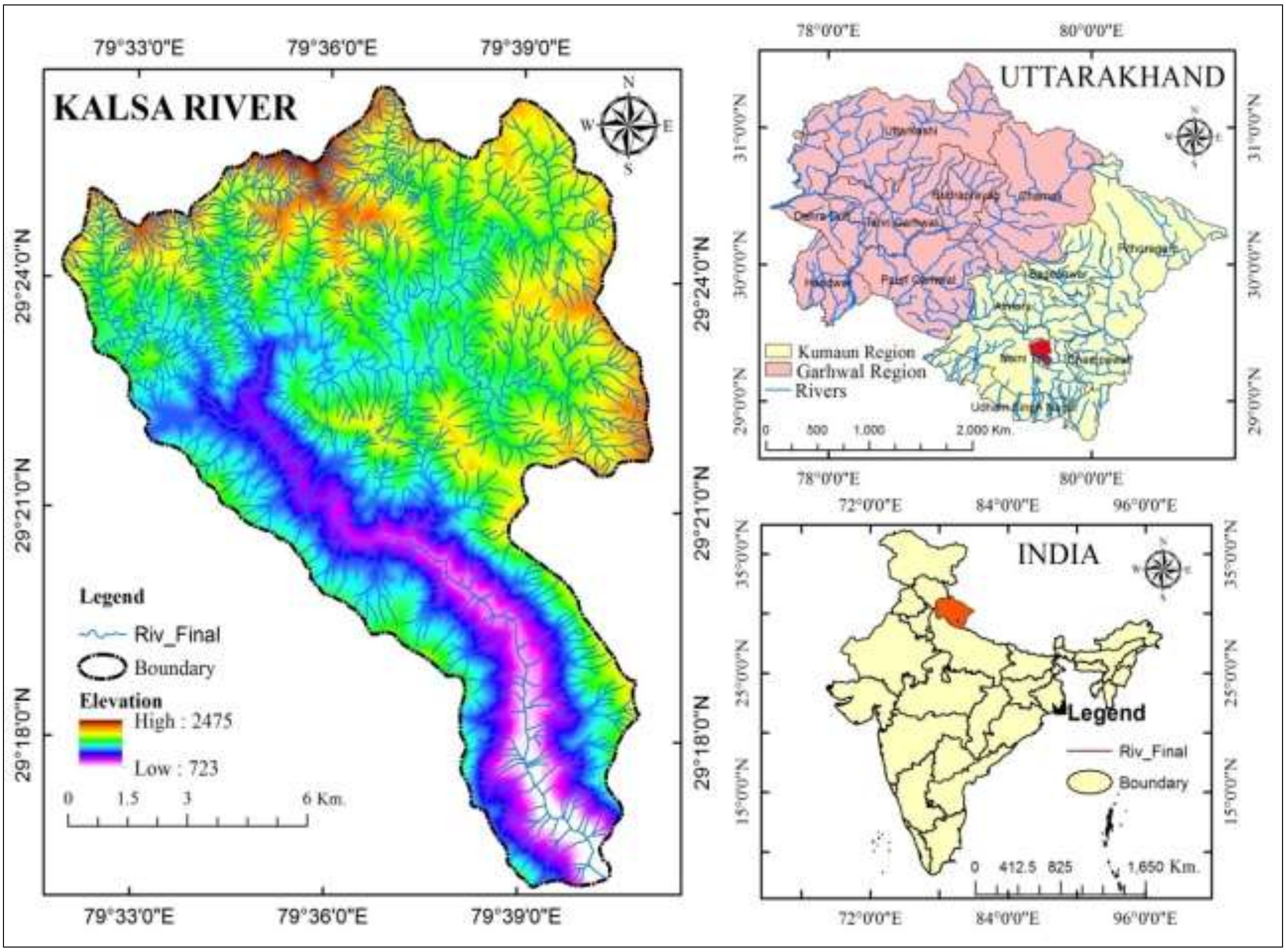
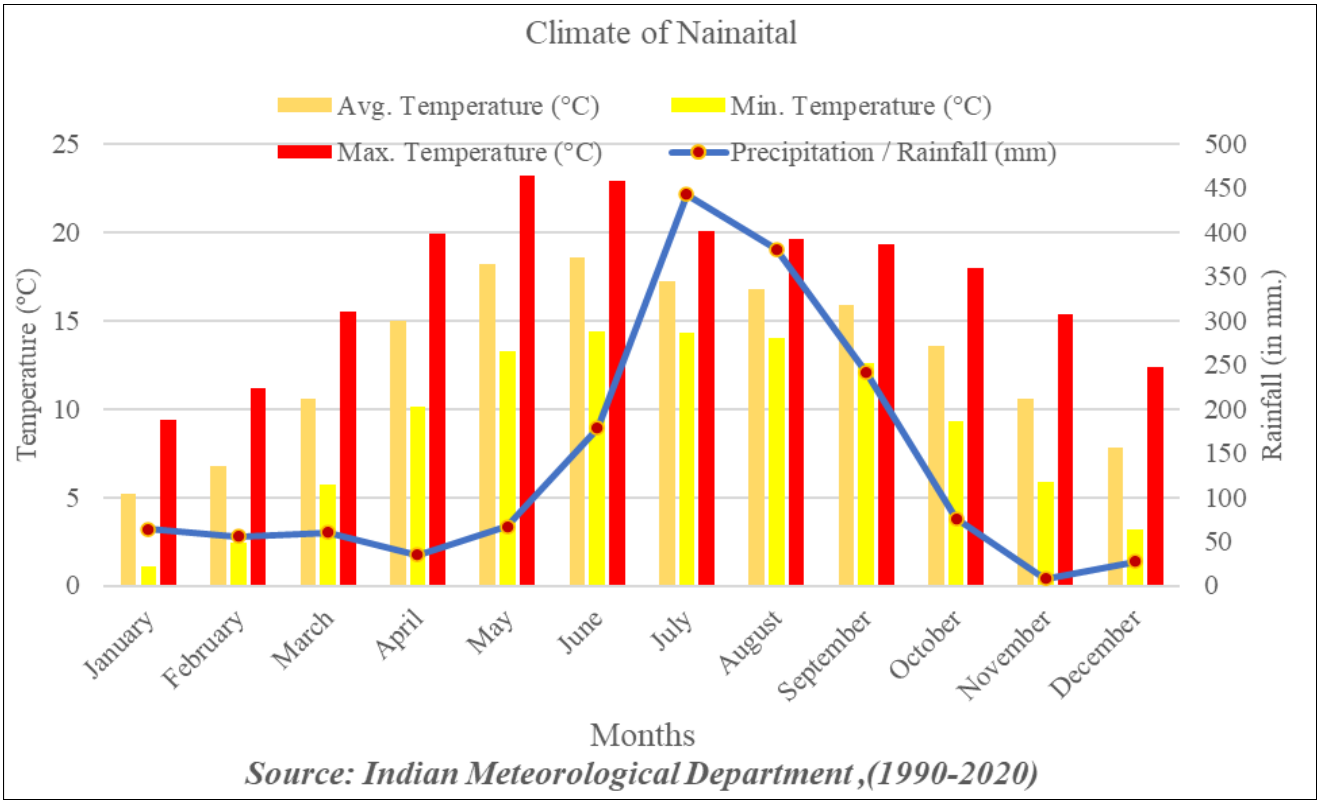


Fig 1: Location Map Kalsa River



Source: Indian Meteorological Department, (1990-2020)

Fig 2: Show Climate of Nainaital

2.2 Data sources

We have used the open series of topographical sheets at a scale of 1:50,000 from the Survey of India (SOI) to determine the size of the basin and other spatial characteristics. Carto-DEM with a 30 m spatial resolution was collected from the Bhuvan portal and was used for the hydrological study (drainage system), relief, slope aspects, and other topographical parameters. The zonal analysis was performed with a pixel size of 1km*1 km to evaluate relative relief, slope, drainage density, stream frequency, drainage texture, and other spatial morphometric parameters. ArcGIS 10.4 was used for data extraction, calibration, processing, and mapping. In regards to rock and formation structures

2.3 Tools and Techniques

After assigning weights and ranks to criteria and their sub-criteria using the AHP method, the input layers were integrated through the weighted overlay method using the equation within the GIS platform, facilitated by ArcGIS software (refer to Figure 1). The following equation was employed for linear scale conversion to transform weights into standardized scores for criteria.

$$LS = \sum_{i=1}^{n} W_i X_i \qquad (7)$$

In equation (1), LS represents the total score of potential land, Wi indicates the weight of the selected land suitability criteria, Xi represents the assigned score of the sub-criteria for the i land potentiality, and n indicates the sum of geo-ecological richness potentiality criteria. The final cumulative map was generated by applying the above equation (7) to integrate the final layers of the criteria, using the weighted overlay tool in ArcGIS software. The cumulative layer was further categorized into four classes of geo-ecological zones: very high, high, moderate, and low geo-ecological richness (refer to Figure 5).

To conduct this assessment, a Multicriteria Decision Making (MCDM) method has been employed. MCDM is an approach that considers multiple criteria simultaneously to make informed decisions. In this case, the focus is on evaluating the geoecological richness of the watershed, which involves a combination of natural and anthropogenic factors.

The specific MCDM method used in this study is the Analytic Hierarchy Process (AHP). AHP is a systematic decision-making technique that breaks down a complex problem into a hierarchy of criteria and alternatives, facilitating the assignment of relative importance or weights to each criterion. It allows for a structured and quantitative evaluation of different factors contributing to the overall geo-ecological richness.

The AHP methodology involves several steps. First, a hierarchical structure is developed, outlining the main criteria (topography, geomorphology, geology, vegetation, and land use) and sub-criteria within each category. Next, pairwise comparisons are conducted to determine the relative importance or preference of one criterion over another (Table 3). This process involves expert judgment or statistical analysis to derive a set of priority values.

2.4 Extraction of Geo-ecological parameters of basin

2.4.1 Elevation

Elevation is a pivotal factor influencing geo-ecological resources in a watershed (Singh *et al.*, 2022) [8]. Its impact is diverse and multifaceted. Higher elevations correlate with cooler temperatures, influencing the types of flora and fauna present. This leads to the formation of distinct vegetation zones, impacting biodiversity. Elevation affects precipitation, contributing to water source formation. It shapes hydrological processes, influencing watersheds and river networks. Different elevations yield distinct soil types, influencing land use. Elevation defines wildlife habitats and contributes to climatic zones. The basin is divided into four distinct elevation zones: the zone below 900 meters, spanning 2.91 sq. km (1.79% of the area) the 901-1500-meter range, covering 37.90 sq. km (23.37%); the 1501-1800-meter zone, encompassing 45.16 sq. km (27.84%); and the elevated areas exceeding 1800 meters, constituting 59.65 sq. km (36.77% of the basin's total area).

Higher elevations are prone to erosion, landslides, and glacier formation, impacting soil stability and freshwater resources. Human settlements, cultural practices, and accessibility vary with elevation. Additionally, elevation attracts tourism and recreational activities, especially in mountainous regions. Overall, elevation's influence on temperature, precipitation, soil, wildlife, and human activities profoundly shapes the geoecological dynamics of a watershed.

2.4.2 Surface Slope

The impact of terrain slope on geo-ecological resources in a watershed is profound, influencing various facets of the ecosystem. Steep slopes intensify water runoff, leading to increased erosion and sedimentation, impacting soil and water quality. These slopes are prone to soil erosion and landslides, causing the loss of fertile topsoil and posing risks to vegetation, infrastructure, and settlements. Microclimate variations, such as temperature, sunlight exposure, and moisture levels, are influenced by slope angles, affecting vegetation distribution and biodiversity. The slope gradient shapes the types of thriving vegetation, potentially limiting plant species diversity and influencing ecosystem composition. Wildlife habitats are affected, with species adapted to specific slope conditions facing distribution and migration challenges. Slope dynamics play a crucial role in water flow, contributing to faster runoff and influencing hydrological processes and water body formation. Land use and agriculture are impacted, as steeper slopes may limit certain activities due to erosion concerns, potentially affecting local livelihoods. Human settlements and infrastructure development are influenced by slope suitability, posing challenges for construction, accessibility, and urban planning on steeper slopes. Ecological connectivity within the watershed is shaped by slope changes, creating barriers or corridors for species movement. Additionally, slope characteristics impact recreational activities and tourism, attracting adventure enthusiasts and contributing to the local economy. Overall, understanding slope effects is vital for effective watershed management and conservation.

To delineate ecological richness zones within the river basin, the surface slope undergoes a reclassification into four distinct categories. The first category, characterized by slopes less than 15°, spans 21.31 sq. km., representing 13.14% of the total basin area. The second category, with slopes ranging from 15.1° to 18°, encompasses about 32.39 sq. km., accounting for 19.97% of the basin. Moving to the third category, slopes between 18.1° and 30° cover an area of 43.41 sq. km., contributing to 26.76% of the basin's total area. Finally, the fourth category, comprising slopes exceeding 30°, extends over 48.51 sq. km., making up 29.91% of the entire river basin.

2.4.3 Geomorphology

The impact of geomorphological attributes, particularly fluvial landscape features, on geoecological resources in a watershed is substantial and diverse. Fluvial landscapes, characterized by rivers and streams, significantly influence hydrological processes, water flow, and the formation of water bodies. These features contribute to sediment transport, erosion, and the formation of fertile floodplains, benefiting agriculture and vegetation. Riverine ecosystems along fluvial landscapes support diverse aquatic and terrestrial species, enhancing biodiversity and providing unique habitats. Riparian zones, influenced by rivers and streams, often harbor distinctive plant communities adapted to changing water levels. The geomorphological diversity of the watershed is shaped by fluvial landscapes, contributing to the formation of various landforms. Fluvial features also influence water quality by transporting nutrients, sediments, and pollutants, necessitating a thorough understanding of ecosystem interactions. Additionally, these landscapes play a key role in regulating flood dynamics, impacting both natural and human systems. Proximity to rivers influences human settlements and infrastructure, offering advantages for transportation and agriculture but also posing risks during flooding. The scenic beauty and recreational opportunities associated with fluvial landscapes attract tourism, contributing to the local economy. Vegetation along riverbanks aids in erosion control, stabilizing soil and preserving the health of fluvial ecosystems. Overall, recognizing the manifold impacts of fluvial landscapes is crucial for effective watershed management and conservation. For the ecological assessment, the whole basin is characterized in to nine major landforms. The predominant landscape within the basin is characterized by Highly Dissected Hills and Valleys, covering a substantial 83.39% of the area, equivalent to 135.25 sq. km. Moderately Dissected Hills and Valleys occupy a smaller, though still notable, portion, comprising about 1.12% of the basin's total area. Additionally, approximately 1.95% of the region is occupied by water bodies found in the main river channels, leaving minimal areas for features such as active flood plains, channel bars, piedmont alluvial plains, ridges, and landslides. These diverse landforms collectively contribute to the overall topographic makeup of the basin.

2.4.4 Lithology

Geological formation profoundly influences various aspects of geo-ecological resources in a watershed. It shapes soil composition, impacting nutrient content and fertility. Geological features affect hydrological processes, including groundwater recharge and water flow patterns. Certain formations give rise to aquifers, influencing groundwater availability and quality. Geological processes shape topography, landforms, and mineral resources, impacting local economies and land use. Vegetation types, biodiversity, and susceptibility to erosion are influenced by geological characteristics. Understanding geological makeup is crucial for land use and infrastructure planning, considering construction practices. Certain formations may contribute to natural hazards like landslides or earthquakes. The geo-ecology of a region is intricately intertwined with its geological history, a narrative that unfolds over time. In delineating ecological zones, due consideration is given to the age of lithological formations. The basin, in its entirety, encompasses rocks from the Neoproterozoic, Mesoproterozoic, Proterozoic, and Meghalayan periods. Consequently, the stability and potential for ecological richness are attributed to older rock formations, whereas newer lithological formations are perceived to have limited opportunities for developing ecological resources within the basin. This holistic approach integrates geological timelines with ecological assessments, providing a comprehensive understanding of the basin's dynamics.

2.5 Vegetation and Landuse

The impact of vegetation and land use on the geo-ecology of a watershed is substantial and varies across different vegetation cover and landuses. Moist Siwalik Sal Forests enhance soil fertility and water retention, preventing soil erosion. Chir Pine Forests influence soil acidity and regulate water flow. Himalayan Sub-tropical Scrub contributes to biodiversity and affects water dynamics. Oak forests, including Ban Oak and Kharsu Oak, stabilize ecosystems, enhance soil fertility, and regulate water flow in watershed management. The Upper or Himalayan Chir Pine Forest covers the largest area (39.86%), while Moist Siwalik Sal Forest have the lowest percentages in the basin region. Water bodies are integral, impacting climate and supporting diverse ecosystems. Agricultural land use directly influences geo-ecology, necessitating sustainable practices to minimize adverse effects.

Table 1: Parameters adopted for geo-ecological richness Indexing

SN	Elevation (m)	AREA (Sq.Km.)	Area in%	Weight
1	< 900	2.91	1.79%	9
2	901-1500	37.90	23.37%	8
3	1501-1800	45.16	27.84%	6
4	>1800	59.65	36.77%	4
SN	**Slope (°)**	**AREA (Sq.Km.)**	**Area in%**	**Weight**
1	<15°	21.31	13.14%	9
2	15.1°-18°	32.39	19.97%	8
3	18.1-30°	43.41	26.76%	6
4	>30°	48.51	29.91%	4
SN	**Geomorphological features**	**AREA (Sq.Km.)**	**Area in%**	**Weight**
1	Waterbody	3.17	1.95%	9
2	Active Flood plain	0.01	0.01%	8
3	Channel Bar	0.03	0.02%	8
4	Piedmont Alluvial Plain	2.11	1.30%	8
5	Terrace	0.95	0.58%	8
6	Landslide	0.32	0.20%	2
7	Moderately Dissected Hills and Valleys	1.82	1.12%	6
8	Highly Dissected Hills and Valleys	135.25	83.39%	4
9	Ridge	1.96	1.21%	4
SN	**Lithological groups (Age)**	**AREA (Sq.Km.)**	**Area in%**	**Weight**
1	NEOPROTEROZOIC	50.35	31.04%	9
2	MESOPROTEROZOIC	42.58	26.25%	8
3	PROTEROZOIC (UNDIFF)	50.53	31.15%	6
4	MEGHALAYAN	2.15	1.33%	4
SN	**Vegetation and Landuse categories**	**AREA (Sq.Km.)**	**Area in%**	**Weight**
1	Moist Siwalik Sal Forest	0.44	0.27%	8
2	Upper or Himalayan Chir Pine Forest	64.65	39.86%	6
3	Himalayan SubTropical Scrub	2.06	1.27%	6
4	Ban Oak Forest (Q.incana)	33.39	20.59%	9
5	Kharsu Oak Forest (Q.Semicarpifolia)	3.23	1.99%	9
6	Ban Oak Forest (Q.incana)	0.18	0.11%	9
7	Water	0.83	0.51%	9
8	Agricultural land	40.74	25.12%	4

Assessment of geo-ecological richness in the Kalsa river basin in the Himalayas is a comprehensive study that takes into account various attributes related to the topography, geomorphology, geology, vegetation, and land use of the watershed. The purpose of this assessment is to understand and quantify the ecological wealth and diversity within the specified geographical area.

Table 2: Showing stepwise detailed assessment of AHP analysis and consistency analysis of method

For a matrix of pairwise elements (Normalization)	$\begin{Bmatrix} C11 & C12 & C13 \\ C21 & C22 & C23 \\ C31 & C32 & C33 \\ \ddots & \ddots & \ddots \end{Bmatrix}$	(Table 6.2)
In step 1, sum the values in each column of the pairwise matrix	$\left[Cij = \sum_{i}^{n} = 1\text{Cij} \right]$	(Equation1)
In step 2, divide each element in the matrix by its column total to generate a normalized pairwise matrix (Synthesized matrix)	$\left[Cij = \frac{Cij}{\sum_{i}^{n} = 1\text{Cij}} \right]$	(Equation 2) (Table 4.5)

	$\begin{pmatrix} X11 & X12 & X13 \\ X21 & X22 & X23 \\ X31 & X32 & X33 \\ \ddots & \ddots & \ddots \end{pmatrix}$	
In step 3, divide the sum of the normalized column of the matrix by the number of criteria used (n) to generate a weighted matrix (priority vector),	$\left[Wij = \frac{\sum_i^n = 1Xij}{n}\right] \begin{pmatrix} X13 \\ X23 \\ X33 \\ \vdots \end{pmatrix}$ $Cv_{11} = \frac{1}{W11} [C_{11}W_{11}+C_{12}W_{21}+C_{13}W_{31}]$ $Cv_{21} = \frac{1}{W21} [C_{21}W_{11}+C_{22}W_{21}+C_{23}W_{31}]$ $Cv_{31} = \frac{1}{W31} [C_{31}W_{11}+C_{32}W_{21}+C_{33}W_{31}]$	(Table 4.6) (Equation 3)
λ_{Max} is calculated by averaging the value of the Consistency Vector,	$\left[\lambda max = \sum_{i-1}^{n} = CVij\right]$	(Equation 4)
In Step 4, CI measures the deviation,	$\left[CI = \frac{\lambda-1}{n-1}\right]$ Where n is a number of criteria used	(Equation 5) (Table 5.10)
	$\left[Cr = \frac{CI}{RI}\right]$ Random Inconsistency indices (RI)	(Equation 6)

Table 3: The preference scale for pair wise comparison in AHP Scale

Scale	Degree of preference	Explanation
1	Two criteria accord equal importance	Two activities lead to the objectives
3	Moderate significance of one aspect to another	Judgments and experience slightly indulge one action to another
5	Strong or essential importance of one parameter over another	Experience and judgments strongly favor one action over another
7	Very strong significance of one parameter over another	An activity is chosen strongly over another, dominance is established in practice
9	Extreme significance of one factor over another	The indication preferring one action over another is of highest probable order of assertion
2,4,6,8	Intermediate values within two nearby judgments	When conciliation is required
Reciprocals	Opposites	Used for inverse comparison

Moreover, this approach combines the analytical power of the AHP method with the spatial analysis capabilities of GIS to comprehensively assess the geo-ecological richness of the Kalsa river basin. The outcome is a nuanced understanding of the varied ecological characteristics and features present in different parts of the watershed, aiding in informed decision-making for conservation and sustainable land management practices.

Table 4: Pair-wise comparison Matrix for Multi- criteria decision-making problem

Criteria	C1	C2	C3	C4	C5
Elevation [C1]	1	2	4	5	6
Slope [C2]	½	1	2	4	5
Geomorphology [C3]	¼	1/2	1	3	4
Lithology [C4]	1/5	1/4	1/3	1	4
Vegetation & Landuse [C5]	1/6	1/5	1/4	¼	1
	2.1	4.0	7.6	13.3	20.0

Table 5: Synthesized matrix for multi-criteria decision making

Criteria	C1	C2	C3	C4	C5	Weight	λ Max
Elevation [C1]	0.47	0.51	0.53	0.38	0.30	0.44	0.92
Slope [C2]	0.24	0.25	0.26	0.30	0.25	0.26	1.03
Geomorphology [C3]	0.12	0.13	0.13	0.23	0.20	0.16	1.22
Lithology [C4]	0.09	0.06	0.04	0.08	0.20	0.10	1.26
Vegetation & Landuse [C5]	0.08	0.05	0.03	0.02	0.05	0.05	0.92
	1.00	1.00	1.00	1.00	1.00	1.00	5.36

Maximum Eigen value (λ) for 5 number of parameters= 5.36
Consistency index (CI) = 0.09
Random Inconsistency indices (RI) Saaty (1980)=1.12 (for 5 parameters)

Consistency ratio (CR) (CI/RI) = 0.081.

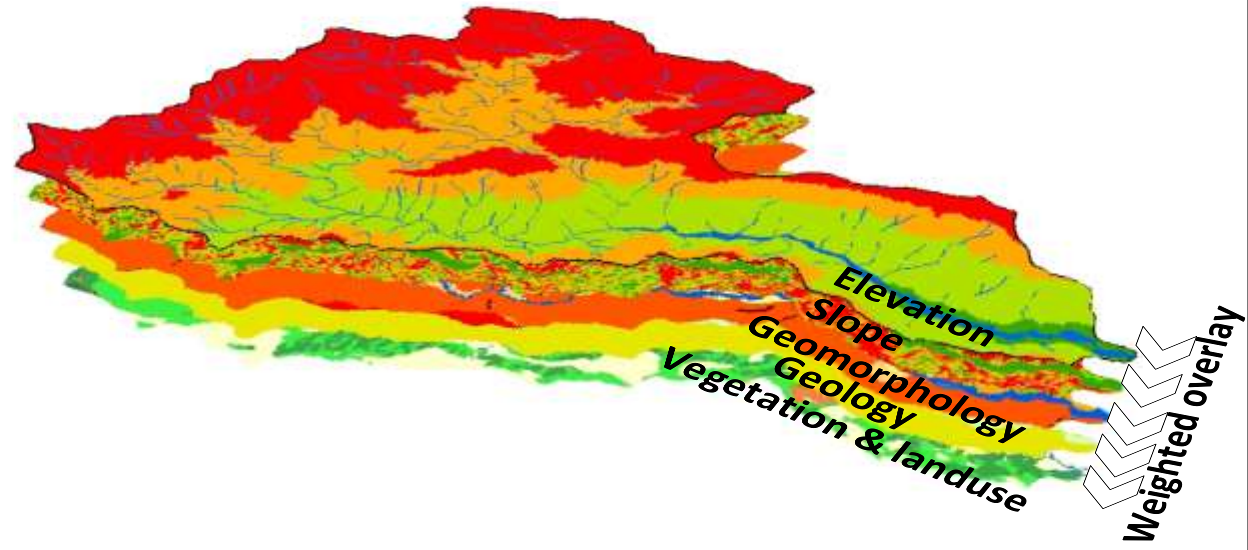
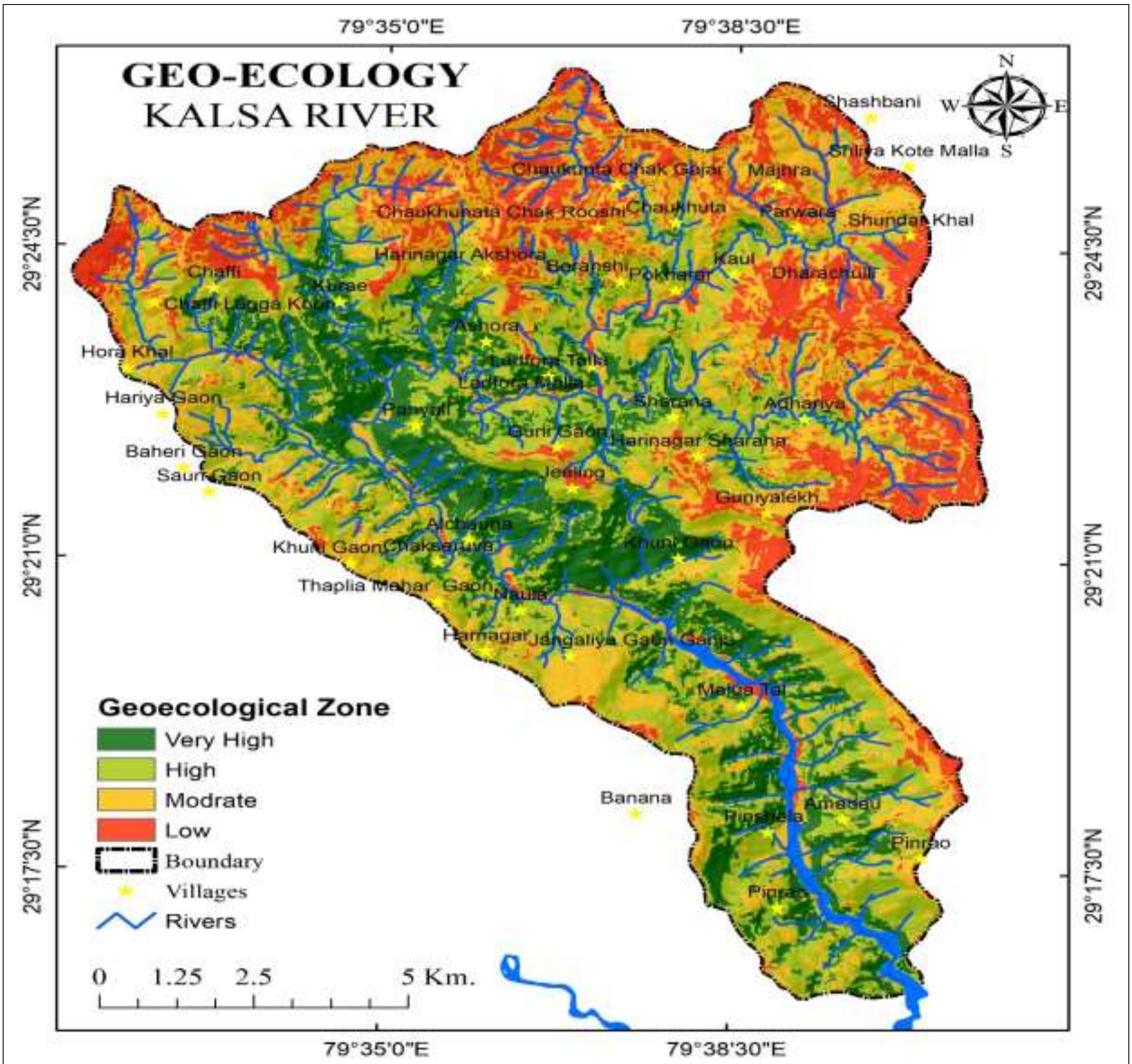


Fig 1: Showing thematic geo-spatial layers used for the weighted overlay analysis to determine the geo-ecological zones



To ensure comparability among the selected criteria layers, a standardization procedure is crucial, requiring uniformity in the measurement unit. This step is essential for comparing scores from different map attributes. The standardization process is executed for each criteria map, converting them into consistent units. The scores lose their dimensionality but become comparable across all criteria. The vector layers, including geology, soils, roads, and rivers, were digitized and transformed into raster layers.

The raster layers underwent categorization for input into the weighted overlay analysis, ultimately generating a map indicating agricultural potentiality. All reclassification and standardization processes were carried out using the spatial analyst tool in ArcGIS. The transformation involved converting criteria characteristics into a range scale from 2 to 9, where 2 signifies the least importance, and 9 indicates the maximum importance (refer to Table 5 and 6). In the Himalayan watershed region, areas with geo-ecological richness are primarily confined to those with rich biodiversity and a suitable environment for resource development.

3. Results

3.1 Geo-ecological zonation

Table 6: Indicating geo-ecological zones and corresponding areal attributes

SN	Geo-ecological richness zone	Area (Sq. Km.)	Area (%)	Remarks
1	Very High	28.07	19.34%	
2	High	45.86	31.59%	
3	Moderate	44.61	30.73%	
4	Low	26.62	18.34%	

Table 7: Indicating areal attribute of geo-ecological zones in different landuse landcover classes

	Ecological Richness Classes				
LULC Types	Very High	High	Moderate	Low	Total
1. Cropland	0.94	4.77	9.03	7.31	22.05
2. Deciduous broadleaved forest	8.85	10.83	7.67	3.06	30.41
3. Evergreen broadleaved forest	1.81	5.85	9.39	8.15	25.20
4. Evergreen needleleaved forest	13.00	18.77	13.12	5.72	50.61
5. Shrubland	3.31	5.30	4.72	1.64	14.97
6. Waterbody	0.15	0.51	0.67	0.58	1.91
Total Area	28.07	46.03	44.59	26.46	145.16

3.1.1 Characterization of zone with very High geo-ecological richness

The zone characterized as having "Very high geo-ecological richness" denotes areas within the watershed that exhibit an exceptional abundance and diversity of geo-ecological resources. These regions are marked by optimal conditions for sustaining a rich and varied array of flora, fauna, and environmental features. The areas confined in the central and lower valley parts of the watershed suggests that these areas are of utmost importance in terms of their ecological significance and potential for supporting diverse ecosystems. This vivid portrayal suggests that the designated area is poised to emerge as a bustling hub of biodiversity, where flourishing natural resources harmoniously coalesce to bolster the robustness and vitality of the entire geo-ecological system. Delving into the spatial dimension, a sprawling 28.07 square kilometers, constituting an impressive 19.34% of the basin, stands testament to the extraordinary richness of geo-ecological resources, painting a picture of an environment teeming with life and ecological abundance.

3.1.2 Characterization of zone with High geo-ecological richness

The zone categorized as having "High geo-ecological Richness" signifies areas within the watershed that boast a substantial abundance and diversity of geo-ecological resources. The side slopes are exhibit favorable conditions for sustaining a diverse array of flora, fauna, and environmental features. Most specifically, the Himalayan Chir Pine Forests and Kharsu Oak Forests (Q. Semicarpifolia) on side slopes hold significant ecological value, contributing to biodiversity and the overall health of the geo-ecological system. While not reaching the level of the very highest richness, these zones still play a crucial role in maintaining a well-balanced and thriving natural environment within the watershed. Exploring the spatial dimensions reveals a vast expanse of 45.86 square kilometers, a remarkable 31.59% of the basin, underscoring the extraordinary wealth of geo-ecological resources. This expansive landscape serves as a region’s exceptional biodiversity, portraying an environment teeming with life and ecological abundance. The intricate interplay of flora and fauna within this sprawling territory creates a captivating tableau, emphasizing the resilience and vitality of the ecosystem.

3.1.3 Characterization of zone with moderate geo-ecological richness

The zone characterized as having "Moderate geo-ecological Richness" indicates areas within the watershed that possess a considerable but intermediate level of geo-ecological resources. On the upper mid-slopes, a captivating mosaic unfolds, characterized by a moderate diversity marked by the presence of Himalayan Sub-Tropical Scrub and Kharsu Oak Forest (*Quercus semecarpifolia*). This region boasts a distinctive floral profile set against the backdrop of rugged terrain. The juxtaposition of these ecological elements not only showcases the resilience of the landscape but also contributes to the unique charm and biodiversity of the area. While not reaching the highest levels of richness, these zones still contribute significantly to the overall ecological balance and health of the watershed. Delving into the spatial dimensions exposes a substantial stretch covering 44.61 square kilometers, constituting a noteworthy 30.73% of the basin. However, this extensive expanse underscores the limitations in geo-ecological resources within the region. The data suggests a critical need for strategic conservation efforts and sustainable resource management to preserve and enhance the ecological balance in this area. They may support a range of biodiversity and maintain a reasonably stable and sustainable environment, making them valuable components of the geo-ecological landscape within the watershed.

In this same zone, significant landslides were observed, primarily along the main channel within the middle part of the basin valley. Geologically, this region is considered unstable due to its complex geological composition. It is situated between the Ramgarh Fault and the South Almora thrust (SAT). The lithology consists of compact rocks such as biotitic schist, chlorite schist, quartz & gneiss, orthogneiss, granite gneiss & granite porphyry, shale, quartzite, limestone, and conglomerate. The middle part of the basin experiences significant disturbance due to human activities, which is evident from their involvement in forest fire events. This has resulted in substantial forest destruction in the region.

Ecofriendly local resource-based treatments – afforestation and horticulture along with mechanical treatments to potentially minimize soil loss rate and the moisture content of soils various measures can be taken, i.e., infiltration hole, small lakes in the way of open water runoff areas, bio-percolation barriers and contour bunding etc.

3.1.4 Characterization of zone with low geo-ecological richness

The zone characterized as having "Low geo-ecological Richness" signifies areas within the watershed with limited abundance and diversity of geo-ecological resources. The northern upper of the basin having absence of vegetation and mainly utilized for agricultural practices by the inhabiting communities exhibit a lower level of ecological richness compared to other zones in the watershed. Exploring the spatial dimensions reveals a significant expanse of 26.62 square kilometers, comprising a notable 18.34% of the basin. Within these areas, there exist challenges in sustaining diverse plant and animal species, making them potentially more susceptible to environmental stressors. This insight underscores the importance of targeted conservation efforts and proactive environmental management practices to safeguard the biodiversity and ecological resilience of these vulnerable regions within the basin. The characterization of low geo-ecological richness zones highlights areas where conservation efforts and sustainable land management practices may be crucial to enhance and restore the ecological balance. Management strategies in these zones should focus on preserving and rehabilitating existing resources to improve overall environmental health.

The sub-watersheds situated in the northeastern part of the basin exhibit moderate slopes, stable lithological conditions, and moderate to sparse forest cover. The landscape characteristics in this zone are characterized by the presence of robust lithological formations, such as porphyritic granite and granite gneiss. A significant portion of the land in these watersheds is utilized for agriculture, which restricts their use for commercial plant production. Terrace farming and the presence of resilient rocks contribute to a lower erosion rate. The combination of undulating terrace agriculture and moderate slopes results in the prevalence of moderately high erosion zones. Instead, they are allocated for recreational activities, wildlife preservation, water supply, or aesthetic purposes. The very limited area of this zone is affected with man-induced forest fire.

It is crucial to avoid excessive land use for intensive agriculture in these areas and encourage farmers to adopt suitable crops that maintain soil fertility. Farmers should be allowed to engage in activities associated with crop production and irrigation in their fields, ensuring the best practices are followed. Implementing social forestry practices integrated with horticulture crops can effectively restore soil conditions and maintain the ecological balance of the region.

4. Discussion

The classification of zones within a watershed according to their geo-ecological richness sparks an important conversation about environmental management and conservation measures. Identifying priority conservation areas, such as zones with very high geo-ecological richness, allows stakeholders to focus their efforts on biodiversity preservation and the maintenance of critical ecosystem services. However, zones of moderate richness pose a distinct problem because, while they may not attract as much attention, they nonetheless require conservation actions to prevent degradation. The vulnerability of zones with low geo-ecological richness highlights the importance of taking action to prevent additional biodiversity loss and ecosystem deterioration in these places. Effective management strategies must include integrated approaches that take into account the unique characteristics and demands of each zone, integrating conservation measures sustainable. landuse practices, and community participation efforts

The discussion also emphasizes the delicate balance between providing for human needs and protecting natural resources. To maintain ecosystems and human community health and well-being in the long run, sustainable development must take into account both environmental and sociological aspects. We cannot stress the value of data-driven decision-making in environmental management. Regular monitoring and assessment of ecosystem health are critical for developing effective conservation plans and adapting management techniques to changing conditions. Understanding the diversity and vulnerabilities of distinct zones within a watershed is critical for designing comprehensive and context-specific conservation and sustainable development strategies. We can endeavor to ensure a healthier and more sustainable future for both natural systems and human society by prioritizing biodiversity conservation, boosting ecosystem resilience, and encouraging stakeholder collaboration.

5. Conclusion

The classification of watershed zones based on their geo-ecological diversity indicates the landscape's diverse environmental demands and conservation goals. Zones with extremely high and high geo-ecological richness are crucial for keeping various flora and fauna and maintaining ecosystem health, while zones with moderate richness necessitate proactive protection to avoid degradation. Low-richness zones, despite being less diverse, require targeted measures to improve ecological resilience and prevent further biodiversity losses. Effective watershed management necessitates customized solutions that address each zone's distinct characteristics. This includes sustainable land use techniques, afforestation, soil protection, the incorporation of local resources, and community involvement. Long-term sustainability relies on balancing ecological preservation with human needs through data-driven decision-making and stakeholder collaboration. Overall, knowing and treating each zone's demands will contribute to the vitality of the entire geo-ecological system, supporting a healthier and more sustainable future for both natural ecosystems and human communities within the watershed.

6. References

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