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Monitoring Land Use and Land Cover Change in Eastern Nepal: a Remote Sensing Perspective on the Dudh Koshi River Watershed (2000–2020)

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Abstract: This study analyzes two decades (2000–2020) of Land Use and Land Cover (LULC) change in the Dudh Koshi River watershed, eastern Nepal—a climatically sensitive and topographically complex Himalayan region. Using multi-temporal satellite imagery and GIS-based analysis across eight sub-basins, we quantified changes in forest, rangeland, snow, bare ground, cropland, built-up areas, and water bodies. Key trends include glacial retreat (–0.9%), rangeland degradation (–2.4%), and a tripling of built-up land (+2.6%). Spatial patterns reflect elevation, road access, and proximity to settlements, while drivers include climate change, rural depopulation, and infrastructure expansion. These dynamics affect ecosystem services, water security, and rural livelihoods. Our findings underscore the need for integrated, community-engaged watershed management and call for future research using high-resolution data and socio-ecological frameworks to inform climate-resilient development in fragile mountain systems.

Keywords: Land Use and Land Cover (LULC) Change; Dudh Koshi Watershed; Remote Sensing and GIS; Climate Change Adaptation; Participatory Governance.

Introduction

Land Use and Land Cover (LULC) change remains a critical concern for environmental management in developing countries, particularly within fragile mountain ecosystems such as the Dudh Koshi River watershed in eastern Nepal (Asian Development Bank, 2016). Spanning approximately 4,100 km², the watershed encompasses a mosaic of alpine meadows, forests, agricultural terraces, glacial zones, and human settlements (ICIMOD, 2010; Khadka, 2017). This ecological and topographical diversity is shaped by steep elevation gradients, climatic variability, and the dynamic interactions between natural processes and human activities (Aryal, et al., 2019).

Over recent decades, the Dudh Koshi watershed has undergone substantial LULC transformations driven by climatic, demographic, and economic forces (Paudel et al., 2021). Climate-induced glacial retreat and the reduction of permanent snowfields have exposed new bare land and disrupted hydrological regimes (Bajracharya et al., 2018). Simultaneously, infrastructure development and population pressures have altered the distribution of cropland, rangeland, and built-up areas (Pokhrel & Kamar, 2023). These land cover changes directly affect critical ecosystem services, water availability, soil stability, and the resilience of rural livelihoods (Shrestha et al., 2015).

In developing country contexts like Nepal, timely and accurate LULC monitoring is indispensable for sustainable watershed management and disaster risk reduction (Apollonio et al., 2025; ICIMOD, 2013; Umukiza et al., 2022). Deforestation and land degradation heighten runoff and sedimentation, exacerbating flood and landslide risks, while degrading water quality and biodiversity (Garrard et al., 2016; Młyński et al., 2025; Novelli et al., 2016; Recanatesi F., 2020). In contrast, reforestation and improved land-use practices can bolster ecosystem resilience and enhance livelihood security (Basnet, 2015; Hanif et al., 2023). However, traditional field-based monitoring methods are often constrained by limited financial and technical capacity, as well as the logistical challenges of rugged terrain (Asian Development Bank, 2016).

Recent advances in Geographic Information Systems (GIS) and Remote Sensing (RS) have transformed the capacity to map and analyze LULC dynamics in such remote and complex landscapes (Kumar & Hole, 2021; Pelorosso et al., 2021). Satellite platforms like Landsat and Sentinel offer systematic, long-term observations, enabling the detection of spatial and temporal patterns at high resolution (FRTC, 2022). In the Dudh Koshi watershed, mapping efforts by ICIMOD and national institutions have confirmed forest cover as the dominant LULC type, alongside significant extents of rangelands, croplands, and glacial terrain (DCRL, 2020).

Several recent studies document notable LULC shifts across the Dudh Koshi basin in the past 20 years (Humagain & Garrard, 2020). Forest cover has fluctuated due to a combination of community forestry initiatives, subsistence harvesting, and land conversion (Basnet, 2015). While community stewardship has promoted reforestation in some areas, others remain under pressure from overgrazing, agricultural expansion, and infrastructure development (Aryal et al., 2019; Garrard et al., 2016). In upland zones, agricultural lands have declined, often due to outmigration and the abandonment of marginal terraces, which in turn are converted to fallow or built-up land (Paudel et al., 2021). Rangelands and bare ground have expanded, especially in high-altitude catchments, driven by overgrazing, erosion, and climate-induced vegetation shifts (Lillesø et al., 2005). Glacial retreat and snow melt, accelerated by rising temperatures, further contribute to bare land expansion and hydrological instability (Nie et al., 2021).

The drivers of LULC change are complex and intertwined. Biophysical factors such as climate variability, glacial melt, and extreme weather interact with socioeconomic forces including population growth, rural-to-urban migration, market integration, and shifting livelihood strategies (Aryal et al., 2019; Pokhrel & Kamar, 2023). Road development, for example, has improved access and enabled economic growth but has also accelerated the conversion of forests and farmland into settlements (Rasool et al., 2021). At the same time, youth outmigration has contributed to land abandonment, altering cultivation patterns and impacting both food security and landscape stability (Paudel et al., 2021).

Effective LULC management in the Dudh Koshi watershed—and similar mountain regions in the Global South—requires more than technological tools; it also demands the integration of traditional ecological knowledge (TEK) and strong institutional frameworks. TEK, encompassing generations of local experience and practices, has long guided sustainable land and water management in Himalayan communities (Rawat & Sah, 2009). Systems such as terraced farming, traditional irrigation canals, and sacred forest protection demonstrate locally adapted strategies for resource conservation and risk reduction (Aryal et al., 2015). Blending TEK with modern geospatial approaches can improve the relevance and legitimacy of LULC assessments, with local knowledge enhancing the interpretation of satellite data and informing context-sensitive management responses (Basnet et al., 2009).

Indeed, in recent years, TEK has increasingly been integrated with geo-informatics (GIS), not only in Himalayan communities. For instance, Zurayk et al. (2001) demonstrated that combining TEK—elicited through participatory rural appraisal—with scientific surveys and GIS analysis enhanced the understanding of land capability and management in Lebanon’s semi-arid regions, fostering stakeholder dialogue and promoting sustainable, locally grounded land use decisions. Later, Al-Adamat et al. (2012) applied a similar approach to identify optimal water harvesting sites in Jordan’s arid Badia region, showing that integrating local community expertise with modern spatial analysis improves decision-making and encourages sustainable, community-supported water management. More recently, Forzini et al. (2022) further illustrated that incorporating TEK and indigenous criteria within a GIS-based multi-criteria framework leads to more accurate and culturally appropriate identification of water harvesting sites in Nepal’s Himalayan region, thereby enhancing water resilience, sustainability, and local acceptance of management solutions.

Institutional and social dimensions are of course equally critical. Community-based governance—through user groups, local committees, and participatory mapping—has proven effective in enhancing the sustainability and inclusiveness of resource management (Aryal et al., 2019; Basnet, 2015). Nepal’s progressive policies on decentralization and community forestry have empowered local actors, fostering collective stewardship and equitable benefits (Government of Nepal, 2015). However, key challenges remain, including limited technical capacity, institutional fragmentation, and the need for mechanisms that ensure the participation of women, indigenous peoples, and marginalized groups (Asian Development Bank, 2016; Paudel et al., 2021).

Despite increased attention to LULC dynamics in Nepal, substantial knowledge gaps persist. Existing studies often focus on national or regional scales, with insufficient detail at sub-watershed levels and limited integration of community perspectives (FAO, 2023). In the Dudh Koshi basin, there is a pressing need for high-resolution, multi-temporal studies that not only map the rates and patterns of land cover change, but also assess their implications for ecosystem services and socio-ecological resilience (Humagain & Garrard, 2020).

This study addresses these critical gaps by conducting a detailed spatial and temporal analysis of LULC change in the Dudh Koshi River watershed between 2000 and 2020. Drawing on multi-temporal satellite imagery and GIS-based classification, the study aims to: (1) quantify the extent and rate of change in key land cover types—forest, rangeland, bare ground, snow, surface water, built-up areas, and cropland; (2) investigate the spatial distribution and drivers of these changes within sub-basins; and (3) explore the implications for watershed management, ecosystem resilience, and rural livelihoods.

The findings of this research contribute to evidence-based strategies for sustainable land and resource governance, while supporting broader goals in climate adaptation, disaster risk management, and inclusive development planning in Nepal’s Himalayan regions (Shrestha et al., 2015).

Materials and Methods

Study area description

The Dudh Koshi River watershed, located in eastern Nepal and shown in Figure 1, forms an important sub-basin of the larger Koshi River system, one of the principal river networks in the Himalayan region. The river originates from the glaciers near the Gokyo Lakes and Mount Everest, with its headwaters situated at approximately 27°8'41" N, 86°25'12" E. It flows southward through rugged mountain terrain, ultimately merging with the Sun Koshi River near Harkapur, around 28°6'50.04" N, 86°59'4" E.

Covering an area of about 4,052 km^2, the watershed exhibits a dramatic elevation range—from 333 meters in the southern valleys to 8,696 meters at the summit of Mount Everest, the highest point on Earth. This elevation gradient produces stark climatic, hydrological, and ecological contrasts across the basin.

The Dudh Koshi basin experiences a diverse climate, transitioning from subtropical and temperate zones in the lower elevations to subalpine and alpine climates in the higher regions. The area is strongly influenced by the South Asian monsoon, which delivers the majority of its annual precipitation—typically between 1,000 mm and 3,500 mm—between June and September. Snowfall occurs at higher altitudes during the winter months, contributing to the accumulation and seasonal melt of glaciers. Average annual temperatures vary significantly, ranging from over 20°C in the lower reaches to well below freezing in the high alpine zones.

Vegetation in the Dudh Koshi watershed reflects its vertical zonation. The lower and mid-hill areas are dominated by broadleaf forests (including species such as *Shorea robusta* and *Quercus spp.*), while coniferous forests (including *Pinus wallichiana* and *Abies spectabilis*) are found in the upper elevations. Above the tree line, alpine shrublands and meadows give way to permanent snow and glacial ice. Land cover includes glaciers, forests, pastureland, cultivated terraces, and scattered rural settlements. Recent studies indicate an upward shift in vegetation zones due to rising temperatures and changing precipitation patterns.

Soils within the basin vary considerably by elevation and slope position. In the mid-hill landscapes, Cambisols are widespread, offering moderate development and supporting mixed agricultural use. At higher elevations, less developed Regosols and very shallow Leptosols become prevalent, especially across steep, rocky, or recently disturbed mountain slopes. These soils are generally thin, weakly structured, and highly susceptible to erosion, particularly where vegetative cover is sparse (Shrestha et al., 2015).

Human activity is largely concentrated in the lower and mid-elevation zones, where conditions are more favorable for settlement and agriculture. Communities practice subsistence farming, cultivating crops such as maize, millet, barley, and potatoes on terraced hillsides. Animal husbandry is also prevalent, with yak and sheep herding common in higher altitudes. Tourism, especially mountaineering and trekking in the Everest region, has become an important economic driver, though it also places pressure on local ecosystems and infrastructure.

The Dudh Koshi watershed is characterized by steep mountainous terrain, deep gorges, glacial lakes, and unstable slopes, making it highly susceptible to natural hazards. These include landslides, debris flows, flash floods, and glacial lake outburst floods, events that are becoming more frequent and severe due to climate change and glacier retreat. Monitoring and adaptation strategies are essential to mitigate these risks and ensure the resilience of both ecosystems and communities.

For the purposes of this analysis, the Dudh Koshi watershed has been subdivided into eight distinct sub-basins, with individual areas ranging from approximately 137 km^2 to 862 km^2. This delineation allows for a more detailed, sub-regional examination of hydrological characteristics and facilitates the development of targeted, basin-specific management and planning strategies. For further details on the Dudh Koshi watershed, reference can be made to Bajracharya et al. (2018), Nie et al. (2021), and (UNDP, 2024).

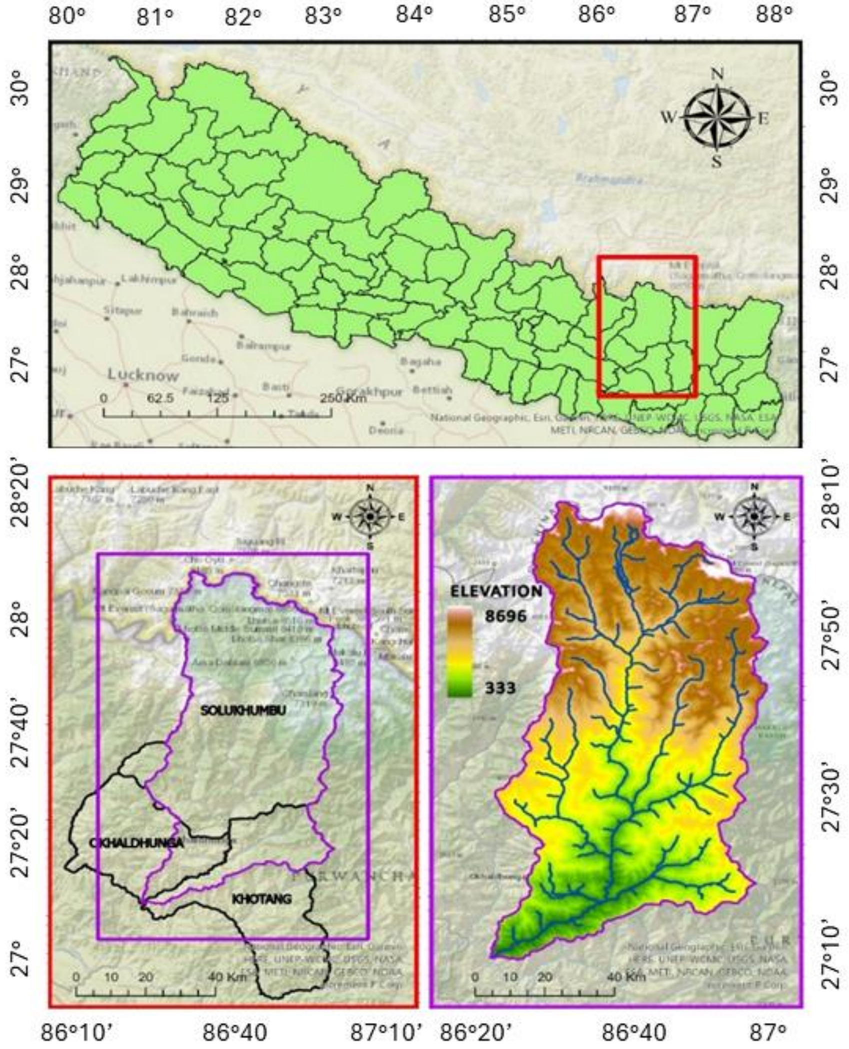


Figure 1. Localization of Dudh Koshi Watershed, Nepal.

Data collection

This study utilized geospatial datasets with a 30-meter spatial resolution to maintain analytical consistency and ensure comparability across the Dudh Koshi River watershed. The primary source of satellite imagery was the Landsat 8 and Landsat 9 Operational Land Imager (OLI), accessed via the USGS Earth Explorer platform. These satellites provide multispectral imagery with a 16-day revisit cycle, enabling effective monitoring of land use and land cover (LULC) changes, water bodies, and environmental dynamics in complex and topographically diverse regions such as eastern Nepal (Chen et al., 2024). The 30-meter resolution offers an optimal balance between spatial detail and data volume, making it suitable for watershed-scale studies where both landscape patterns and classification accuracy are critical (Petroselli, 2012; Omali, 2018). In this study, raw Landsat scenes were not downloaded or processed; the analysis relied directly on the Global Land Analysis and Discovery (GLAD)–derived layers. Specifically, the GLAD LULC layers are generated from 30 m Landsat surface-reflectance composites for the reference years 2000, 2005, 2010, 2015, and 2020.

Topographic analysis was conducted using the Shuttle Radar Topography Mission (SRTM) 30-meter Digital Elevation Model (DEM), also sourced from USGS. The SRTM

DEM is widely recognized for its accuracy and reliability in hydrological modelling, watershed delineation, and terrain analysis. It provides essential information on elevation, slope, and drainage patterns, all of which are foundational for morphometric and hydrological assessments (Farr et al., 2007). Comparative evaluations have shown a high degree of alignment between SRTM-derived and traditional toposheet-derived elevation data, supporting its continued use in Himalayan watershed studies (Tejaswini, 2025).

All geospatial datasets underwent comprehensive preprocessing, including geometric correction, atmospheric correction, and reprojection into a common coordinate system. These steps, directly performed from GLAD, are vital to mitigate distortions arising from sensor inconsistencies, terrain effects, or atmospheric interference, and to ensure accurate spatial alignment across datasets (Ranaparkhi, 2019). Additional preprocessing operations—such as image stacking, mosaicking, and subsetting—were carried out to extract the study area and enhance image clarity for subsequent analytical procedures (Ranaparkhi, 2019).

The selection of 30-meter resolution data was a deliberate methodological choice aimed at balancing spatial granularity with processing efficiency. Although higher-resolution imagery can offer finer spatial details, the 30-meter scale has proven effective for regional-scale watershed research, particularly due to its availability as free, open-access data and its established utility in land classification and hydrological analysis critical (Omali, 2018; Petroselli, 2012). This approach aligns with international best practices in the use of medium-resolution remote sensing for environmental monitoring and sustainable resource management (Chen et al., 2024).

By relying solely on 30-meter resolution datasets from authoritative sources such as USGS Landsat and SRTM DEM, this study ensures a high level of methodological consistency, analytical rigor, and reproducibility, supporting globally accepted standards in watershed-scale geospatial research. In particular, Table 1 reports the datasets that have been acquired for the present research.

Table 1. Dataset acquired for the present study

DATA	SOURCE
SRTM DEM 30 m	USGS Earth Explorer https://earthexplorer.usgs.gov/
Land Cover	Global Land Analysis and Discovery https://glad.umd.edu/dataset/GLCLUC2020
Landsat 8-9 OLI /TR C2 L2 Satellite Imagery	USGS Earth Explorer https://earthexplorer.usgs.gov/

Watershed Delineation and Land Use/Land Cover Data Processing

The delineation of the Dudh Koshi River watershed and the assessment of land use and land cover (LULC) dynamics were performed using ArcGIS Pro, incorporating a combination of digital elevation data and multi-temporal satellite-derived LULC datasets. Preprocessing steps performed in the present study included clipping, sub-basin extraction, and vectorization. All analyses were conducted using the WGS 84 / UTM Zone 45N coordinate reference system.

In particular, a 30-meter resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) served as the base layer for hydrological analysis. To ensure a hydrologically sound surface, the DEM was preprocessed using the 'Fill Sink' tool to remove spurious depressions. Subsequently, flow direction and flow accumulation were derived using standard hydrological tools to delineate drainage networks. The watershed boundary was generated using the 'Watershed' tool, with the outlet defined at the confluence near Harkapur. For sub-regional analysis, the watershed was subdivided into eight hydrologically discrete sub-basins using pour points placed at major tributary junctions.

LULC data for the years 2000, 2005, 2010, 2015, and 2020 were sourced from the Global Land Analysis and Discovery (GLAD) platform. The range 2000-2020 was selected because the GLAD LULC products remained methodologically consistent over this period, ensuring results that are both comparable and reliable. Indeed, Eastern Nepal experienced substantial socio-ecological changes during these two decades, including community forestry expansion, rural-to-urban migration, and agricultural land abandonment. These changes coincided with contemporaneous policy developments. The LULC classification included the following categories: tree cover, dense short vegetation, sparse short vegetation, snow/ice, built-up area, barren land, cropland, open surface water, and salt pan. The area of each LULC category within each sub-basin was calculated, yielding both absolute areas (in km²) and proportional coverage for temporal comparison.

This workflow facilitated a spatially explicit and temporally detailed quantification of LULC changes across the Dudh Koshi watershed from 2000 to 2020. The workflow of the investigated methodology is presented in Figure 2.

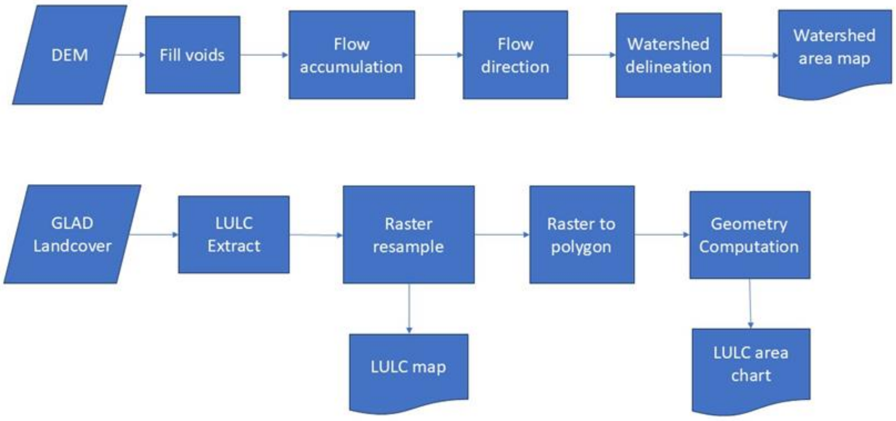
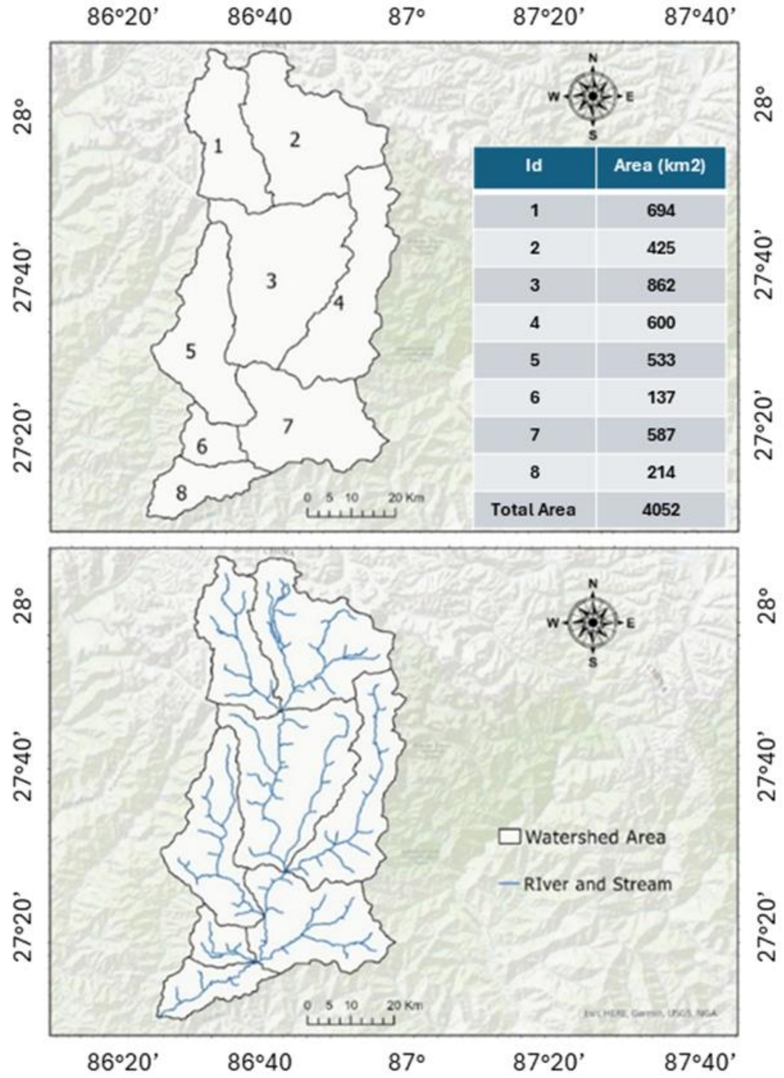


Figure 2. Workflow of the investigated methodology.

Results and Discussion

This section presents the principal findings from the spatial analysis of the Dudh Koshi River watershed, derived from 30-meter resolution remote sensing and GIS datasets. The analysis reveals significant land cover transformations over the study period, including notable forest loss, agricultural expansion, and glacial retreat. These landscape changes are accompanied by emerging hydrological concerns, such as increased sediment transport, elevated runoff accumulation, and the identification of flood-prone areas. The spatial patterns and temporal trends observed are contextualized within the broader framework of regional environmental challenges and local stakeholder priorities. The findings provide actionable insights to inform evidence-based watershed management, enhance ecosystem resilience, and support adaptive planning strategies in response to ongoing climatic and land use pressures.

Figure 3 provides a detailed spatial representation of the Dudh Koshi River watershed in eastern Nepal, highlighting its hydrological structure and the internal subdivision, as mentioned in paragraph 2.1. Figure 3 overlays the river and stream network on the watershed boundary, revealing the region's dense and complex drainage system. The mapped flow pattern, characterized by a north-to-south direction from high-elevation zones to lower valleys, is typical of Himalayan Mountain watersheds. Main rivers and tributaries are represented by blue lines, illustrating hydrological connectivity across the basin.



Id	Area (km2)
1	694
2	425
3	862
4	600
5	533
6	137
7	587
8	214
Total Area	4052

Figure 3. Watershed Delineation of Dudh Koshi River

The decision to subdivide the watershed into eight sub-basins was guided by both scientific and practical considerations. From a hydrological perspective, this partitioning increases the internal homogeneity of each unit, improving the accuracy of spatial analyses involving slope, soil type, and land cover. The selected number of sub-basins balances the need for spatial resolution with analytical manageability over the two-decade study period (2000–2020). This approach is consistent with methodologies applied in other Himalayan watershed studies, facilitating cross-comparisons and supporting regional policy development (Sharma & Mahajan, 2020). Furthermore, several sub-basin boundaries align with existing administrative or management zones, enhancing the relevance of findings for local governance and conservation planning. Overall, the sub-basin framework strengthens the scientific robustness and practical applicability of the watershed assessment.

A comprehensive series of LULC maps from 2000 to 2020, shown in Figure 4, reveals both enduring stability and significant transitions in the Dudh Koshi watershed, located in the climatically and topographically diverse eastern Himalayas of Nepal. These high-resolution, temporally consistent maps, classified into key LULC categories—tree cover, dense and sparse short vegetation (rangelands), bare ground, snow and ice, surface water, built-up areas, croplands, and salt pans—enable detailed spatial-temporal analyses in a region where consistent environmental data is limited. By subdividing the watershed into eight hydrologically meaningful sub-basins, the study provides a nuanced understanding of LULC change patterns and their implications for watershed management, ecosystem resilience, and rural livelihoods. Table 2 presents the percentage coverage of various land features over the years 2000, 2005, 2010, 2015, and 2020.

Table 2. Percentage coverage of different land features from 2000 to 2020

Land Cover	Year									
	2000 (%)	2000 (ha)	2005 (%)	2005 (ha)	2010 (%)	2010 (ha)	2015 (%)	2015 (ha)	2020 (%)	2020 (ha)
Barren area	2.1	8507.1	2.6	10532.6	2.6	10532.6	2.0	8102.0	2.5	10127.5
Built-up area	1.4	5671.4	2.1	8507.1	2.2	8912.2	2.6	10532.6	4.0	16204.0
Cropland	1.0	4051.0	1.0	4051.0	1.0	4051.0	1.0	4051.0	1.3	5266.3
Dense short vegetation	27.2	110187.2	26.5	107351.5	26.3	106541.3	25.9	104920.9	24.8	100464.8
Open surface water	0.6	2430.6	0.5	2025.5	0.5	2025.5	0.8	3240.8	0.9	3645.9
Salt pan	0.1	405.1	0.2	810.2	0.2	810.2	0.1	405.1	0.1	405.1
Snow/Ice	14.6	59144.6	13.9	56308.9	13.6	55093.6	14.3	57929.3	13.7	55498.7
Sparse short vegetation	14.3	57929.3	14.5	58739.5	14.7	59549.7	14.6	59144.6	14.5	58739.5
Tree	38.6	156368.6	38.7	156773.7	38.8	157178.8	38.7	156773.7	38.3	155153.3

Regarding the extent and rate of LULC Change in the investigated period, the watershed remained dominated by forest and rangeland, although notable shifts occurred. Tree cover declined slightly from 38.6% to 38.3%, indicating ecological resilience but also hinting at emerging pressures. Dense short vegetation—a key rangeland component—decreased more significantly from 27.2% to 24.8%, suggesting possible degradation due to overgrazing, agro-pastoral abandonment, or changing land management practices. In contrast, sparse vegetation increased modestly from 14.3% to 14.5%, potentially due to vegetation succession or partial rangeland degradation.

The cryospheric component, comprising snow and ice, declined from 14.6% to 13.7%, consistent with regional trends of glacial retreat driven by climate warming—an especially critical concern for Himalayan watersheds. Built-up areas experienced the most dramatic anthropogenic change, nearly tripling from 1.4% to 4.0%, reflecting expanding infrastructure and rural settlement. Bare ground increased from 2.1% to 2.5%, likely associated with erosion, land abandonment, or resource extraction. Cropland remained relatively stable, fluctuating between 1.0% and 1.3%, suggesting saturation of arable land or labor constraints. Surface water bodies grew slightly from 0.6% to 0.9%, while salt pans maintained a minimal and stable presence (0.1–0.2%).

The LULC changes observed throughout the study period for each sub-basin are comprehensively summarized in Table 3.

Table 3. Temporal changes in land-cover classes (area in hectares) across the investigated sub-basins.

	SUB-BASIN 1					SUB-BASIN 2				
	YEAR					YEAR				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
LAND COVER	AREA (HA)					AREA (HA)				
Barren area	2602.9	3139.5	3088.9	2113.0	2541.3	3998.7	5000.1	5053.4	3602.4	4200.5
Built-up area	38.4	49.8	54.6	58.0	65.4	52.5	69.3	72.8	75.2	82.6
Cropland	0.0	0.0	0.0	0.0	0.9	0.4	0.4	0.4	0.4	1.2
Dense short vegetation	10695.2	10726.7	10696.2	10713.0	10659.0	14529.9	14519.1	14483.5	14461.5	14415.7
Open surface water	366.0	258.1	337.2	484.7	599.7	916.8	696.9	818.6	1158.1	1359.4
Salt pan	7.7	18.7	10.7	9.8	9.9	41.3	88.8	61.9	39.4	37.6
Snow/Ice	12518.6	11928.5	11823.3	12804.1	12325.3	24125.0	22913.3	22510.4	23948.9	23188.0
Sparse short vegetation	14767.4	14899.8	15007.2	14912.9	14812.9	23212.9	23586.3	23846.6	23680.3	23494.3
Tree	1434.3	1409.2	1412.2	1334.8	1417.3	2495.8	2498.8	2525.3	2406.8	2593.4
	SUB-BASIN 3					SUB-BASIN 4				
	YEAR					YEAR				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
LAND COVER	AREA (HA)					AREA (HA)				
Barren area	941.4	1174.8	1214.4	1186.7	1726.6	860.5	1130.4	1186.8	1073.8	1574.7
Built-up area	430.1	630.8	684.0	806.2	1464.4	182.6	255.3	286.5	334.6	754.2
Cropland	374.7	322.8	261.8	253.6	271.3	411.5	292.1	224.1	255.4	493.0
Dense short vegetation	25892.5	25655.8	25584.8	25517.6	25038.6	13010.0	12994.6	13009.6	12965.9	12435.6
Open surface water	410.2	281.7	343.3	483.9	598.0	274.6	247.0	252.7	445.4	490.7
Salt pan	108.2	157.9	149.3	78.8	91.6	299.0	421.9	428.7	256.4	281.9
Snow/Ice	11494.4	11075.4	10661.6	10704.2	10055.9	9608.4	9119.3	8787.1	8996.4	8420.9
Sparse short vegetation	9317.1	9551.6	9844.4	9855.4	9798.7	8377.8	8503.2	8736.8	8673.6	8652.9
Tree	37190.8	37308.6	37415.9	37273.0	37046.8	26960.9	27020.9	27072.1	26983.6	26880.5
	SUB-BASIN 5					SUB-BASIN 6				
	YEAR					YEAR				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
LAND COVER	AREA (HA)					AREA (HA)				
Barren area	101.3	132.7	144.6	138.0	205.1	0.0	0.0	0.0	0.0	0.0
Built-up area	1374.8	1878.5	1972.3	2525.1	3801.6	1859.7	3067.9	3150.5	3334.2	3989.1
Cropland	249.4	240.6	233.5	220.6	232.7	856.9	814.5	808.3	785.4	717.4
Dense short vegetation	17011.6	16415.1	16044.1	15460.8	14607.7	5070.7	4193.4	4067.8	3896.8	3466.6
Open surface water	37.7	32.7	32.2	50.6	46.8	0.0	0.0	0.0	0.0	0.0
Salt pan	36.1	45.9	37.0	22.1	47.1	0.0	0.0	0.0	0.0	0.0
Snow/Ice	1426.6	1374.6	1351.2	1362.8	1272.9	0.0	0.0	0.0	0.0	0.0
Sparse short vegetation	1804.6	1821.0	1841.7	1837.4	1836.7	51.3	23.4	19.2	20.8	20.8
Tree	31196.6	31297.5	31581.9	31621.2	31188.6	5873.2	5612.9	5666.4	5675.0	5518.1
LAND COVER	SUB-BASIN 7					SUB-BASIN 8				

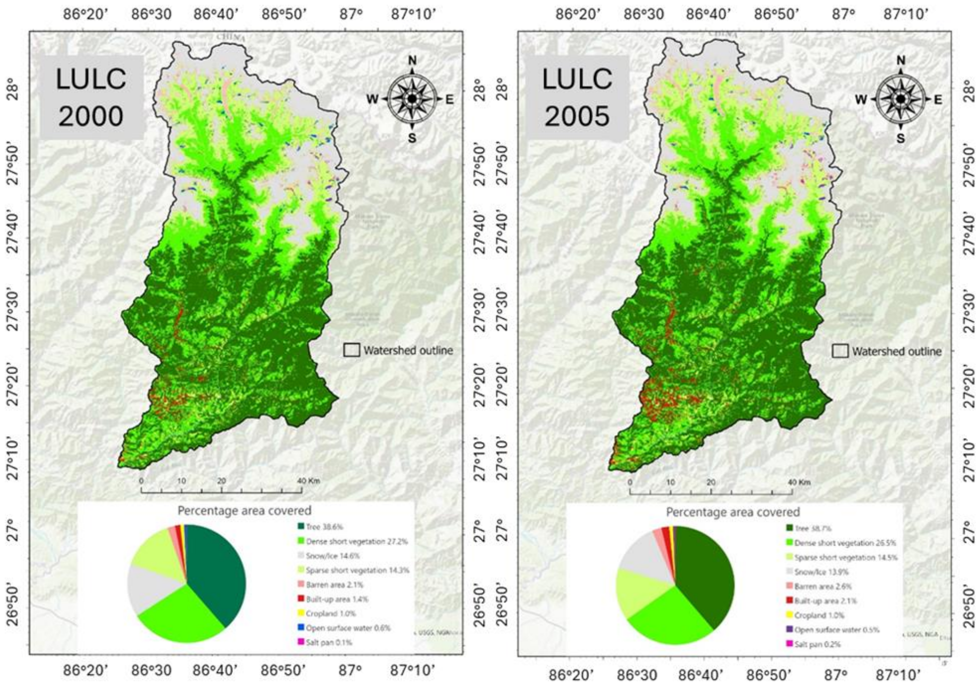
			YEAR					YEAR		
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
			AREA (HA)					AREA (HA)		
Barren area	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2
Built-up area	1067.7	1400.2	1468.1	1839.3	3995.8	764.1	1159.7	1204.3	1405.8	1926.1
Cropland	1274.1	1344.5	1357.8	1338.0	1511.9	1076.8	1190.1	1282.2	1366.3	1892.5
Dense short vegetation	14334.8	13742.4	13573.1	13216.4	11782.5	9640.7	9220.2	9056.2	8821.6	8015.9
Open surface water	93.1	95.9	118.3	142.9	159.1	251.4	221.9	269.4	275.1	286.3
Salt pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Snow/Ice	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sparse short vegetation	121.8	88.6	53.2	44.4	35.2	144.6	148.0	106.5	103.9	90.1
Tree	41795.2	42015.2	42116.2	42105.8	41202.1	9555.6	9493.5	9514.8	9460.9	9222.7

Across all eight sub-basins, the LULC analysis from 2000 to 2020 reveals clear patterns of both human-driven and environmental change. Built-up areas increased markedly in every sub-basin—for example, from 38.4 ha to 65.4 ha in Subbasin 1, 430.1 ha to 1464.4 ha in Subbasin 3, and 1067.7 ha to 3995.8 ha in Subbasin 7—indicating substantial expansion of urban and settlement areas. Barren land also increased in several basins, such as Subbasin 1 (from 2602.9 ha to 2541.3 ha, with fluctuations) and Subbasin 4 (from 860.5 ha to 1574.7 ha), reflecting intensified land degradation or exposure of previously vegetated land. Dense short vegetation generally showed gradual declines, particularly in Subbasin 5, where it decreased from 17,011.6 ha to 14,607.7 ha. Snow and ice cover, present mainly in the northern basins, consistently decreased—for instance, Subbasin 1 dropped from 12,518.6 ha to 12,325.3 ha, while Subbasin 3 declined from 11,494.4 ha to 10,055.9 ha—indicating a retreat of cryospheric elements. Tree cover remained relatively stable in some areas but decreased in others, such as Subbasin 7, where it fell from 41,795.2 ha to 41,202.1 ha. Open water surfaces exhibited variable trends, with notable increases in Subbasin 1 (from 366.0 ha to 599.7 ha) and Subbasin 8 (from 251.4 ha to 286.3 ha). Overall, the LULC dynamics illustrate expanding anthropogenic influence alongside shifts in vegetation, hydrological features, and snow/ice coverage across the watershed.

Regarding the LULC spatial distribution and sub-basin patterns, the maps in Figure 4 reveal a distinct altitudinal gradient. Tree cover and dense vegetation dominate the southern and mid-elevation zones, supported by moderate climatic conditions and traditional agroforestry practices. In contrast, the northern high-altitude zones are primarily covered by snow, ice, and sparse vegetation, where glacial and climatic dynamics predominate. Built-up areas and croplands are concentrated in lower-elevation valleys and accessible mid-hill sub-basins, closely aligned with transportation corridors and historical settlement patterns. Sub-basin-level analyses indicate that proximity to roads, urban nodes, and administrative centers correlates with faster land transformation. Conversely, more remote sub-basins show relatively intact natural vegetation but are increasingly exposed to pressures from climate variability, grazing, and land abandonment. These spatial patterns suggest that both ecological and infrastructural accessibility strongly influence land-use decisions.

The observed land use and land cover (LULC) changes in the Dudh Koshi Basin have significant consequences for both ecosystem functions and rural livelihoods. Forest expansion contributes positively by enhancing carbon storage, reducing soil erosion on steep slopes, and sustaining streamflows during dry periods. In contrast, the abandonment of mid-hill agricultural terraces and the decline of cultivated land diminish local food production, increasing reliance on purchased food or remittances from relatives abroad. The growth of settlements in lower valley areas further pressures water resources and alters hydrological processes by replacing naturally permeable surfaces with impermeable ones.

These landscape transformations have broader implications for watershed management, ecosystem resilience, and socio-economic stability. Reductions in dense vegetation and rangeland threaten erosion control, water retention, and biodiversity, while losses of snow and ice cover jeopardize seasonal water availability for both human and ecological needs downstream. The expansion of built-up areas increases the risk of flash floods and landslides, particularly in steep and geologically fragile terrain. For rural communities, the degradation of rangelands and the abandonment of agricultural land can undermine food security, reduce income diversity, and weaken resilience to economic shocks. At the same time, the relative stability of cropland and forest cover offers opportunities for targeted interventions, such as rangeland restoration and the adoption of climate-adaptive farming practices, to enhance both ecosystem services and livelihoods.



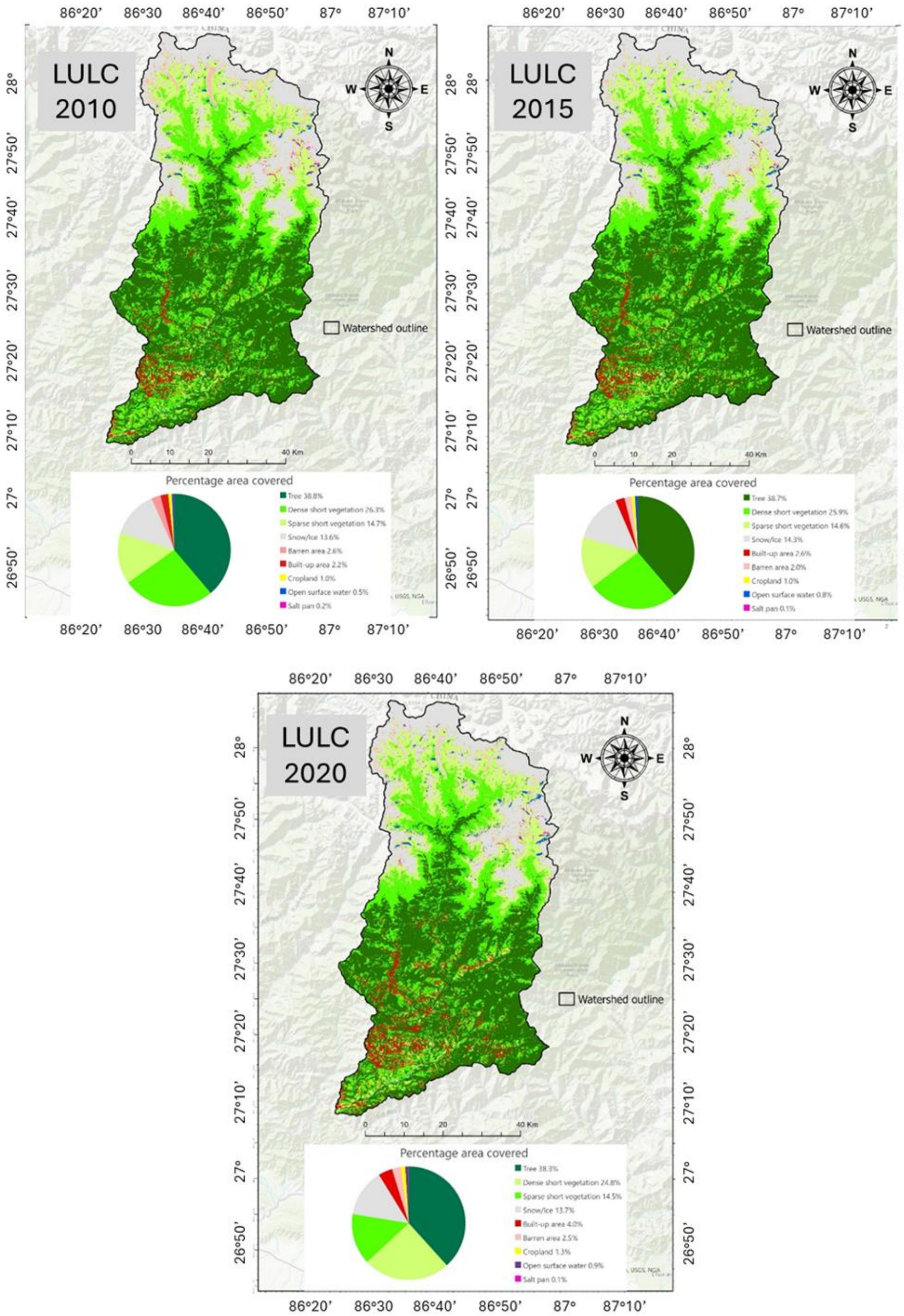


Figure 4. LULC maps of 2000, 2005, 2010, 2015, 2020

In this study, primary data collection did not involve participatory approaches, and TEK was not used as direct empirical evidence. But it is important to know that future studies could incorporate participatory approaches—such as community-based mapping to ground-truth LULC classifications or participatory land-use assessments that combine local knowledge with geospatial data—to better identify land-use drivers and management practices. Integrating TEK in this way could provide valuable context for socio-ecological change and offer stakeholders a more nuanced understanding of how local knowledge systems influence landscape management. These perspectives could highlight opportunities for future research to meaningfully engage local communities and support more inclusive and sustainable watershed planning.

In brief, the Dudh Koshi watershed presents a case of relative land cover stability punctuated by localized yet meaningful changes, particularly in rangelands, snow cover, and built-up areas. These dynamics underscore the urgency of integrating spatial monitoring tools with ground-based knowledge and participatory planning. The approach used here—combining multi-temporal remote sensing, sub-basin analysis, and TEK considerations—offers a scalable and replicable model for other mountainous, data-scarce regions facing rapid socio-environmental transitions.

Conclusions

This study provides a comprehensive assessment of two decades (2000–2020) of land use and land cover (LULC) change in the Dudh Koshi watershed, Nepal, revealing a complex interplay between ecological resilience and emerging socio-environmental pressures. While forest and cropland areas have remained relatively stable, significant trends—including the decline of dense rangeland vegetation, glacial retreat, and the rapid expansion of built-up areas—highlight the dual influence of climate change and human development in shaping this fragile Himalayan landscape. Spatial analyses across sub-basins show that accessibility, elevation, and historical land use are key determinants of LULC dynamics, with more remote regions retaining natural cover but increasingly vulnerable to climatic variability and land degradation.

The take-home message is the following: sustainable watershed management in high-mountain regions must go beyond monitoring change—it must actively integrate traditional ecological knowledge (TEK), participatory governance, and adaptive policy frameworks to respond effectively to both global and local drivers of landscape transformation. Strengthening community-based management and aligning it with geospatial intelligence can bolster ecosystem services, enhance rural livelihoods, and build resilience against future climate risks.

Looking ahead, future work should prioritize higher-resolution LULC mapping, seasonal variability analysis, and the incorporation of socio-economic and ethnographic data (e.g.: census data, household surveys) to better understand local land-use decisions and their long-term sustainability. This approach would enable a more comprehensive socio-ecological assessment of the underlying drivers of LULC change. Ground-truthing and participatory mapping will be indeed essential for validating satellite-derived classifications and for capturing finer-scale changes, particularly in smallholder agricultural systems, community forests, and glacial environments. Moreover, expanding this integrative approach to neighboring watersheds can inform broader regional strategies for climate adaptation and sustainable mountain development.

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