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## Article

# Transforming Landscapes, Shaping Risk: Land Cover Change and Disaster Vulnerability in Parshuram Municipality (2005–2025)

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## ABSTRACT

Parshuram Municipality, situated at the fragile Chure–Inner Terai interface of Dadeldhura District, embodies a landscape shaped by young, erodible geology and mounting human pressures. This study explores spatiotemporal land-use and land-cover (LULC) change from 2005 to 2025 and its driving forces. Freely available Landsat 5, 7, and 8 images were downloaded from USGS and subset to the municipal boundary in UTM45N WGS84, and seven LULC classes—forest, agriculture, grassland, water body, sedimentation, landslide, and settlement were defined per the Land Use Act 2019. Supervised maximum likelihood classification with seven training samples per class was performed in GIS and validated against ground truth in Google Earth Pro. Agricultural land expanded from 8% to 60% between 2005 and 2015, then contracted to 33% by 2025 (–27%). Forest cover declined from 29 % to 5 % (–24 %) before recovering to 14 % (+9 %). Grasslands fell from 35 % to 9 % (–26 %), while sedimentation areas surged from 5 % to 32 % (+27 %). Water bodies remained near 4 %, settlements shrank from 14 % to 6 % (–8 %), and landslide zones shifted from 7 % to 3 % (–4 %). Concurrent increases in flood and landslide events documented in municipal disaster records underscore the compounded risk posed by these LULC shifts. These trends reflect human encroachment, haphazard settlement expansion, and intensified erosion under monsoonal extremes. Mitigating disaster vulnerability and fostering sustainable development will require integrated land management, targeted reforestation, nature-based slope stabilization, and a geospatial early-warning system.

## KEYWORDS

Land use and landcover change; Parshuram municipality; remote sensing; sedimentation; disaster vulnerability; nature-based solutions.



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## 1. Introduction

Land use and land cover (LULC) change—alterations in the extent and quality of land uses and biophysical covers—has emerged as a core driver of Earth system transformation, shaping climate regulation, biodiversity, soils, and hydrology through multi-scale feedbacks (IPCC, 2019; Song et al., 2018; Curtis et al., 2018; De Palma et al., 2021; Mahtta et al., 2022; Liu et al., 2024). Conceptually, LULC sits at the nexus of coupled human–environment processes: “land use” encodes management choices (e.g., agriculture, settlement), “land cover” denotes surface properties (e.g., forest, cropland, built-up), and changes propagate through interacting biophysical and socioeconomic forcings (IPCC, 2019; Huang et al., 2021; Zhao et al., 2021; Wei et al., 2023). Accordingly, robust explanations integrate proximate pressures with underlying drivers—markets, infrastructure, technology, institutions, and demography—within a land-change science frame (IPCC, 2019; World Bank, 2020; Mahtta et al., 2022; Liu et al., 2024).

In Nepal, national syntheses and recent EO products reveal LULC trajectories shaped by migration, road expansion, tenure/policy reforms, climate variability, and livelihood transitions, yielding increasingly fine-grained mosaics of forest, shrub, grassland, cropland, and built-up land (Paudel et al., 2023; Devkota et al., 2023; ICIMOD, 2024; ICIMOD, 2025). Over the last two decades, cropland-to-built-up conversion has accelerated around urban and peri-urban nodes, while forest cover has stabilized or recovered in many districts under community stewardship—often with quality shifts (dense→open forest) that coarse labels can mask (World Bank, 2020; Devkota et al., 2023; Tripathi et al., 2020; FRTC/DoFRS, 2024; Smith et al., 2023; Rayamajhi et al., 2019). This simultaneity of urban expansion and forest regrowth complicates linear degradation narratives and foregrounds governance and institutions as the mediators of land transitions (IPCC, 2019; Paudel et al., 2023; Kant, 2024; ICIMOD, 2024; Liu et al., 2024).

The Terai—Nepal’s agrarian heartland—exemplifies these tensions: rapid settlement growth, market integration, and infrastructure have converted croplands and riparian corridors, while community forestry and improved local governance underpin forest recovery after earlier declines (World Bank, 2020; Devkota et al., 2023; ICIMOD, 2024; Paudel et al., 2023). The balance remains precarious, as cropland losses to construction land can erode food security and heighten exposure to hydroclimatic extremes, underscoring the need for spatially explicit, policy-relevant evidence at subnational scales (ADB, 2019; Amadio et al., 2023; Shreevastav et al., 2022; Zachariah et al., 2025; ICIMOD, 2025).

The Inner Terai–Chure (Siwalik) belt adds distinctive fragility: young, unconsolidated lithologies are prone to landslides, gullying, riverbank erosion, and pulsed sediment delivery to the Terai plains (MoFE, 2018; ADB, 2019; Pathak, 2019; Koirala et al., 2020). Intense monsoon events and land-use pressures on steep/sandy slopes amplify sediment loads and channel instability, increasing downstream flood risk and damaging infrastructure (ADB, 2019; Shreevastav et al., 2022; Amadio et al., 2023; Thapa et al., 2024). Even modest land-use decisions—road cuts, riverbed aggregate extraction, encroachment—can yield outsized geomorphic and social impacts in this belt (ADB, 2019; Thapa et al., 2024; Hasan et al., 2024; Darji & Ahmad, 2024).

Recent empirical studies across Chure municipalities document settlement expansion, localized cropland decline, grassland increases, and elevated erosion risk, especially where braided channels and aggregate extraction destabilize banks (Khatti & Shrestha, 2025; Jaishi et al., 2024; Joshi & Poudel, 2024; ADB, 2019). Advances in remote sensing and machine learning—e.g., Landsat/Sentinel-2 classification, CA-Markov, and deep learning for sand-plant detection—are sharpening detection and early warning of conversion hotspots (Kafle et al., 2023; Liu et al., 2024; Zhao et al., 2021; Naxa/ADPC, 2024; Tripathi et al., 2020). Aligning land-use regulation with watershed processes in erosion-prone belts is therefore essential (MoFE, 2018; ADB, 2019; World Bank, 2020).

Border river systems magnify these vulnerabilities. Along the Mahakali, training works, channel shifts, and bank erosion threaten settlements and agricultural terraces, raising transboundary coordination and local land-use planning challenges (Pariyar, 2020; The Rising Nepal, 2025; Khabarhub, 2025; CUTS, 2025). Infrastructure siting, sand/gravel extraction, and floodplain encroachment interact with monsoon hydrology to amplify hazard exposure and livelihood risk (Amadio et al., 2023; Thapa et al., 2024; Shreevastav et al., 2022; Paudel et al., 2023). These pressures are consequential for municipalities sited on dynamic corridors and migrating channels (Pandey et al., 2021; The Kathmandu Post, 2022).

Agro-ecological constraints sharpen the challenge. In the Bhabar–Inner Terai, coarse alluvium and sandy soils limit moisture retention and natural storage, reducing yields where irrigation is inadequate or poorly managed, with growing evidence of groundwater stress and recharge disruption (Pathak, 2019; Joshi et al., 2024; Maskey et al., 2023; Khabarhub, 2025; Kathmandu Post, 2023; CUTS, 2025). Community perspectives underscore water stress, climate uncertainty, and competing claims over forests and land—highlighting how perception and governance shape adaptation choices (Nash et al., 2019; Thapa, 2019; Amadio et al., 2023). Where groundwater access is uneven, drought exposure and livelihood precarity increase, influencing land-use decisions and migration (Maskey et al., 2023; Pathak, 2019; Joshi et al., 2024).

Evidence from comparable Inner Terai and Chure settings contextualizes likely trajectories. In Dang and adjoining districts, 1990–2015/2020 analyses indicate simultaneous forest degradation and recovery, with transitions among forest, shrub, and agriculture that reflect non-linear, reversible pathways rather than one-way conversion (Tripathi et al., 2020; Koirala et al., 2020; Paudel et al., 2023). In Chitwan's Inner Terai municipalities, 2001–2021 mapping documents pronounced built-up growth at cropland's expense, driven by governance restructuring, migration, and infrastructure pressures—patterns echoed along westward corridors and border markets (Devkota et al., 2023; ICIMOD, 2024; Timilsina et al., 2025; Liu et al., 2024). Hilly and mid-hill municipalities likewise report LULC shifts tied to demographic change and road expansion, reinforcing that infrastructure sequencing conditions spatial patterns of conversion (Paudel et al., 2023; Koirala et al., 2020; Amadio et al., 2023).

Against this backdrop, a municipal-scale study of Parshuram helps close a persistent evidence gap: fine-grained, spatiotemporal assessments in the fragile Chure–Inner Terai interface remain sparse relative to policy needs (Paudel et al., 2023; Devkota et al., 2023; ICIMOD, 2024). By quantifying class extents and change, identifying dominant conversion pathways, and linking biophysical with socioeconomic drivers, municipal analysis can inform land-use zoning, watershed restoration, and risk-informed infrastructure and livelihood planning (MoFE, 2018; ADB, 2019; Amadio et al., 2023; World Bank, 2020). Framing local transitions within regional Chure dynamics and national trends provides an actionable evidence base for sustainable land-use that reconciles development imperatives with geomorphic limits and ecosystem-service protection (IPCC, 2019; World Bank, 2020; ICIMOD, 2024; ICIMOD, 2025).

Recent studies in disaster risk management increasingly emphasizes the need to move beyond hazard-focused, reactive responses toward building systemic community resilience that integrates social, institutional, and livelihood dimensions. For instance, Milenković, Cvetković, and Renner (2024) show that indicator-based frameworks such as the BRIC method can help systematically assess community resilience across multiple dimensions — offering a structured basis to monitor progress in disaster-prone areas. Similarly, in the context of Nepal and other flood-prone regions, *Assessing Agricultural Vulnerability to Climate Change: A Study on Flood-Induced Loss and Damage in Rajapur, Bardiya, Nepal* (Paudel et al., 2025) highlights how extreme flood events inflict severe economic and livelihood losses — especially among small and medium farmers — thereby underscoring that resilience must address not only lifesafety but also livelihood security and foodsystem stability. At the same time, emerging work such as *Leveraging Artificial Intelligence for Enhanced Disaster Response Coordination* (Öcal & Torun, 2025) argues for the strategic integration of AI and data-driven tools to improve early warning, response coordination, and resource allocation — pointing to the potential of technology to strengthen disaster preparedness and adaptive capacity, especially in complex, multihazard and multistakeholder contexts. Furthermore, broader conceptualizations of disaster risk — including industrial, technological, and systemic hazards — as advocated by *Industrial Disasters and Hazards: From Causes to Consequences—A Holistic Approach to Resilience* (Cvetković, Renner & Jakovljević, 2024) highlight that resilience programming must evolve to address a wide spectrum of risks beyond natural disasters alone. In this light, the present study builds on these insights by combining community-based early warning, livelihood and water-resource resilience, and institutional strengthening — offering evidence from the transboundary river basin context to contribute to a more holistic, contextsensitive disaster risk management paradigm.

Considering that this study aims to characterize LULC trends through time, inform policy and planning, and illuminate the drivers of change, our approach prioritizes reproducible EO methods, transparent uncertainty, and explicit links to governance levers so evidence can be directly mobilized in municipal decision-making (IPCC, 2019; Zhao et al., 2021; Devkota et al., 2023; ICIMOD, 2025).

While several studies have examined LULC dynamics in Nepal's Chure and Inner Terai, most rely on coarse district-level data and seldom link land-change trajectories to municipal disaster patterns. This study addresses these gaps by providing a fine-scale, 20-year assessment of Parshuram Municipality—an understudied, geomorphically fragile Chure–Inner Terai interface.

Accordingly, the study pursues the following objectives:

1. To quantify spatiotemporal LULC changes in Parshuram Municipality from 2005–2025 using reproducible EO and GIS methods.
2. To identify the dominant land-transition pathways and the biophysical and socio-economic drivers influencing these shifts.
3. To analyse how LULC changes have shaped local flood, landslide, and sedimentation risk and to outline implications for municipal land-use and DRR planning.

This study provides municipality-scale, 20-year LULC analyses in the western Chure–Inner Terai that explicitly couples satellite-derived land transitions with local disaster records. The identification of the post-2015 sedimentation surge as a cascading impact of earlier forest loss and agricultural expansion offers a unique contribution compared with existing Chure studies.

This study provides a understanding of land use and disaster dynamics in the Chure region by combining multiple elements that are rarely integrated in previous research. First, it examines LULC changes across three distinct time steps (2005, 2015, 2025), allowing for the identification of both long-term trends and recent shifts. Second, the inclusion of “sedimentation” as a land cover class captures an important physical process often overlooked in standard LULC studies, linking landscape change to soil erosion and flood risk. Third, the integration of municipal disaster records with LULC analysis provides empirical context for interpreting how landscape transformations may coincide with changes in floods, landslides, and productive land loss. Collectively, these features make the study particularly relevant for Chure conservation, highlighting areas where ecosystem degradation increases disaster vulnerability, and provide actionable insights for local risk governance and land management planning.

Changes in land use and land cover (LULC) are both driven by socio-economic and biophysical factors such as population growth, agricultural expansion, and infrastructure development and generate feedbacks that alter ecosystem services and landscape stability. These landscape changes influence the three key components of disaster risk: hazard (e.g., floods and landslides intensified by sedimentation and slope destabilization), exposure (e.g., settlements and productive land in high-risk areas) and vulnerability (e.g., reduced adaptive capacity of communities dependent on degraded ecosystems). By explicitly connecting land-change dynamics to these disaster risk components, the study frames subsequent analyses of how LULC transformations in Parshuram Municipality may shape local risk patterns, providing a clear theoretical anchor for later discussion of causal pathways, correlations and management implications.

## 2. Methods

### 2.1. STUDY AREA

Parshuram Municipality, located in the southwestern region of Dadeldhura District within Sudurpashchim Province, Nepal was formed in 2014 (2071 B.S.) through the administrative merger of the former Village Development Committees (VDCs) of Jogbudha and Shirsha. The municipality spans approximately 414.07 square kilometers and is currently divided into 12 wards. Positioned around 29.2°N latitude and 80.5°E longitude, its topography ranges from roughly 300 to 1,530 meters above

sea level encompassing a transition from the lower Bhabar plains to the undulating Chure hills. A significant portion of the municipality, around 61.3% of its land area is forested, as per the Department of Forest Research and Survey (DFRS, 2018) and predominantly managed under community and leasehold forestry systems.

Parshuram Municipality in Dadeldhura is situated at the Chure foothills with the Mahabharat to the north and the Mahakali River to the west offers a salient microcosm of these processes, where fragile terrain intersects with development demands (Parshuram Municipality, 2024; UNCRD, 2023). Local plans identify recurrent landslides, floods, and sedimentation as binding constraints on livelihoods and infrastructure, reflecting the municipality's exposure to hillslope and riverine hazards (PCTMCDB, 2017; UNCRD, 2023).

Census records indicate a population decrease from 43,942 in 2011 to 35,590 in 2021, driven in part by out-migration amid limited local employment with implications for labor availability, land management and disaster readiness (CBS, 2012; CBS, 2022; UNCRD, 2023).

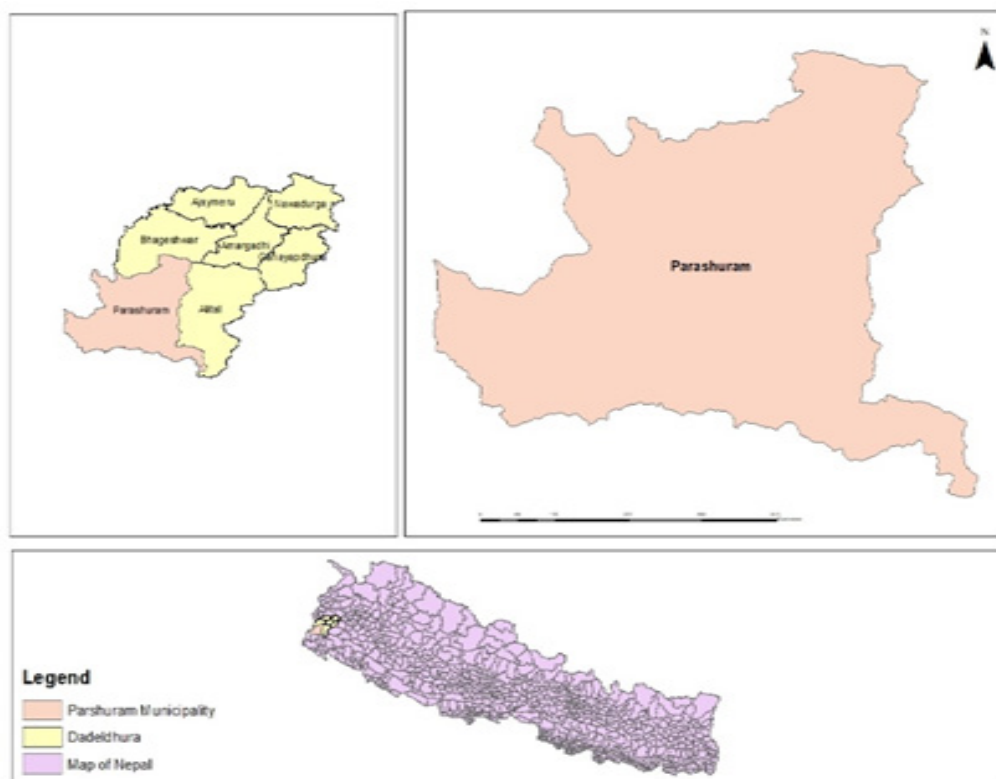


*Figure 1: Map of Study Area (Parshuram Municipality, Dadeldhura)*

## 2.2. DATA COLLECTION

Spatial data and socio-economic information were gathered to assess the LULC change process. Landsat satellite images for the years 2005, 2015, and 2025 related to the study area were obtained from the USGS Earth Explorer. These data are imported into GIS in (tar.) format. Subsequently, satellite image processing software was utilized to generate a false color composite. The composite band has been modified based on land classification. BGR-652 for farming, BGR-562 for robust greenery, BGR-564 for soil/water, BGR-764 for metropolitan areas. The images were captured using several bands. Thus, to merge various bands into one composite band layer, a stacking procedure was executed. Layer stacking refers to the method of merging different colored bands into one image. The temporal image was subsequently obtained by sub setting a shape file of Parshuram Municipality using the same datum and transformation namely UTM45N, WGS 1984.

For each reference year, cloud-free or minimally cloudy Landsat scenes were selected from the post-monsoon dry season (October–December) to minimize seasonal spectral variability and vegetation greenness peaks. Landsat 7 and Landsat 8 images were acquired from USGS Earth Explorer with a cloud cover threshold  $\leq 5\%$ , ensuring optimal atmospheric conditions for classification. The years 2005, 2015, and 2025 were chosen to (i) represent approximately decadal intervals, (ii) correspond to distinct socio-environmental phases in Parshuram Municipality (pre-expansion, expansion peak and post-expansion adjustment) and (iii) align with available cloud-free Landsat scenes.

### 2.3. DATA ANALYSIS

#### 2.3.1. IMAGE PROCESSING

Since the images were captured during various months of the year depending on the availability of cloud-free data, they may be affected by seasonal variations and atmospheric influences such as aerosols, dust, clouds, and changing sun angles. Additionally, noise in the data also arises from the sensor's limitations, signal digitization or the data recording process. Subsequently, radiometric and geometric correction were accomplished through pan-sharpening the acquired images. Remote sensing software was utilized to eliminate periodic line dropouts and to bridge the gap present in the Landsat images from 2005, 2015 and 2025.

#### 2.3.2. LAND COVER CLASSIFICATION

A supervised maximum likelihood classification was implemented using seven training samples per class, selected to maximize spectral separability while maintaining within-class homogeneity. Although sample numbers may vary across studies, seven high-quality, internally consistent samples per class were sufficient due to the municipality's relatively simple spectral landscape and the clear contrast among the seven LULC categories (forest, agriculture, grassland, water body, sedimentation, landslide, settlement). Additional field validation was conducted using high-resolution Google Earth Pro imagery.

The subsequent steps were carried out to conduct the classification: -

- Formation of training set and development of the signature file: 7 training samples were generated for creating the signature file for each class.

Seven LULC classes were defined following the Land Use Act (2019) and visual-spectral characteristics relevant to Chure–Inner Terai landscapes. Forest includes dense and open tree cover with continuous canopy. Agriculture represents cultivated cropland, fallow fields, and terraced areas showing characteristic seasonal vegetation signatures. Grassland comprises herbaceous cover, shrubs below 1 m, and grazing-dominated areas. Water bodies include perennial and seasonal rivers, ponds and reservoirs. Sedimentation refers to actively deposited riverbed and floodplain surfaces dominated by sand, gravel, and silt; these are spectrally distinguishable from other bare surfaces through high reflectance in visible and SWIR bands and linear association with river channels. Landslide represents recent mass-movement scars, exposed soils, and debris slopes on hillsides with irregular textures, high SWIR reflectance, and geomorphic context separating them from sedimentation or barren agricultural fields. Settlement includes built-up areas, roads, compacted surfaces, and urban materials exhibiting high NIR absorption and strong SWIR contrast.

Mixed pixels and transitional zones—common in steep slopes, river edges, and patchy agro-forestry mosaics—were minimized through three measures: (i) selecting post-monsoon imagery when vegetation phenology is most stable, reducing ambiguity between grassland and cropland; (ii) using homogeneous training samples placed only in spectrally pure areas validated with Google Earth Pro; and (iii) applying manual post-classification refinement in areas prone to spectral confusion (e.g., new river deposits versus degraded crop fields). Edge pixels near riverbanks and landslide

toes were cross-checked against high-resolution reference imagery to reduce misclassification of transitional bare surfaces.

- Utilized the maximum likelihood classification tool for categorization.
- Accuracy and evaluation were conducted by collecting random samples and contrasting them with the ground truth using Google Earth Pro.

### 2.3.3. PREPARATION OF LANDCOVER MAPS

Beginning with data collection, the final land use and land cover (LULC) maps for the years 2005, 2015, and 2025 were created, including accuracy evaluation. The map featured a scale of 1:141235 for accurate representation and interpretation grid scale for enhanced clarity.

### 2.3.4. CHANGE DETECTION

Land use change detection has been carried out by superimposing the output features from various time periods, specifically 2005, 2015 and 2025 utilizing GIS software. Land cover change has been identified through the analysis and assessment of changes in an Excel sheet.

Change detection was performed using a post-classification comparison approach, which overlays independently classified LULC maps from 2005, 2015, and 2025 to quantify class-to-class conversions. This method minimizes atmospheric and sensor-related differences across dates and allows direct measurement of net gains, losses, and class transitions. A LULC transition matrix was generated for each period (2005–2015, 2015–2025, and 2005–2025), enabling the identification of dominant land-transition pathways. The most prominent transitions included: forest → agriculture and grassland → agriculture between 2005–2015 during the expansion phase; and agriculture → sedimentation, agriculture → forest (natural regeneration), and grassland → shrub/forest between 2015–2025. River-adjacent agricultural land showed significant conversion to sedimentation, consistent with increased erosion and channel instability in the Chure belt. These transitions highlight a shift from anthropogenic expansion to geomorphically driven degradation and partial ecological recovery in the later decade.

## 3. Results

Over the twenty-year period from 2005 to 2025, Parshuram Municipality has experienced profound and complex changes in its land use and land cover (LULC) patterns. These changes are indicative of broader socio-economic transformations and environmental pressures that have reshaped the landscape with important implications for ecological health, climate resilience and disaster vulnerability.

| Year             | 2005         |        | 2015         |        | 2025         |       | Change %<br>(2015-2025) | Overall<br>Change %<br>(2005-2025) |
|------------------|--------------|--------|--------------|--------|--------------|-------|-------------------------|------------------------------------|
| Land Cover Class | Area (Sq.km) | Area % | Area (Sq.km) | Area % | Area (sq.km) | Area% |                         |                                    |
| Water Body       | 7.08         | 2%     | 15.25        | 4%     | 14.89        | 4%    | 0%                      | 2%                                 |
| Forest           | 121.72       | 29%    | 19.88        | 5%     | 58.86        | 14%   | 9%                      | -15%                               |
| Grassland        | 144.45       | 35%    | 57.15        | 14%    | 35.59        | 9%    | -5%                     | -26%                               |
| Agriculture      | 32.25        | 8%     | 249.37       | 60%    | 135.31       | 33%   | -28%                    | 25%                                |
| Sedimentation    | 20.17        | 5%     | 23.69        | 6%     | 131.67       | 32%   | 26%                     | 27%                                |
| Landslide        | 30.13        | 7%     | 8.95         | 2%     | 11.85        | 3%    | 1%                      | -4%                                |
| Settlement       | 56.85        | 14%    | 38.36        | 9%     | 24.49        | 6%    | -3%                     | -8%                                |

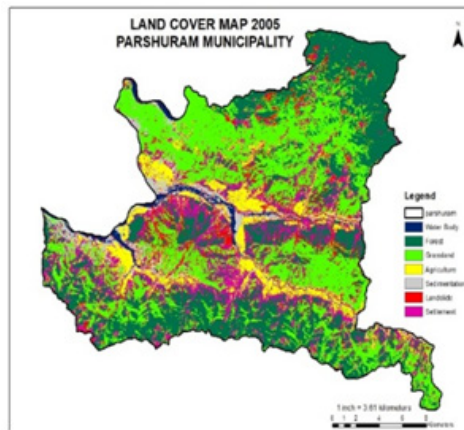


Figure 2: - Land use and Land cover map of Parshuram Municipality, Dadeladhura (2005)

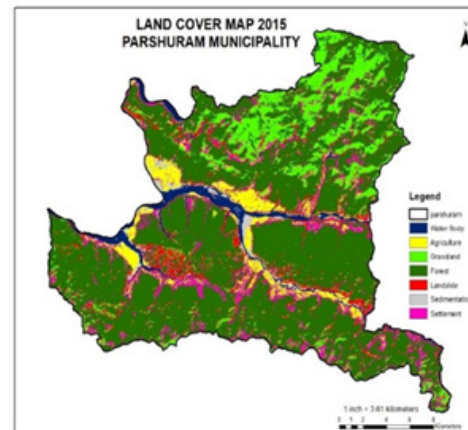


Figure 3: - Land use and Land cover map of Parshuram Municipality, Dadeladhura (2015)

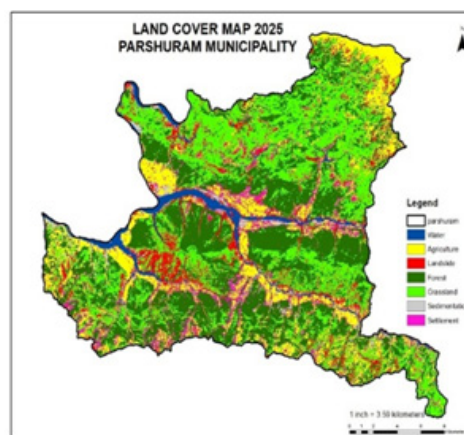


Figure 4: - Land use and Land cover map of Parshuram Municipality, Dadeladhura (2025)

Figure 2, Figure 3, and Figure 4 present the LULC maps for 2005, 2015, and 2025, respectively, clearly illustrating the spatial patterns underlying the numerical changes reported in Table 1. As shown in Figure 2, forest and grassland dominated the landscape in 2005, particularly across the Chure foothills and mid-elevation slopes. By 2015 (Figure 3), agricultural expansion is visibly widespread, replacing extensive areas of forest and grassland in the central and southern parts of the municipality. In Figure 4, the 2025 map highlights the pronounced growth of sedimentation zones along major river corridors and floodplains, as well as pockets of forest regeneration in areas previously converted to agriculture. These visual patterns reinforce the quantitative trends in Table 1 and make the trajectory of landscape transformation over the two decades more evident.

Between 2005 and 2025, Parshuram Municipality experienced notable land cover shifts, reflecting interactions between human activity, demographics, and environmental processes:

**Agriculture:** Expanded from 8% to 60% (2005–2015) and contracted to 33% (2016–2025). Expansion co-occurred with population growth and subsistence farming; contraction aligns with outmigration, changing livelihoods, and possible land restoration initiatives.

**Forest:** Declined sharply from 29% to 5% (2005–2015) due to clearing and extraction, then partially recovered to 14% by 2025, likely supported by community forestry and natural regeneration.

**Grasslands:** Declined steadily from 35% to 9%, reflecting conversion to agriculture and urban expansion. Their loss may increase soil erosion and reduce natural buffers.

**Sedimentation:** Increased from 5% to 32%, consistent with erosion from deforested and cultivated lands; intensified rainfall may also contribute.

**Water bodies:** Slight expansion (2% → 4%) then stabilization, possibly linked to artificial ponds, river course changes, or seasonal variation.

**Landslides and settlements:** Landslide areas decreased initially but rose slightly to 3% by 2025; settlement coverage fell from 14% to 6%, likely reflecting migration and land-use changes.

Observed patterns document temporal co-occurrence between LULC changes, demographic trends, and environmental outcomes. While these patterns suggest plausible links to ecosystem degradation and disaster vulnerability, causal relationships remain hypotheses, and other factors such as extreme rainfall and infrastructure changes may also play a role.

## 4. Discussion

These LULC trends in Parshuram Municipality have direct bearings on climate resilience and disaster vulnerability. The early deforestation and aggressive agricultural expansion compromised natural buffers such as forests and grasslands, accelerating soil erosion and sedimentation. These changes likely contributed to increased frequency and severity of flooding and landslides, as natural drainage and slope stability were undermined. The recent partial recovery of forests may help reverse some degradation, but the extensive sedimentation and ongoing grassland loss highlights persistent vulnerabilities.

Moreover, these changes interact with broader climate trends including increased rainfall variability, stronger monsoons and prolonged dry spells. Without sustainable land management and restoration efforts, the municipality's communities remain exposed to escalating disaster risks, threatening livelihoods, infrastructure and ecosystem health. The land use transformation pattern in Parshuram Municipality between 2005 and 2015 has had cascading impacts on local disaster risk patterns.

| Period    | # of flood incident | # of landslide incident | # of death | Productive land lost (ha) |
|-----------|---------------------|-------------------------|------------|---------------------------|
| 2005-2025 | 27                  | 42                      | 10         | 68                        |
| 2016-2025 | 32                  | 49                      | 14         | 75                        |

Table 3: - Disaster Loss and Damage Data (Source: - Parshuram Municipality Disaster Records (2005-2025))

Between the first and second periods, flood events increased by 19%, landslides by 17%, deaths by 40% and productive land loss by 10%. This upward trend underscores the compounded effect of climate extremes and anthropogenic land use changes. The reduction in natural vegetation has not only diminished ecosystem services but also amplified the municipality's exposure and vulnerability to hydrometeorological hazards.

Disaster loss and damage information was obtained from the official municipal disaster records maintained by Parshuram Municipality, which compile incident reports submitted by ward offices, police posts, community disaster management committees (CDMCs), and sectoral departments. These records cover floods, landslides, deaths, injuries, and “productive land lost,” defined as agricultural or grazing land rendered unusable due to erosion, sediment deposition, or landslide scarring. As with many local administrative datasets, the records are subject to under-reporting, especially for small or unreported events in remote Chure settlements; however, major incidents are consistently recorded and provide a reliable basis for temporal comparison.

The two comparison periods—2005–2015 and 2016–2025—were selected to align with the major phases of landscape transition identified in the LULC analysis. Although the windows are unequal, they correspond to (i) the decade of rapid agricultural expansion and forest loss (2005–2015), and (ii) the subsequent period characterized by agricultural contraction, forest regeneration, and rising sedimentation (2016–2025). This alignment allows a more meaningful interpretation of how distinct LULC phases relate to changes in disaster frequency, rather than strictly equal time blocks. The

comparison therefore helps illustrate how shifts in land systems have influenced flood and landslide patterns over time.

LULC changes and disaster trends in Parshuram Municipality reflect temporal co-occurrence rather than direct causation. While the data show that periods of rapid deforestation and agricultural expansion coincided with increases in floods, landslides, and productive land loss, other factors—such as inter-annual rainfall variability, extreme weather events, and local infrastructure changes—also contribute to hazard occurrence and severity. Therefore, statements regarding LULC-driven disaster risk are interpretive hypotheses based on observed patterns, ecological understanding, and prior research, rather than empirically proven causal relationships. Distinguishing between documented trends and inferred linkages ensures that conclusions remain scientifically cautious while still highlighting plausible pathways through which land use change may influence disaster vulnerability.

The observed LULC trajectories in Parshuram Municipality are closely intertwined with local socioeconomic and demographic dynamics. The early phase of rapid forest loss and agricultural expansion (2005–2015) coincided with higher population density and reliance on subsistence agriculture, reflecting the pressure on land for cultivation and grazing. Subsequent trends, including partial forest regeneration and contraction of cultivated areas (2016–2025), align with patterns of population decline and out-migration, particularly of working-age residents seeking employment elsewhere. These demographic shifts have reduced direct pressure on agricultural land but also contributed to the abandonment of some terraces and the accumulation of sediment in lower slopes and riverbeds. Changes in livelihoods—from primarily subsistence farming to diversified or off-farm income—further influenced land management decisions, with implications for slope stability, grassland conservation, and natural buffer restoration. Governance changes, including strengthened municipal planning, forest management initiatives, and community forestry programs, appear to have facilitated localized recovery of forest cover, illustrating how in

By explicitly linking LULC patterns with population trends, migration, livelihoods, and governance, the analysis moves beyond a purely ecological interpretation, highlighting the coupled human–environment system in which landscape changes and disaster vulnerability co-evolve. This framing also underscores why disaster risk patterns are not solely a function of physical processes, but emerge from the interaction of social, economic, and institutional drivers with environmental change.

If current patterns of deforestation, unplanned settlement expansion and agricultural encroachment continue, Parshuram Municipality may experience further escalation in disaster incidents, reduced agricultural productivity and long-term ecosystem degradation. This highlights the urgent need for integrated land management strategies, ecosystem restoration programs and climate-resilient livelihood planning to break the feedback loop between land degradation and disaster vulnerability.

The link between LULC change and disaster risk in Parshuram is profoundly spatial, defined by a cascade of vulnerability from the hillslopes to the river corridors. In the fragile Chure hills, the expansion of agriculture and the decline of forest cover act as a primary trigger, creating landslide clusters on steep, destabilized slopes. This mass wasting feeds a colossal sediment load into the river systems. As these rivers exit the steep terrain and enter the gentler gradients of the Inner Terai, the sudden drop in velocity forces the material to deposit, resulting in sedimentation clustering in the active river corridors. This aggradation elevates riverbeds and reduces channel capacity, directly translating the upstream LULC change into a severe downstream hazard—amplified flood inundation and bank erosion that threaten settlements and agricultural land in the low-lying areas of the municipality.

## 5. Conclusions

The analysis of land use and land cover (LULC) change in Parshuram Municipality from 2005 to 2025 revealed a complex and non-linear trajectory of landscape transformation. The initial decade (2005–2015) was characterized by a dramatic expansion of agricultural land, primarily driven by the

conversion of natural forests and grasslands. This aggressive land use changes likely contributed to the observed decline in forest cover and reduction in grassland areas. These shifts suggest a period of intensified human-environment interaction where agricultural expansion dominated the land-change dynamic at the expense of ecological stability.

The subsequent decade (2015–2025) demonstrates a reversal in this trend with agricultural land decreasing by and forest cover recovering. However, this recovery did not fully mitigate the environmental consequences of the previous decade. The most critical finding was the increase in sedimentation areas between 2015 and 2025 which persistent vulnerability of the Chure region's geomorphology, indicating that initial deforestation has led to a cascade of long-term geomorphic processes such as increased soil erosion and fluvial sediment deposition. The overall decline of grasslands highlights a sustained loss of critical ecological buffers. These findings emphasize that LULC change in this fragile Inner Terai-Chure interface is not a simple linear process but a complex feedback loop where initial human land management triggers long-term environmental degradation demanding a more integrated and technically informed approach to land management.

Based on the LULC change trajectories and the observed environmental consequences, the following technical recommendations are proposed for sustainable land management in Parshuram Municipality:

1. Monitoring and Early Warning Systems (Short-term, relatively low-cost)
  - Strengthen local hazard monitoring and reporting through community disaster management committees (CDMCs) and ward offices.
  - Implement low-cost, real-time rainfall and river gauge monitoring to support early warning dissemination.
  - Train local communities in interpreting warnings and undertaking rapid response measures.
2. Land-Use Planning and Zoning (Medium- to long-term, structural)
  - Enforce land-use regulations to restrict settlement and agriculture in high-risk flood and landslide zones.
  - Promote slope stabilization measures and integrate hazard mapping into municipal planning.
  - Encourage relocation or retrofitting of vulnerable infrastructure in hazard-prone areas.
3. Nature-Based Solutions and Ecosystem Restoration (Medium- to long-term)
  - Expand community forestry programs and support regeneration of degraded forests and grasslands.
  - Restore riparian buffers and implement soil and water conservation measures to reduce sedimentation.
  - Promote agroforestry and climate-smart agriculture to balance production with ecosystem protection.
4. Community Engagement and Capacity Building (Short- to medium-term)
  - Conduct awareness campaigns on disaster preparedness, climate risks, and sustainable land management.
  - Train local youth and community volunteers in first aid, search and rescue, and early warning response.
  - Strengthen participatory decision-making to ensure local knowledge informs planning and response.
5. Governance and Institutional Strengthening (Medium- to long-term)
  - Improve coordination among municipal departments, CDMCs, NGOs, and development partners for integrated DRM and CCA interventions.
  - Establish clear roles, responsibilities, and accountability mechanisms for disaster risk management.
  - Integrate LULC monitoring and disaster risk assessments into routine municipal planning and budgeting.
  - By grouping recommendations into thematic areas and indicating timeframes and relative costs, the municipality can prioritize actions that deliver immediate benefits while building long-term resilience and sustainability.

## 6. Limitations and Future Research

This study has several limitations. First, the Landsat satellite imagery used for LULC analysis is constrained by moderate spatial resolution and seasonal variations, which may affect the precision of land cover classification. Second, classification uncertainty and potential misclassification between similar land cover types (e.g., grassland vs. shrubland) could influence trend estimates. Third, disaster loss and damage records from the municipality, while useful for temporal comparison, are subject to under-reporting, particularly for minor events in remote areas. Finally, the study focuses on a single municipality, limiting the generalizability of findings to other contexts.

Future research could address these limitations by integrating higher-resolution and multi-season imagery, incorporating finer-scale hazard overlays, and conducting household- or community-level vulnerability assessments. Scenario modeling of climate change impacts combined with LULC transitions could further support planning for long-term resilience.

**Conflicts of Interest:** The authors declare no conflict of interest.

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