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Land-use and land-cover patterns of the Himalayan landscape: Goriganga watershed as a case study (Central Himalaya, India)

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Abstract

Mapping and monitoring land use and land cover (LULC) in the Himalayan region are essential for sustainable development planning, ecological assessment and resource management. This study analyses the current (2023) LULC patterns of the Goriganga watershed in the Central Himalayas using field surveys, Google Earth imagery, ALOS PALSAR (12.5 m) elevation data and GIS-based manual classification. The watershed covers 2244 km² and exhibits substantial altitudinal variability (559–7383 m), resulting in distinct ecological and land cover zones. Ten major LULC categories were identified: snow and glacier, barren rocky land, alpine meadows (Bugyals), grassland, forest (dense, moderately dense and scattered), agriculture, built-up land and water bodies. Forests constitute the largest class (34.78%), followed by alpine meadows (27.01%) and snow and glaciers (17.94%). Built-up areas cover only 0.43% of the basin indicating limited human settlement at high elevations. Altitudinal zonation strongly influences spatial distribution, with snow and glacier cover dominating above 4500 m, alpine meadows between 3000–4500 m and agricultural land concentrated below 3000 m. The findings indicate the ecological significance of high-altitude Bugyals and the pronounced vertical stratification of land cover in the Central Himalaya. The updated LULC dataset provides a baseline for future land-use change assessments, environmental monitoring, and sustainable development planning in this climatically sensitive region.
Keywords: *land use, land cover, Goriganga valley, Himalaya, Bugyals*

Introduction

The Himalayas represent one of the world's most ecologically diverse yet environmentally fragile mountain systems. The rugged and undulating topography, diverse climate and complex human environment relationships influenced patterns of land use and land cover (LULC). These patterns are continuously shaped by natural processes and human activities such as agricultural activities, road construction, resource extraction and climate driven environmental changes. Remote and inaccessible terrain and a negligible amount of scientific documentation have left several Himalayan regions underexplored, including the higher reaches of the Kumaun Himalaya.

Land resource is a multifunctional natural entities comprising soil, water, vegetation and associated ecosystems that serve as the backbone for a wide range of human activities (Rahman et al., 2012; Chen et al., 2019; Popescu et al., 2024). In the Himalaya, traditional land-use practices have evolved such as subsistence agriculture, livestock rearing and the utilization of forest resources (Chand et al., 1995). But uncontrolled extraction of natural resources, increasing demographic pressure and infrastructure development have exaggerated land-use transformations, often at the cost of ecological stability.

The advancement of Remote sensing and Geographic Information System (GIS) technology has significantly improved the ability to map, classify and monitor land cover in mountainous terrains (Hathout, 2002; Herold et al., 2003; Lambin et al., 2003; Li et al., 2017). In the context of the Himalayas, several studies have documented LULC changes, including declining snow cover (Negi & Irfan, 2022), glacier retreat (Bajracharya et al., 2014), forest fragmentation (Batar et al., 2017), rising built-up areas (Rasool et al., 2021), and shifts in alpine ecosystems (Pandey et al., 2021). These studies reveal strong elevational gradients that shape vegetation types, land use, and human settlement patterns.

The Goriganga watershed is a geomorphologically complex basin in the higher Central Himalaya but remains insufficiently studied despite increasing research in the Himalayas. Available literature focuses on vegetation, glaciers and biodiversity, although high resolution recent LULC assessments are almost negligible. Considering the environmental and socio-economic changes witnessed in the study area, updated and high resolution LULC mapping is essential for sustainable land management, ecological importance and climate adaptation strategies. Recent studies in the Central Himalaya highlight how topographic limitations, human settlement pressures and climate variability together influence LULC dynamics (Sati et al., 2024). The advancement in cloud processing platforms such as Google Earth Engine have further accelerated Himalayan LULC assessments (Gu et al., 2021), although high-resolution ground-validated mapping remains limited in many higher himalaya including Goriganga. The difficulty of differentiating landuse and landcover types in typical rugged Himalayan terrain has been reported by Aryal et al. (2023), who documented discrepancies between global and local land-cover maps driven by topographic shadowing and mixed pixels.

Objectives of the study

a. To map a detailed LULC map (2023) of the Goriganga watershed using Google Earth imagery, field surveys, and GIS techniques.

b. To classify and quantify major LULC categories and understand their spatial distribution across the watershed.

c. To understand the altitudinal zonation of LULC classes and vertical ecological stratification.

d. Document unique high-altitude land cover categories, particularly Bugyals (alpine meadows) and their ecological significance.

Study area

The Goriganga watershed is located in the eastern part of the Kumaun region of Uttarakhand, India, forming an important component of the Central Himalayan mountain system. The study area is bounded by the international border with the Tibetan Autonomous Region of China to the north and Nepal to the southeast, near the confluence of the Goriganga and Kali Rivers. The Goriganga River originates from the Milam Glacier at approximately 3600 m altitude and flows southward to meet the Kali River at Jauljibi, at an elevation of about 630 m.

The spatial extent of the Goriganga watershed extends between longitudes 79°59′11″ to 80°29′25.95″ E and latitudes 29°44′58.6″ to 30°35′52.74″ N, with a geographical area covering 2244 km², which represents approximately 4% of the total area of Uttarakhand. The basin has significant altitudinal variation, ranging from 559 m to 7383 m at the peak of Nanda Devi East, one of the three prominent >7000 m summits along the upper reaches of the watershed. This dramatic elevation gradient creates a complex mosaic of climatic zones, vegetation types, and land cover classes.

The uppermost region of the watershed lies within the Trans-Himalayan zone, experienced an arid, cold desert environment with scattered vegetation and is mostly covered with glacial landforms. The middle and lower elevations lie in the Higher Himalaya and Lesser Himalaya. It consists of rugged and undulating topography, incised valleys, mixed forest cover, pasture lands and small agricultural terraces. The watershed contains 29 major and medium-sized glaciers that contribute significantly to the perennial waterbodies and geomorphology of the basin.

Because of the diverse terrain characteristics, such as steep slopes, valleys, variable precipitation and differential solar exposure, the region has strong ecological zonation. Different types of Vegetation, from subtropical pine forests at lower elevations to mixed temperate and subalpine forests to alpine meadows (Bugyals) and snowfields at higher altitudes. Human settlements are mostly situated in the lower and mid-altitude zones, where climatic conditions support agriculture, horticulture and pastoral activities.

Methodology

This study employs remote sensing, GIS-based classification and field validation to generate an updated Land Use and Land Cover (LULC) map for the Goriganga watershed for the year 2023. The methodological workflow consists of four main stages: (1) data collection (2) data processing, (3) Landuse and Landcover classification and (4) accuracy assessment and validation.

Data sources

Two primary data are:

• **Google Earth Imagery (2023)**: High-resolution (2.5–4 m) imagery from 2023 was used as the primary source for visual interpretation. Its high spatial resolution is particularly best suited and helps to identify the classes even in mountainous terrain, where automated classification often struggles with shadowing, different spectral reflection of the same features, steep slopes, mixed pixels and snow cover.

• **ALOS PALSAR Digital Elevation Model (DEM), 12.5 m (2007)**: ALOS PALSAR DEM (Scene ID: AP_07405_FBD_F0590_RT1) was used to derive elevation, slope and altitudinal zones.

The Field surveys were carried out in the year 2023 for ground truthing and validation of classification and accuracy assessment.

Data processing

The steps were carried out in ArcGIS 10.8.2:

i. **Georeferencing and projection**: All datasets were brought into a similar coordinate system (WGS 84 / UTM Zone 44N).

ii. **Watershed boundary extraction**: The study area boundary was demarcated using DEM and the spatial analyst tool.

iii. **Preparation of altitudinal zones**: The basin was classified into four altitudinal classes: <1500 m, 1500–3000 m, 3000–4500 m and >4500 m, based on ecological and physiographic transitions.

LULC classification approach

A manual digitization technique was used for Landuse and Landocover classification, changes and landscape changes at a local scale and biodiversity paterns (Piao et al., 2023; Darvishi et al., 2024). This method was chosen over automated supervised or unsupervised classification due to the following reasons:

• High undulating, rugged terrain and shadow effects in the Himalayas often misinterpret the features and affect the accuracy of automated classifiers.

• Higher visual interpretation potential to identify in comparison to spectrally similar categories (e.g., alpine meadows vs. grasslands).

• High accuracy supported by field photographs and observations.

Digitization of the polygon was performed at scales ranging from 1:3000 to 1:8000, depending on terrain complexity. Each polygon was carefully delineated through on-screen interpretation supported by field notes.

LULC classes identified

Ten LULC classes were mapped: Snow and Glacier, Barren Rocky, Alpine Meadows (Bugyals), Grassland, Dense Forest, Moderately Dense Forest, Scattered Forest, Agriculture, Built-up Area and Water Bodies. The classification was based on vegetation density, surface characteristics, landform type and field validation inputs.

Field data collection and validation

Fieldwork was carried out during the 2023 summer season across accessible locations of the watershed. Ground truth data included: GPS locations of different LULC types, Field photographs, Identification of vegetation type, different landforms and land use types and seasonal variations in alpine and subalpine zones.

These ground reference GPS points were used both to refine the classification and to improve the accuracy assessment.

Accuracy assessment

An error/confusion matrix was constructed using field-collected and verified sample points representing each LULC class. A minimum of five validation points per class was considered, consistent with field accessibility limitations in high-altitude terrain. Accuracy metrics computed include User's Accuracy (UA), Producer's Accuracy (PA), Overall Accuracy (OA), and Kappa Coefficient (κ). The standard formulas for OA and κ were applied to evaluate classification performance.

Results

Relief and terrain characteristics

The Goriganga watershed spans a highly varied topographic region of the Central Himalaya, extending from approximately 559 m to 7383 m above sea level (Fig. 1). The upper portion of the basin encompasses parts of the Trans-Himalayan and Higher Himalayan ranges, dominated by glacial landforms, steep rocky slopes, and perennial snow cover. The southern and middle elevations are characterized by rugged, undulating terrain with deeply incised valleys, mixed forest cover, and terraced agricultural fields. The river originates from the Milam Glacier and flows southwards, forming a major fluvial corridor through the watershed. This substantial altitudinal gradient shows strong control over climatic conditions, vegetation types and land-use patterns in the region.

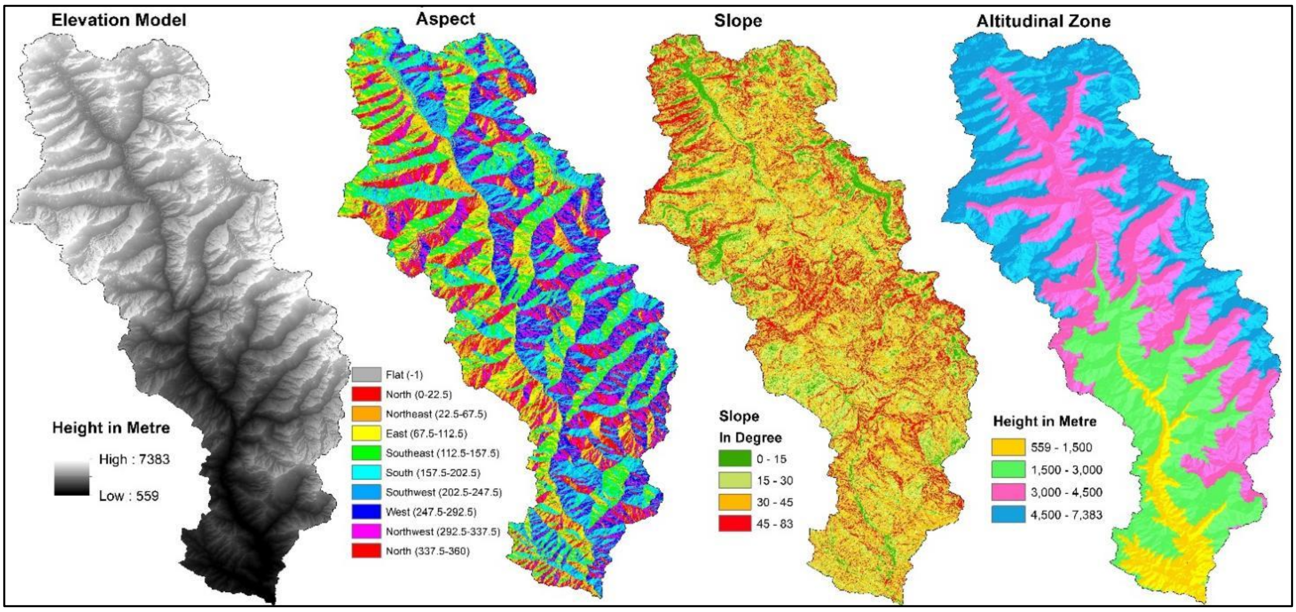

Figure 1: Illustrates the relief parameters of the Goriganga basin

Land Use and Land Cover (LULC) classification (2023)

The total geographical area of the Goriganga watershed is 2244 km². Based on visual interpretation of Google Earth imagery, supported by field validation, ten major LULC categories were delineated (Table 1, Fig. 2). The watershed exhibits distinct spatial distributions of natural vegetation, agricultural land, built-up areas, and cryospheric features due to its elevational and geomorphological diversity.

Table 1: Current status of Landuse and Landcover (2023)

Sl. No	Classes	Area (Km²)	In %
1	Snow and Glacier	402.58	17.94
2	Barren Rocky	303.83	13.54
3	Agriculture	78.14	3.48
4	Dense forest	279.14	12.44
5	Moderately Forest	153.63	6.85
6	Scattered Forest	347.58	15.49
7	Built-Up	9.57	0.43
8	Waterbody	10.31	0.45
9	Alpine Medows	606.03	27.01
10	Grassland	53.20	2.37
Total		**2244.00**	**100.00**

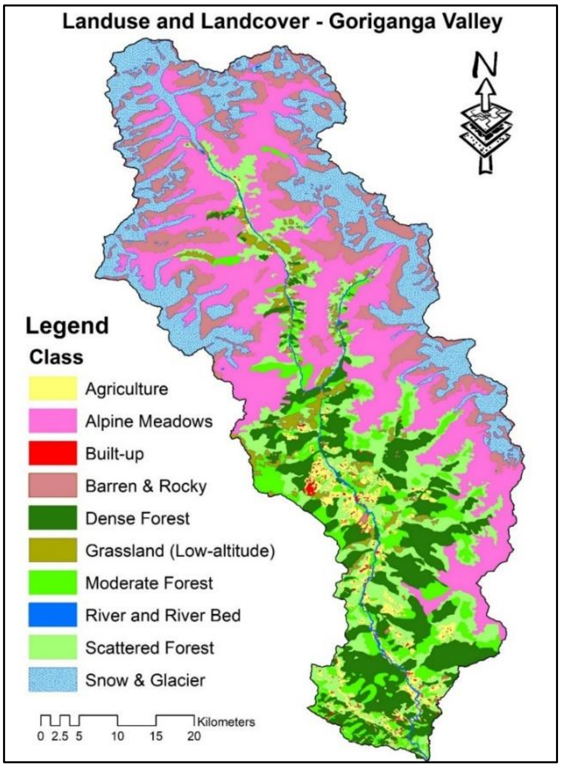

Figure 2: LULC Map (2023) of Goriganga watershed, Central Himalaya, India

Forest cover

Forests constitute the largest LULC class, collectively covering 780.35 km² (34.78%) of the watershed. Forests were classified into three density categories:

- **Dense forest**: 279.14 km² (12.44%). Characterized by high canopy density, dominated by species such as *Pinus wallichiana*, *Betula utilis*, *Quercus semecarpifolia*, *Drepanostachyum falcatum* and other temperate taxa. These forests are mainly distributed between 1500–3000 m elevation (Fig. 3).
- **Moderately dense forest**: 153.63 km² (6.85%). Represents intermediate canopy cover, occurring in transitional zones.
- **Scattered forest**: 347.58 km² (15.49%). Characterized by sparse tree cover and shrub vegetation, typically located in drier or steeper slopes.

Figure 3: Dense forest of Atthasi Reserve Forest near village Ringu (30.119101°; 80.345438°; Altitude: 2450 – 3450m; Species: *Pinus wallichiana, Betual utilis, Quercus semecarpifolia, Quercus leucotricophora, Drepanostachyum falcatum* etc.)

Snow and glacier

Snow-covered areas and glaciers occupy 402.58 km² (17.94%) of the watershed, dominating landscapes above 4500 m and associated with major glacier systems such as Milam, Lwa, Sangkalpa, and Shalang (Fig. 4, Table 1).

Figure 4: Snow-capped Mountain and Lateral Moraine visible of Kathapu Glacier (Panchachuli Mountain Group; 30.185167°; 80.465554°; Altitude: 6904m)

Alpine meadows (Bugyals – a unique LULC class)

Alpine meadows (Bugyals) comprise 606.03 km² (27.01%) of the watershed. They are primarily distributed between 3000 – 4500 m, forming unique high-altitude ecosystems dominated by herbaceous vegetation. These meadows support seasonal grazing activities and host diverse medicinal and aromatic plant species.

Bugyals are ecologically and culturally significant high-altitude meadows that regenerate rapidly in the short summer season, supporting species of medicinal value like *Picrorhiza kurrooa*, *Aconitum heterophyllum*, *Ophiocordyceps sinensis* and providing grazing grounds for Himalayan ungulates and pastoral herds. Despite the challenging high-altitude conditions that keep it covered with snow for 6-9 months annually, the Bugyals of Goriganga demonstrate remarkable resilience. The snowfall, usually starting in September-October and melting at the beginning of April, triggers the growth of fresh grasses, a testament to the adaptability of this unique habitat.

The Bugyals are rich in biodiversity, both in flora and fauna. The grasses fed the herbivores viz, blue sheep and Himalayan Thar and herb diversity is also rich in this area with medicinal values. The burials are considered a storehouse of valuable herbs; the most demanding is keedajadi (*Ophiocordyceps sinensis*), which grows above 3500 m to 5000 m. The Bugyal land here is used as pasture along with keedajadi. Local shepherds take their sheep to Bugyals in April-May and return in August-September (Fig. 5).

Figure 5: Bugyal (Alpine Meadows) with domesticated sheep grazing the land (Place: Nagni Dhura; 30.142175°; 80.297771°; Altitude: 3650 – 4000m)

Barren rocky land

Barren rocky terrain occupies 303.83 km² (13.54%) (Fig. 6), typically situated below snow-covered zones and above forested slopes.

Figure 6: Barren Rocky Mountain with seasonal snow (Location: Hansling Peak; Altitude:5163m ;30.239454° and 80.249017°)

These areas are characterized by loose rock debris, exposed bedrock, steep gradients and minimal vegetation.

Agriculture

Agricultural land covers 78.14 km² (3.48%) (Fig. 7), concentrated primarily along valley floors and river terraces below 3000 m. Cropping systems include potato, wheat, mustard, and horticultural produce.

Figure 7: High altitude Agriculture Land (Milam Village; 30.434053° and 80.151732°; Altitude: 3440m; Major Crops: Pottato, Wheat, Mustard etc.)

Built-up areas

Built-up land accounts for 9.57 km² (0.43%) (Fig. 8), representing small settlements and rural infrastructure, mainly located at lower elevations.

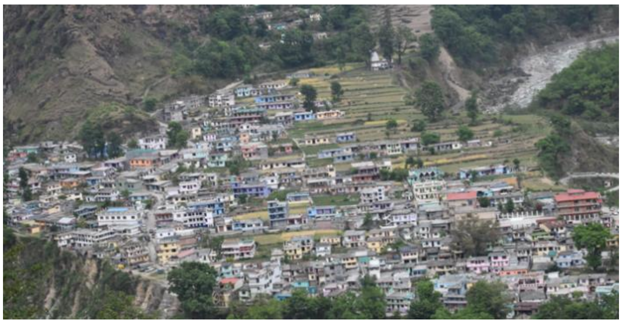

Figure 8: RCC buildings in Madkote Village (30.058650° and 80.293514°; Altitude:1270m)

Water bodies

Water bodies, including rivers and high-altitude lakes (e.g. Kedarkund, Patoti Kund, Kulkakund), cover 10.31 km² (0.45%). The Goriganga River is the primary hydrological feature, originating from the Milam Glacier.

Grasslands (Grazing lands)

Grasslands cover 53.20 km² (2.37%), supporting seasonal pastoral activities and acting as transitional zones between forest and alpine ecosystems (Fig. 9).

Figure 9: Grassland (Near Chulkot Dhar; 30.239454° and 80.249017°; Altitude: 2244m)

Accuracy assessment

The classification accuracy was evaluated using a confusion matrix derived from field-verified sample points (Table 2). User's and Producer's Accuracy values were calculated for each class. Overall Accuracy and Kappa coefficient were computed to assess classification performance. The accuracy assessment confirms that manual digitization, supported by high-resolution imagery and field validation, yields reliable LULC mapping for this complex high-relief terrain.

Errors are calculated using confused matrix (Table 2). The confused matrix is: -

$$Kappa\ Coefficient(T) = \frac{TS\ \times TCS - \sum(Column\ Total\ and\ Row\ Total)}{TS^2 - \sum(Column\ Total\ and\ Row\ Total)} \times 100$$

'Ts' is Total number of samples and 'TCS' is total number of correctly identified samples.

$$Kappa\ Coefficient = \frac{50\ \times 45 - (100)}{2500 - (100)} \times 100$$

Kappa Coefficient = 89.58 % Overall Accuracy

Table 2: Accuracy assessment of LULC

Class	Ag	AM	BR	Built-Up	DF	GRS	MF	SF	SG	W	User Accuracy
Agriculture (Ag)	5	0	0	0	0	0	0	0	0	0	5
Alpine Medows (AM)	0	5	0	0	0	0	0	0	0	0	5
Barren Rocky (BR)	0	0	5	0	0	0	0	0	0	0	5
Built-Up	0	0	0	5	0	0	0	0	0	0	5
Dense forest (DF)	0	0	0	0	5	0	0	0	0	0	5
Grassland (GRS)	0	0	0	0	1	3	1	0	0	0	5
Moderate forest (MF)	0	0	0	0	2	0	3	0	0	0	5
Scattered forest (SF)	0	0	0	0	0	0	0	5	0	0	5
Snow and Glacier(SG)	0	0	0	0	0	0	0	0	5	0	5
Waterbody (W)	0	1	0	0	0	0		0	0	4	5
Producer Accuracy	5	6	5	5	8	3	4	5	5	4	50

Table 3: Data shows the altitudinal distribution of LULC and the % contribution in the basin area

Agriculture	Area (Ha)	In %	Area (Ha)	In %	Area (Ha)	In %	Area (Ha)	In %	Area (Ha)	In %
	-	42.67	-	53.41	-	3.92	-	-	-	100
	3333.68	19.30	4174	8.51	306	0.38	-	-	7813.68	3.48
Alpine Medows	-	-	-	0.57	-	74.37	-	25.06	-	100
	-	-	345	0.70	45064.6	56.45	15192.6	19.38	60602.2	27.01
Barren Rocky	-	0.79	-	0.81	-	6.22	-	92.18	-	100
	223.8	1.30	245.65	0.50	1901.2	2.19	28012.65	35.72	30383.3	13.54
Built-Up		37.64		60.03		2.33				100
	360.1	3.61	574.25	1.17	22.3	0.03	-	-	956.65	0.43
Dense forest	-	20.17	-	69.84	-	9.99	-	-		100
	5630.8	32.50	19495.14	39.73	2788	3.41	-	-	27913.94	12.44
Grassland	-	0.12	-	45.87	-	54.01	-	-	-	100
	6.27	0.03	2440.3	4.97	2873.5	3.51	-	-	5320.07	2.37
Moderate Forest	-	17.92	-	48.24	-	33.83	-	0.01	-	100
	2753.2	15.01	7410.7	15.10	5197	6.42	1.83	0.00	15362.73	6.85
Scattered Forest	-	12.68	-	40.98	-	46.33	-	0.01	-	100
	4409.4	25.25	14241.3	29.02	16102.8	21.00	5.28	0.01	34758.78	15.49
Snow and Glacier	-	-	-	-		12.61	-	87.39	-	100
	-	-	-	-	5076.6	6.21	35181.4	44.87	40258	17.94
Waterbody	-	50.24	-	14.00	-	33.94	-	1.82		100
	517.75	3.00	144.3	0.30	349.8	0.40	18.8	0.02	1030.65	0.45
Total		7.68		21.88		35.50		34.94		100
	17235	100	49070.64	100	79681.8	100	78412.56	100	224400	100

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Altitudinal distribution of LULC

Altitudinal gradients strongly influence LULC distribution. The basin was divided into four elevation zones: <1500 m, 1500–3000 m, 3000–4500 m, and >4500 m. Notable patterns include:

a. **<1500 m**: dominant dense forests, agriculture, scattered forest and built-up areas;

b. **1500–3000 m**: peak forest cover (dense and moderate);

c. **3000–4500 m**: dominance of alpine meadows and grasslands;

d. **>4500 m**: snow, glacier, and barren rocky land dominate.

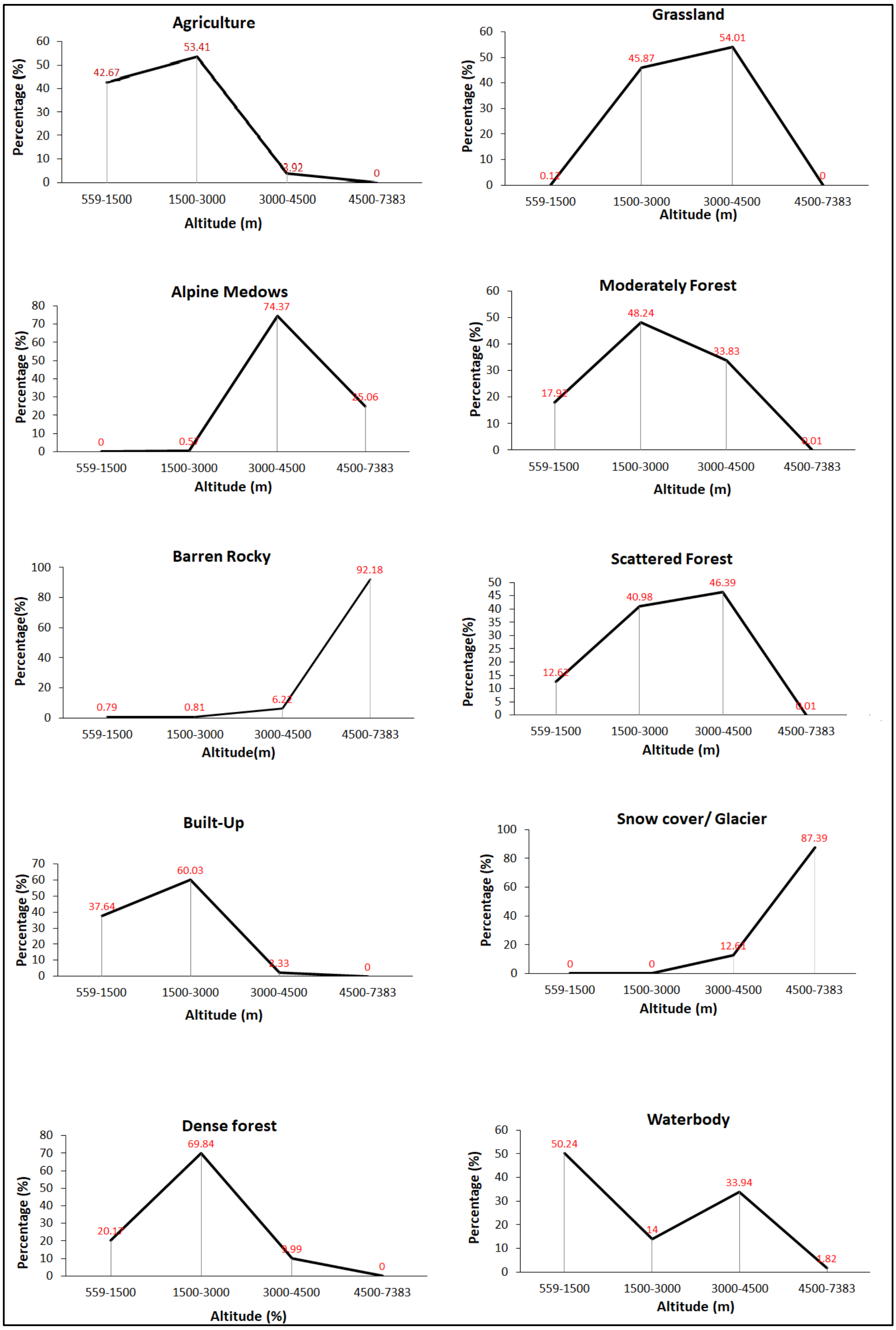

Figure 10: Percentage share of LULC in different altitudinal zone

Discussions

The Goriganga watershed shows a highly heterogeneous pattern of LULC, shaped primarily by its extreme altitudinal variation, rugged terrain, and climatic gradients. The results highlight the dominance of forest cover (34.78%), significant alpine meadows (27.01%), and extensive snow and glacier cover (17.94%). These findings align with other Himalayan studies emphasizing vertical stratification of vegetation and land-use distribution (Pandey et al., 2021; Chand et al., 2022).

Himalaya is known for its resources, and despite having a fragile ecosystem, there is continuous extraction of its resources. The Himalayan ecosystem is also widely threatened because of global climate change, which is directly affecting livelihoods (Chand et al., 2022). The Himalayan population has almost doubled from 550 million to 1050 million between 1975 and 2015, and 66% of its people live in urban areas (Hussain et al., 2023). Due to anthropogenic activities, changes in land use are prominent, but the region's major driver is climate change (Gogoi et al., 2019).

Land use in the Great Himalayan range has also observed because of climate change and the exploitation of natural resources over the decades, such as the growth of the tourism industry in the Himalayan region (Hussain et al., 2023). Alpine and sub-alpine regions of the Himalaya are vacated from seasonal snow as summer begins, which lasts longer in higher altitudes. However, variability can be seen in the growing season of vegetation in different altitudes (Padalia et al., 2023). Darma-Byans landscape is situated in the higher Himalaya, where the threat of habitat degradation is because of over exploitation of caterpillar fungus. (Negi et al., 2020). Himalayan land use changes are prominent and can be seen in length and breadth. A recent study of Gilgit Baltistan observed changes or transformations of Agriculture and uncultivated land to the built-up areas (Ali et al., 2022). Baramulla district, located in the North-western Himalaya, 2000-2020 study found that the area experienced a conversion of fallow land and agricultural land due to the human population (Bashir et al., 2022).

Vertical ecological zonation and land-cover patterns

Elevation is the principal determinant of land-cover distribution in the Central Himalaya. Lower elevations (<3000 m) supports agriculture, human settlements and dense forests due to favorable climate and accessibility (Rai et al., 1994; Bashir et al., 2022). The study area above 3000 m transition into alpine meadows and grazing lands, consistent with observations in the Western and Sikkim Himalaya (Mishra et al., 2020; Padalia et al., 2023). Above 4500 m, the environmental conditions limit vegetation, resulting in barren rocky terrain and snow and glacier cover.

Alpine meadows (Bugyals) as critical high-altitude ecosystems

The extent of Bugyals underscores their ecological value. These meadows support medicinal plants and pastoral livelihoods but are sensitive to overgrazing and unsustainable harvesting of high-value species (Negi et al., 2020). Their concentration between 3000–4500 m makes them vulnerable to climatic shifts that could alter growing seasons and species distributions.

Influence of climate change on snow, glacier and vegetation zones

Regional studies indicate glacier recession across the Himalayas driven by rising temperatures and altered precipitation regimes (Bajracharya et al., 2014; Hussain et al., 2023). Although the present study provides a spatial baseline for the year 2023, temporal analyses incorporating multi-date satellite datasets are necessary to quantify trends in glacier shrinkage and vegetation shifts.

Human–environment interactions and land use dynamics

Human activities are primarily concentrated below 3000 m. While built-up and agricultural extents are modest, increasing connectivity, tourism and pastoralism contribute to localized land-use transitions. Drivers in the Goriganga watershed include topography, climate, socio-economic factors and traditional land-use practices (Sati et al., 2024; Gogoi et al., 2019).

Mapping challenges and comparison with regional studies

Mapping in rugged terrain is challenging due to topographic shadows and mixed pixels; discrepancies between global and local LULC datasets have been reported (Aryal et al., 2023). The manual digitization approach used here, which is further supported by field validation, reduces misclassification chances and captures fine scale land-cover heterogeneity.

Limitations and future research directions

Limitations include subjectivity in manual digitization and limited temporal coverage. Future research should include temporal change detection using multi-date imagery, integration of climatic and socio-economic datasets, and the use of semi-automated classification supported by field data to enhance reproducibility.

Conclusion

The Goriganga watershed demonstrates distinct LULC patterns strongly influenced by elevation. Forests dominate below 3000 m, Bugyals occupy 3000–4500 m, and snow/glacier cover dominates above 4500 m. The updated 2023 LULC dataset provides a baseline for monitoring environmental change and informing sustainable land management and conservation planning in the Central Himalaya. Long-term monitoring and integration of climatic and socio-economic data are necessary to better understand LULC dynamics and to guide conservation and development interventions.

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Author contribution

Conceptualization: K.S.K., M.R., and R.C.J.; Methodology: K.S.K. and M.R.; Formal analysis: R.C.J.; Investigation: K.S.K., M.R., and R.C.J.; Writing—original draft: K.S.K. and M.R.; Writing—review and editing: K.S.K., M.R., and R.C.J. All authors have read and approved the final version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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