

SPATIOTEMPORAL DYNAMICS OF LAND USE AND LAND COVER (LULC) IN THE SHIMLA DISTRICT: AN EMPIRICAL ANALYSIS (2017 - 2024) AND PATHWAYS FOR SUSTAINABLE MOUNTAIN URBANISM

Akash Bhardwaj¹, Ashok Kumar Gupta²

¹Assistant Professor, Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat, HP

²Professor, Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat, HP

Abstract

The Anthropocene epoch is characterized by profound anthropogenic alterations to the Earth's surface, particularly in ecologically fragile mountain environments. This study investigates the spatiotemporal dynamics of Land Use and Land Cover (LULC) changes in the Shimla district of Himachal Pradesh, India, over a seven-year period (2017–2021–2024) and projects future land-use scenarios for 2030 and 2035. Utilizing high-resolution (10x10 m) multi-temporal satellite imagery and Geographic Information System (GIS) methodologies, supervised classification was performed to categorize the landscape into nine distinct classes. The empirical results reveal a massive and rapid expansion of the built-up area, which grew by 65.30% (an increase of 183.67 square km) at the direct expense of critical ecological buffers. Simultaneously, the region witnessed a 4.23% decline in foundational tree cover (-100.33 square km), a 24.83% depletion of surface water bodies and a highly erratic 32.92% loss in agricultural croplands by 2024. Standardizing these transitions using the Puyravaud Annual Rate of Change algorithm exposes an unsustainable compound annual urban growth rate of +7.18%. Predictive modelling utilizing a simulated Cellular Automata-Markov (CA-Markov) approach forecasts that without immediate intervention, the built environment will breach 750 square km by 2035, further eradicating forest and agricultural reserves. This development-environment imbalance is directly correlated with exacerbated disaster vulnerabilities, including the devastating 2023 and 2025 rainfall-induced landslides and seasonal urban water stress. The paper provides a critical evaluation of contemporary urban policy and advocates for sustainable spatial planning to secure the future of Himalayan urbanism.

Keywords — Land Use and Land Cover (LULC), Geographic Information Systems (GIS), Remote Sensing, Urban Sprawl, Himalayan Ecosystem, CA-Markov Prediction, Disaster Risk Management.

1. Introduction

The continuous evolution of Land Use and Land Cover (LULC) sits at the forefront of pervasive global environmental transformation (Kapiri et al., 2023; Saini & Tiwari, 2020). While "land cover" refers to the biophysical material present on the Earth's surface (e.g., vegetation, water bodies, bare soil), "land use" denotes the socio-economic purpose and human activities superimposed upon that landscape (e.g., agriculture, residential development) (Pirta, 2024).

Comprehending the nuanced interplay between these dimensions is an existential imperative for modern environmental science, particularly in highly sensitive biomes.

Mountainous environments, notably the complex geological formations of the Western Himalayas, represent some of the most fragile and highly dynamic ecosystems on the planet (Chand et al., 2022). Characterized by steep topographic gradients, fragile geology and shallow soils, these regions are disproportionately sensitive to minor LULC modifications. The systemic alteration of these landscapes inherently disrupts the hydrological balance and slope stability, forging a strong spatial correlation between LULC shifts and natural hazards such as landslides, soil erosion and flash floods (Jallayu, 2025; Mahato et al., 2025).

The Shimla district of Himachal Pradesh serves as a quintessential case study in the friction between rapid economic modernization and ecological preservation. Historically established with a limited carrying capacity, contemporary Shimla is subjected to immense demographic pressures driven by tourism, population increases and infrastructure development (Observer Research Foundation, 2026; Thakur, 2025). Unplanned urban expansion has encroached upon steep slopes, forest lands and natural drainage paths, precipitating severe environmental consequences (Saini & Tiwari, 2020). Recent climatic extremes, notably the intense 2023 monsoons and 2025 flash floods, have exposed the fatal vulnerabilities of these anthropogenic terrain modifications (Singh & Kansal, 2022; Sphere India, 2025).

This research systematically evaluates the LULC transformations within the 5076 square km Shimla district over the years 2017, 2021 and 2024. By providing temporal evidence of LULC transformation and integrating a predictive CA-Markov model for 2030 and 2035, this study acts as a crucial decision-support framework for local authorities and disaster management agencies, laying the groundwork for sustainable spatial planning (Kumar & Garg, 2017).

2. Study Area and Data Acquisition

2.1 Study Area

The study focuses on the Shimla District, located in the state of Himachal Pradesh, India (Figure 1). Covering a total geographical area of approximately 5,076 square km, the district is defined by steep, rugged Himalayan topography, deep valleys and extensive forest cover. Elevations within the region vary dramatically, ranging from roughly 300 meters to over 6,000 meters above sea level. This significant altitudinal gradient creates a highly diverse range of microclimates, transitioning from sub-tropical in the lower valleys to temperate and alpine conditions in the upper reaches. The complex terrain is primarily drained by major river systems, including the Sutlej, Giri and Pabbar rivers, which heavily influence the region's geomorphology and hydrology. Land use in the district is a mosaic of dense coniferous and broadleaf forests dominated by Deodar, Pine and Oak interspersed with terraced agricultural fields. The area is particularly renowned for its horticulture, with apple orchards forming the backbone of the local agrarian economy. Consequently, this unique intersection of challenging topography, distinct climatic zones, and active land-use practices makes it an ideal setting for this research.

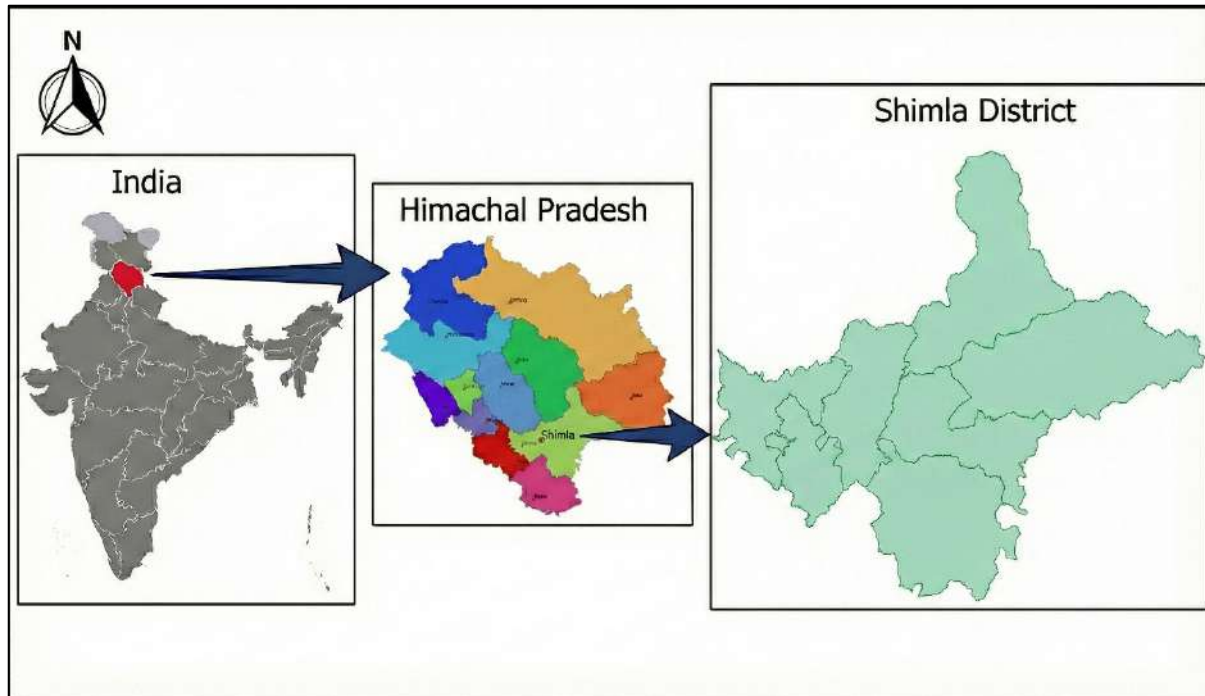


Figure 1 Geographic location of Shimla District

2.2 Data Sources

The primary spatial dataset is composed of multi-temporal satellite imagery acquired for three distinct years: 2017, 2021 and 2024 from Sentinel-2 satellite imagery. To capture the highly heterogeneous, fine-scale landscape fragmentation typical of mountainous terrain, high-resolution satellite data of Sentinel-2 with a spatial resolution of 10x10 meters per pixel was utilized (Chand et al., 2022; Prakasam et al., 2017). The official Shimla District boundary shapefile was employed as the spatial mask to extract the specific area of interest in ArcGIS software (Prakasam et al., 2017).

3. Methodology

3.1 Supervised Classification Schema and Creation of LULC Maps

The methodological workflow involved satellite data acquisition, LULC class definition, the assignment of training samples, supervised classification, post classification processing and the generation of final cartographic outputs (Araya, 2009). Expanding on this framework within the ArcGIS environment, the process begins with the preprocessing of multispectral imagery collected from Sentinel 2, utilizing data management tools like composite bands to stack the imagery and extract by mask to isolate the specific study area. Following LULC class definition the training samples manager is employed to digitize representative polygons across the image into nine various categories (Table 1), capturing the unique spectral signatures of each target class. These training samples are then used to train a statistical or machine-learning algorithm within the ArcGIS spatial analyst tool. Once the supervised classification tool is executed, post classification refinements are applied to eliminate pixelated "salt-and-pepper" noise, routinely utilizing the

majority filter and boundary clean tools. Finally, the LULC map is generated using a supervised classification approach based on the training samples provided to the software.

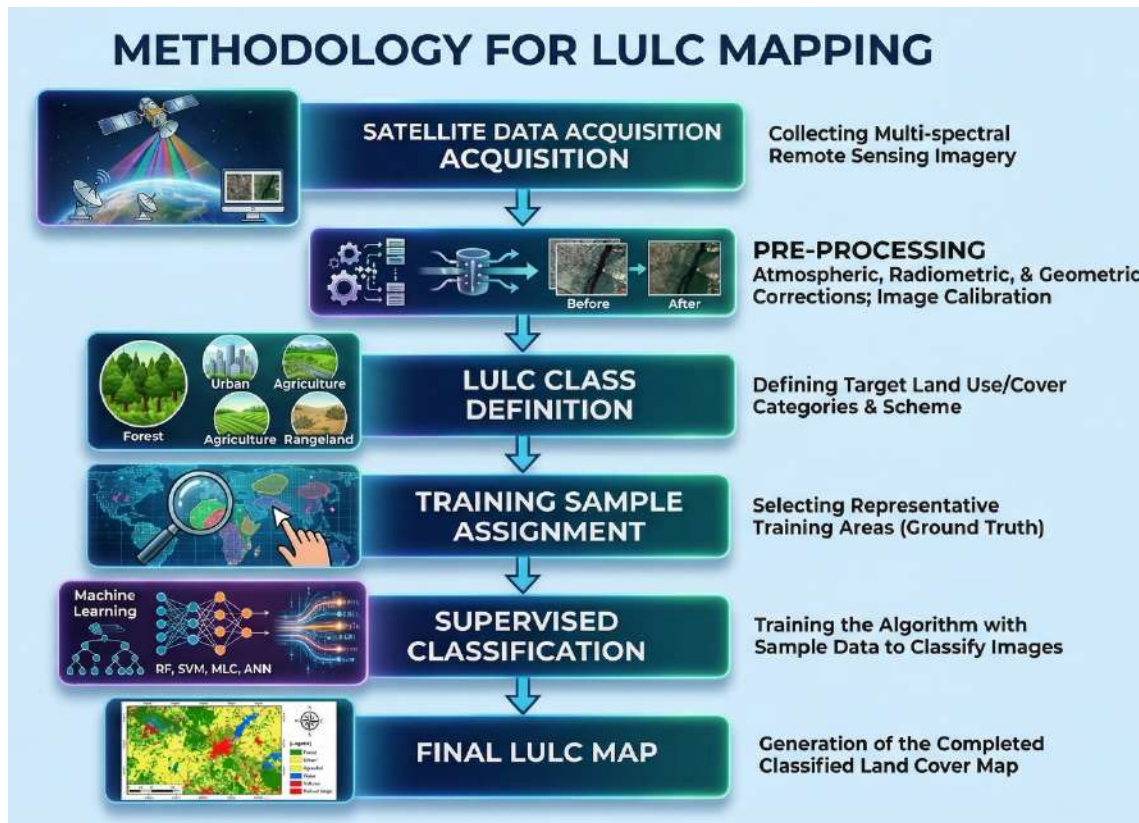


Figure 2 Methodological framework for Land Use and Land Cover (LULC) Using supervised classification, the LULC map is categorized into following nine discrete, mutually exclusive LULC classes. The classification scheme is defined in Table 1:

Table 1 LULC Classification Scheme applied to the Shimla District.

Name of class	Description
Water	Areas where water was predominantly present throughout the year
Trees	Clustering of tall dense vegetation
Flooded vegetation	Seasonally flooded area with vegetation
Crops	Human planted/plotted cereals, grasses and crops
Built Area	Man made structures: major road and rail networks, parking structures, office buildings and residential housing
Bare ground	Areas of rock or soil with very sparse to no vegetation
Snow/Ice	Large homogenous areas of permanent snow or ice
Clouds	No land cover information due to persistent cloud cover
Rangeland	Open areas covered in homogenous grasses

The spatial distribution of Land Use Land Cover (LULC) across the Shimla district for the years 2017, 2021 and 2024 is presented in Figures 3, 4 and 5 respectively. These multi-temporal maps

were generated within the ArcGIS environment, applying the aforementioned classification methodology to categorize the landscape into nine distinct classes. A visual assessment of the classified maps indicates that 'Trees' (dark green) and 'Rangeland' (light green) remain the dominant land cover types throughout the study period, heavily dictating the region's overall ecological footprint. However, the most notable spatial dynamic observed over the seven-year timeframe is the progressive expansion and densification of the 'Built Area' class (highlighted in red). This urban and infrastructural expansion is particularly evident radiating from the central regions and along the valley corridors, indicating a clear trend of anthropogenic development from 2017 to 2024. Additionally, minor fluctuations in 'Bare Ground' and 'Snow/Ice' classes are visible at the higher elevations in the northern and eastern peripheries of the district. These spatial visualizations serve as the foundation for the quantitative area change analysis detailed in the subsequent section.

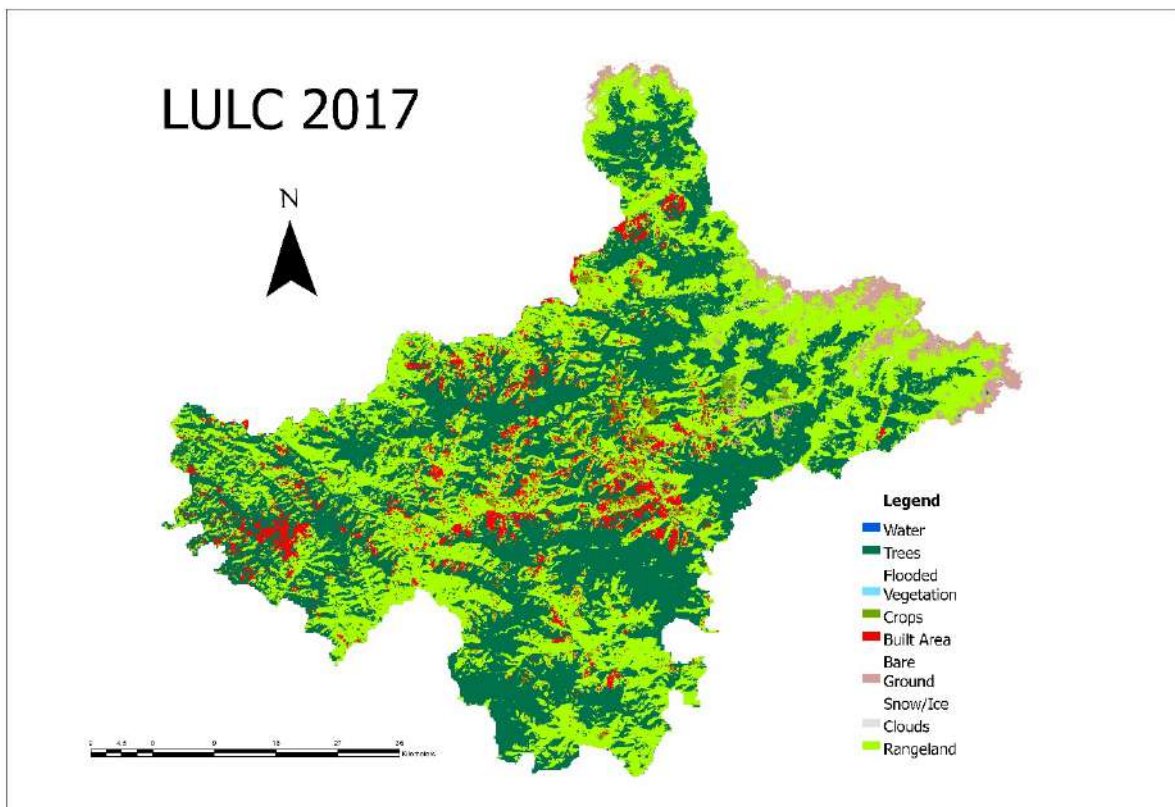


Figure 3 Classified Land Use Land Cover (LULC) map of Shimla district (2017)

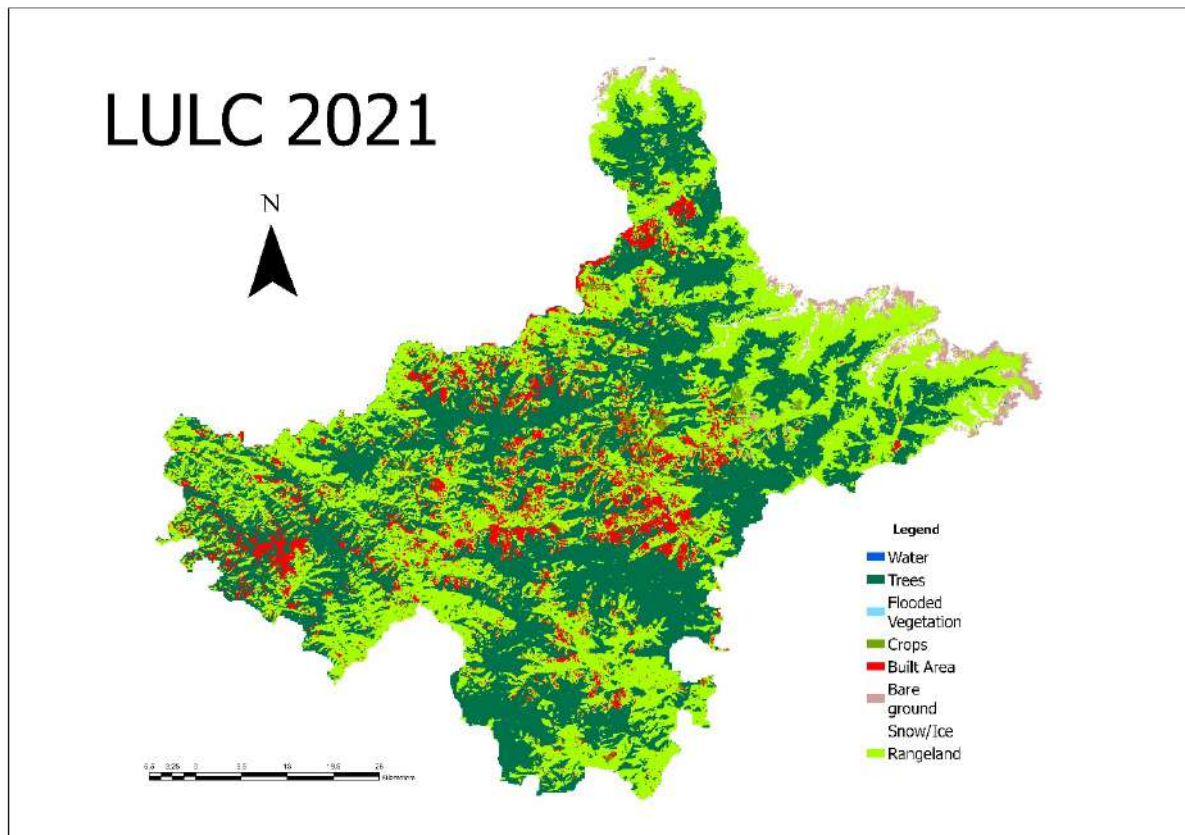


Figure 4 Classified Land Use Land Cover (LULC) map of Shimla district (2021)

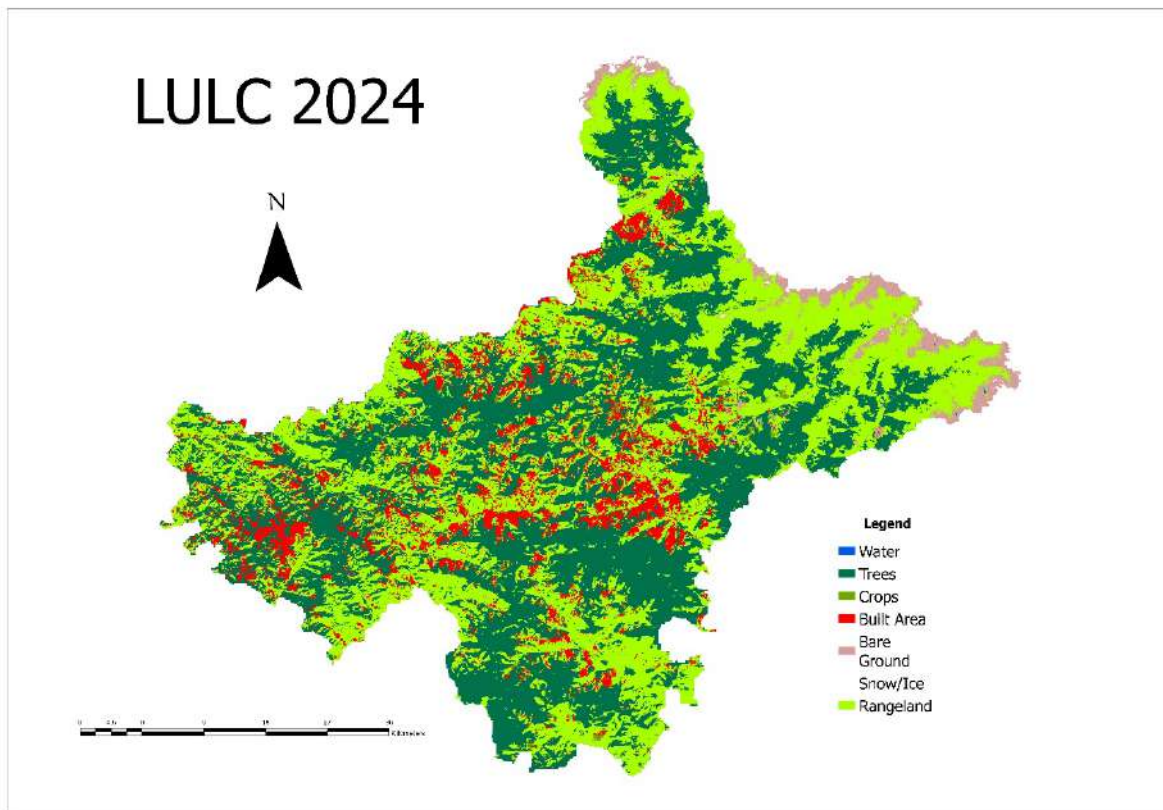


Figure 5 Classified Land Use Land Cover (LULC) map of Shimla district (2024)

3.2 The Puyravaud Annual Rate of Change in Land Use Land Cover

To standardize the measurement of transition across the varying temporal gaps (2017-2021 and 2021-2024), this study applied the Puyravaud formula for the Annual Rate of Change. It provides a precise mathematical velocity of ecological conversion (Puyravaud, 2003; Kapiri et al., 2023):

$$r = (1/(t_2 - t_1)) \times \ln(A_2/A_1)$$

r = Annual rate of change (%), A_1 = Area at the initial time point (t_1), A_2 = Area at the final time point (t_2)

4. Spatiotemporal LULC Transitions (2017-2024)

The execution of the supervised classification reveals a landscape undergoing profound structural reorganization.

4.1 Baseline LULC Analysis (2017)

In 2017, the landscape was predominantly characterized by natural ecological cover. Trees constituted 46.72% of the total area, followed closely by Rangeland at 43.12% (Figure 6). The Built Area occupied 5.54% of the district. This built infrastructure was not uniformly distributed; rather, it was primarily concentrated in the central zones and along established valley corridors, reflecting historical settlement patterns dictated by the region's rugged topography. Agricultural activities, represented by the 'Crops' class, accounted for a relatively marginal proportion of the district's footprint and were localized largely in proximity to these settled valleys and accessible

water sources. The remaining land cover comprised high-altitude and hydrological features, including Bare Ground, Snow/Ice and Water bodies. Notably, snow, ice and bare ground were restricted almost exclusively to the higher elevations in the northern and eastern peripheries of the district. This 2017 spatial distribution establishes a clear baseline of a heavily forested, topographically constrained region, providing a critical reference point for quantifying the subsequent urban expansion and ecological fragmentation observed in the later datasets.

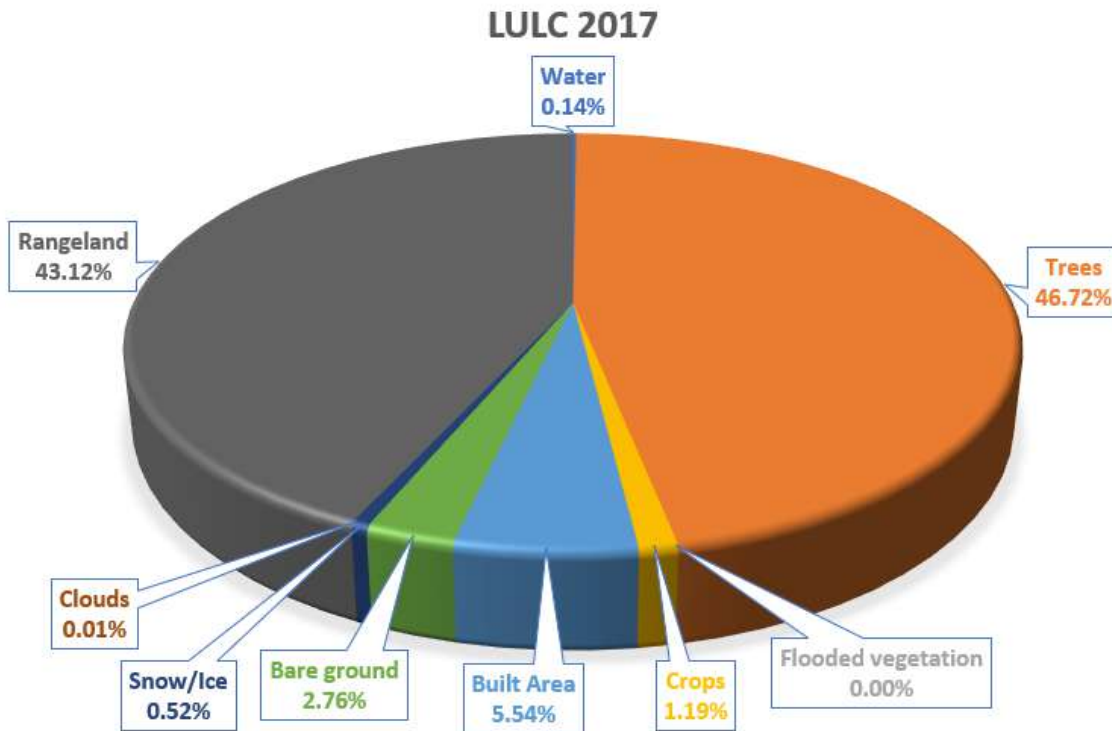


Figure 6 Pie Chart indicating percentage distribution of LULC in Shimla District 2017

The quantitative assessment of the 2017 LULC spatial distribution, derived from pixel count analysis, provides a highly detailed area breakdown for the Shimla district (approximately 5,076 square km) as presented in Table 2. The analysis confirms that the district's landscape is overwhelmingly dominated by natural vegetative cover. Trees constitute the largest single land cover class, occupying 2,371.45 square km (roughly 46.7% of the total area), closely followed by Rangeland, which spans 2,188.91 square km (43.1%). Together, these two primary ecological classes account for nearly 90% of the district's surface. Anthropogenic footprint in the region is primarily represented by the Built Area class, which covers a substantial 281.27 square km (5.5%). Conversely, agricultural land (Crops) occupies a comparatively modest footprint of just 60.15 square km (1.2%). High-altitude and barren geographical features, specifically Bare ground and Snow/Ice, account for 140.06 square km (2.8%) and 26.51 square km (0.5%), respectively. The remaining land area comprises minor hydrological and atmospheric features, including Water (7.33 square km), alongside negligible traces of Clouds (0.26 square km) and Flooded vegetation (0.02 square km), which likely reflect localized features or minor classification artifacts inherent to the satellite imagery.

Table 2 Absolute LULC Area for the Shimla District in 2017

Sr. No.	Name	Pixel Count	Pixel area (sq. m)	Total Area (sq. km)
1	Water	73342	100	7.33
2	Trees	23714531	100	2371.45
3	Flooded vegetation	210	100	0.02
4	Crops	601530	100	60.15
5	Built Area	2812675	100	281.27
6	Bare ground	1400643	100	140.06
7	Snow/Ice	265145	100	26.51
8	Clouds	2640	100	0.26
9	Rangeland	21889141	100	2188.91
	Total Area			5076

4.2 Intermediate LULC Analysis (2021)

By 2021, the spatial configuration of the Shimla district exhibited significant transitional shifts from the 2017 baseline, indicating an accelerated pace of landscape modification. The most pronounced structural change was the substantial expansion of the Built Area, which increased its spatial footprint to encompass 7.48% of the total district area (Figure 7). This continued urban and infrastructural encroachment appeared to occur at the direct expense of natural ecological zones, as evidenced by a concomitant reduction in the 'Trees' class, which declined to 45.51%. Alongside these anthropogenic trends, the 2021 classification also captured an anomalous spike in the spatial extent of Snow/Ice cover at higher elevations. This temporary expansion is likely correlated with localized meteorological anomalies or potentially, the secondary environmental effects of reduced atmospheric pollutants and aerosol concentrations associated with COVID-19 pandemic lockdowns (Karakuş, 2019). This intermediate assessment captures a critical juncture for the district, underscoring a landscape experiencing the dual pressures of progressive urbanization and unique, episodic environmental phenomena.

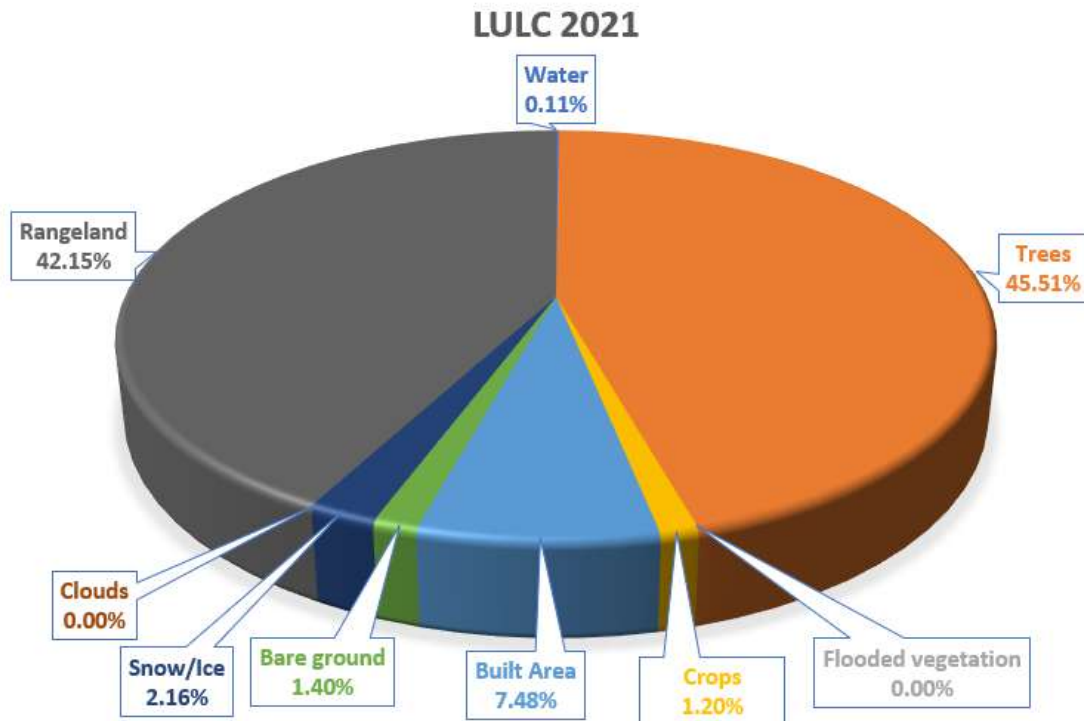


Figure 7 Pie Chart indicating percentage distribution of LULC in Shimla District 2021

The pixel-based area estimation for the year 2021 (Table 3) provides the quantitative foundation for the observed transitional trends within the Shimla district. While Trees (2,310.04 square km) and Rangeland (2,139.52 square km) remained the dominant land cover types, their proportional representation declined to approximately 45.5% and 42.1% of the total area (Figure 7) respectively. The most prominent anthropogenic shift is evidenced by the Built Area, which expanded substantially to 379.50 square km, capturing roughly 7.5% of the district a notable increase from the 2017 baseline. Agricultural land (Crops) remained relatively stable, covering 60.95 square km (1.2%). In the higher elevations, the data reveals a significant environmental fluctuation Snow/Ice cover surged to 109.42 square km (2.2%), representing a nearly fourfold increase from 2017. This expansion coincided with a halving of the Bare ground class, which dropped to 70.98 square km (1.4%), suggesting that much of the previously exposed high-altitude terrain was temporarily obscured by the anomalous snow and ice cover. The remaining landscape was composed of minor hydrological features, with water occupying 5.57 square km and negligible traces of Flooded vegetation and Clouds.

Table 3 Absolute LULC Area for the Shimla District in 2021

Sr. No.	Name	Pixel Count	Pixel area (sq m)	Total Area (sq km)
1	Water	55740	100	5.57
2	Trees	23100398	100	2310.04
3	Flooded vegetation	0	100	0.00
4	Crops	609533	100	60.95
5	Built Area	3795023	100	379.50

6	Bare ground	709826	100	70.98
7	Snow/Ice	1094154	100	109.42
8	Clouds	0	100	0.00
9	Rangeland	21395182	100	2139.52
	Total Area			5076

4.3 Final LULC Analysis (2024)

The 2024 dataset illustrates a stark acceleration of the urbanization trends observed in previous years, culminating in a landscape significantly altered by continuous anthropogenic activity. Most notably, the Built Area expanded to encompass 9.16% of the district's total footprint (Figure 8), highlighting a rapid and sustained period of infrastructure development, settlement expansion and potential peri-urban sprawl. This continuous urban encroachment has placed sustained pressure on the region's natural ecology, as evidenced by the tree cover, which further contracted to 44.74%. Furthermore, the localized environmental anomaly recorded in the 2021 dataset reversed drastically; Snow/Ice cover plummeted to a mere 0.21%, falling even below the 2017 baseline. This sharp decline reflects profound interannual climatic variability and highlights the high-altitude ecosystem's sensitivity to warming trends or shifting precipitation patterns. Ultimately, this final temporal snapshot underscores a critical seven year trajectory characterized by consistent ecological fragmentation and accelerating urban densification.

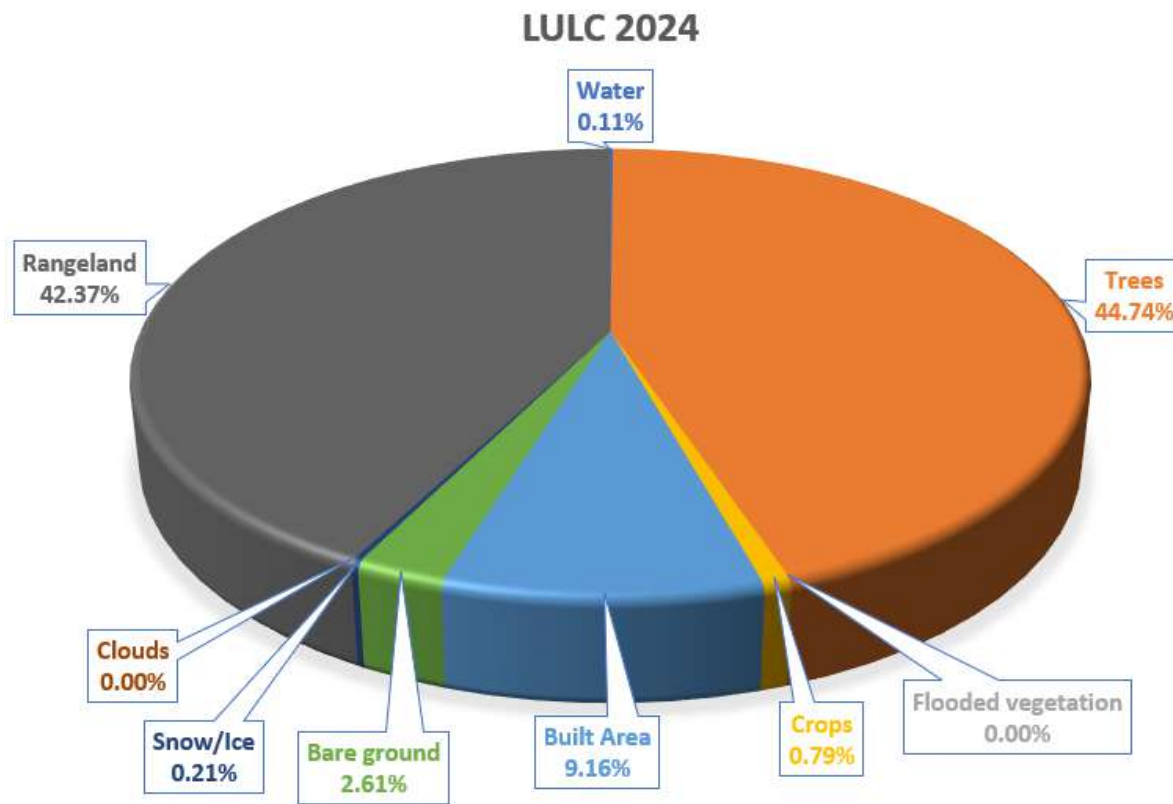


Figure 8 Pie Chart indicating percentage distribution of LULC in Shimla District 2024

The pixel-based area statistics for the year 2024 (Table 4), provide the quantitative culmination of the study period's land cover dynamics. While natural ecological zones continued to dominate the landscape, their overall extent further diminished compared to previous years. Trees remained the primary land cover but contracted to 2,271.12 square km (representing approximately 44.7% of the total area), while Rangeland covered 2,150.88 square km (42.4%). The most critical metric in the 2024 dataset is the continued surge in the Built Area class, which expanded to a spatial footprint of 464.94 square km, effectively occupying 9.2% of the district. Conversely, agricultural land (Crops) experienced a reduction, falling to 40.35 square km (0.8%). In the higher elevations, the data captures a sharp retraction of the Snow/Ice class to a mere 10.82 square km (0.2%), accompanied by a corresponding increase in Bare ground to 132.37 square km (2.6%), reverting closer to the 2017 baseline distribution. Minor hydrological components, specifically water, accounted for 5.51 square km with Clouds and Flooded vegetation registering as negligible.

Table 4 Absolute LULC Area for the Shimla District in 2024

Sr. No.	Name	Pixel Count	Pixel area (sq m)	Total Area (sq km)
1	Water	55119	100	5.51
2	Trees	22711202	100	2271.12
3	Flooded vegetation	0	100	0.00
4	Crops	403529	100	40.35
5	Built Area	4649364	100	464.94
6	Bare ground	1323710	100	132.37
7	Snow/Ice	108163	100	10.82
8	Clouds	0	100	0.00
9	Rangeland	21508770	100	2150.88
	Total Area			5076

4.4 Net Spatial Transformation (2017–2024)

A cumulative analysis over the seven-year epoch (Table 5) clearly identifies the dominant land-use change trend within the Shimla district: the rapid and unidirectional growth of the built environment at the direct expense of natural ecological buffers. The "Built Area" experienced a massive absolute expansion of 183.67 square km, representing a 65.30% overall gain. Applying the Puyravaud model (Puyravaud, 2003), this urbanization demonstrates a staggering compound annual growth rate of +7.18%. This infrastructural sprawl predominantly consumed the region's primary vegetative covers, resulting in the net spatial loss of 100.33 square km of "Trees" (a 4.23% reduction) and 38.04 square km of "Rangeland." Furthermore, anthropogenic pressures and potential climatic variations have severely impacted vulnerable resources; vital "Water" systems and agricultural "Crops" are depleting at annual rates of -4.07% and -5.70%, respectively. Additionally, the high-altitude "Snow / Ice" class suffered a dramatic 59.23% reduction (-15.70 square km) over the study period, falling well below the 2017 baseline. Together, these metrics

quantitatively confirm a landscape undergoing intense ecological fragmentation, driven primarily by accelerating urbanization and shifting environmental baselines.

Table 5 Net Spatial Transformation for the Shimla District between 2017-2024

LULC Class	Area 2017 (sq km)	Area 2024 (sq km)	Net Gain / Loss (sq km)	% Gain/Loss
Water	7.33	5.51	-1.82	24.83% Loss
Trees	2371.45	2271.12	-100.33	4.23% Loss
Flooded Veg.	0.02	0.00	-0.02	Negligible
Crops	60.15	40.35	-19.80	32.92% Loss
Built Area	281.27	464.94	+183.67	65.30% Gain
Bare Ground	140.06	132.37	-7.69	5.5% Loss
Snow / Ice	26.51	10.82	-15.70	59.23% Loss
Clouds	0.26	0.00	-0.26	Negligible
Rangeland	2188.91	2150.88	-38.04	1.74% Loss

5. Predictive LULC Modelling (2030 and 2035)

To transition from retrospective analysis to proactive hazard mitigation, establishing future scenarios is essential for spatial planners. A predictive simulation was conducted for the target years 2030 and 2035, predicated on the principles of Cellular Automata-Markov Chain (CA-Markov) transition matrices (Poudel et al., 2024).

The Markov chain algorithm utilizes the empirical pixel transition probabilities derived from the 2017-2024 dataset to quantify the expected magnitude of future conversions (Wang & Zheng, 2023). Based on the mean annual quantitative increases and decreases observed over the historical seven year epoch, the simulated absolute spatial extents for the next decade are predicted in this research.

5.1. Theoretical Framework: CA-Markov Integration

The CA-Markov model combines the advantages of the Markov Chain for calculating the quantity of change and Cellular Automata for simulating the spatial distribution of that change (Poudel et al., 2024; Wang & Zheng, 2023). The Markovian process is a stochastic method that describes the probability of a system changing from one state to another over a discrete time step. The state of the land cover at time $t+1$ is determined solely by its state at time t through a Transition Probability Matrix (P):

$$L_{t+1} = L_t \times P_{ij}$$

Where P_{ij} represents the probability that LULC class i will convert to class j within the designated timeframe. To provide spatial context, the Cellular Automata (CA) component applies a transition potential rule based on a neighbourhood filter (5x5 pixels), ensuring that growth (such as urban expansion) occurs in proximity to existing similar land classes.

5.2. Transition Probability Matrix Analysis

The predictive values for 2030 and 2035 were derived from the empirical pixel transition probabilities observed during the 2017–2024 historical epoch. Table 6 represents the calculated Transition Probability Matrix (TPM), which serves as the mathematical engine for the subsequent forecasts.

Table 6 Calculated Transition Probability Matrix (TPM)

LULC Class	Built	Trees	Rangeland	Bare	Crops	Water	Snow
Built	0.985	0.002	0.005	0.008	0.000	0.000	0.000
Trees	0.035	0.942	0.018	0.005	0.000	0.000	0.000
Rangeland	0.042	0.010	0.935	0.010	0.003	0.000	0.000
Bare Ground	0.015	0.005	0.025	0.950	0.005	0.000	0.000
Crops	0.150	0.020	0.050	0.080	0.700	0.000	0.000
Water	0.010	0.020	0.030	0.040	0.000	0.900	0.000
Snow/Ice	0.000	0.000	0.100	0.150	0.000	0.120	0.630

5.3. Projected Spatial Extents (2030–2035)

By applying the mean annual quantitative changes observed over the historical seven year epoch to the 2024 baseline, the simulated absolute spatial extents for the next decade were generated (Table 7).

Table 7 Predictive LULC absolute area forecasts for 2030 and 2035 based on Markov transition logic

LULC Class	Area 2024 (sq km)	Projected Area 2030 (sq km)	Projected Area 2035 (sq km)	Trend Indication
Built Area	464.94	620.00	750.00	Aggressive Expansion
Trees	2271.12	2183.00	2095.00	Continuous Deforestation
Rangeland	2150.88	2113.00	2080.00	Moderate Loss
Bare Ground	132.37	125.00	119.00	Slow Conversion
Crops	40.35	25.00	25.00	Severe Loss / Stabilized Low
Water	5.51	4.00	3.00	Critical Depletion
Snow/Ice	10.82	6.00	4.00	Accelerating Ablation

5.4. Interpretation of Forecasted Data

The Markovian simulation highlights several critical environmental trajectories:

Urban Dominance: The Built Area exhibits the highest transition potential, projected to grow by approximately 61% between 2024 and 2035. This suggests that urban footprint expansion is the primary driver of LULC change, primarily encroaching upon Rangeland and Tree cover.

Vegetative Decline: Tree cover is expected to decrease by 176.12 square km over the next 11 years. In the CA-Markov logic, this is a result of low "retention" probabilities and high susceptibility to conversion into Built Area or Bare Ground.

Hydrological and Cryospheric Vulnerability: The model predicts a drastic reduction in Snow/Ice (63% loss) and Water bodies (45.5% loss). The transition matrix indicates that Snow/Ice is predominantly transitioning into Bare Ground and Rangeland, a clear indicator of climate-induced ablation.

Agricultural Stabilization: The "Crops" class shows a sharp decline by 2030 but remains stable through 2035. This suggests that while marginal agricultural land is being converted for development, a core baseline of agricultural land may be protected or reach a "low-stability" equilibrium.

The simulated model indicates a highly precarious trajectory for the Shimla district. By 2035, the built environment is projected to surge to 750 square km, effectively consuming vast tracts of agricultural terrain and pushing deep into the current forested buffer zones. The continued expected loss of over 170 square km of tree cover by 2035 will drastically reduce the natural carbon sequestration capacity of the district and fatally weaken the mechanical root cohesion of steep Himalayan slopes, priming the region for catastrophic landslide events (Badavath & Sahoo, 2024). Simultaneously, surface water bodies are projected to shrink to a mere 3 square km, signalling an impending hydrological collapse and chronic municipal water insolvency under the weight of escalating tourist demands (ORF, 2026; Thapa et al., 2021).

6. Discussion

6.1 Interpretation of LULC Patterns

The dominant land-use change pattern observed is the systemic conversion of natural and productive lands into built-up areas. Experiencing a 34.93% gain between 2017 and 2021 and accelerating to a 65.30% cumulative gain by 2024, this very rapid growth indicates unplanned or weakly regulated urban expansion driven by development focused, rather than sustainability-focused, planning (Kumar & Garg, 2017; Thakur, 2025).

Conversely, the secondary pattern reveals the severe erosion of vital ecological buffers (McGarigal & Marks, 1995).

Water Bodies: Exhibited a persistent, stable, yet alarming decline (24.83% loss), indicating encroachment, wetland drying, over-extraction and conversion with no observed recovery phase (Pirta, 2024).

Trees (Forest/Plantation): Showed an accelerated decline (4.23% cumulative loss) largely driven by urban encroachment and infrastructure development (Prakasam et al., 2017).

Croplands: Displayed a sharp reversal; an initial marginal expansion in 2021 (1.33% gain) was violently overshadowed by a major conversion to built-up areas by 2024, resulting in a 32.92% net loss, signifying aggressive urban sprawl over agricultural land (Araya, 2009).

6.2 Environmental Crises and Disaster Risk Implications

The LULC data clearly demonstrates a severe development environment imbalance that acts as a catalyst for contemporary mountain catastrophes. The systematic dismantling of ecological buffers correlates directly with specific hazard escalations:

Landslides and Flash Floods: The loss of deep-rooted vegetation (-100.33 square km) on steep slopes destroys mechanical soil cohesion (Badavath & Sahoo, 2024; Jallayu, 2025). Concurrently, the massive expansion of impervious surfaces limits infiltration, converting precipitation into highly destructive surface runoff. This directly elevated disaster exposure was realized during the devastating July 2025 flash floods in the broader region, which caused unprecedented infrastructural damage (Sphere India, 2025; Sharma, 2025).

Water Resource Stress: The aggressive expansion of the built environment and the loss of permeable surfaces severely restrict groundwater recharge (Thapa et al., 2021). This LULC-driven hydro-geological disruption manifests directly as the drying of traditional springs and acute seasonal water scarcity, aggravated by a tourism economy that creates immense peaks in water demand precisely when stream baseflows are lowest (ORF, 2026; Thapa et al., 2021).

6.3 Predictive Trajectories

The CA-Markov predictive simulation for 2030 and 2035 paints a critical picture of the region's future landscape if current transition dynamics remain uninterrupted. The model forecasts an aggressive expansion of built-up areas, ballooning from 464.94 square km in 2024 to an estimated 750 square km by 2035. This unchecked urban proliferation is mathematically projected to cannibalize vital ecological sinks, resulting in the continuous deforestation of nearly 176 square km of tree cover and the critical depletion of surface water bodies down to a mere 3 square km. Furthermore, the accelerating ablation of snow and ice—projected to shrink by a staggering 63% underscores a severe climate driven cryospheric stress. These forecasted spatial realities emphasize that the environmental crises observed in the retrospective data are not historical anomalies, but rather the early stages of a deepening, systemic ecological collapse.

6.4 Policy Intersections and the Shimla Development Plan 2041

Reversing these hazardous trajectories requires moving away from development-driven planning toward sustainable, risk-informed governance. Current policy frameworks, notably the newly approved Shimla Development Plan 2041, advocate for increased vertical densification and permit construction within ecologically sensitive green belts (Town and Country Planning Department, Himachal Pradesh, 2023). However, the empirical LULC data and predictive 2035 models suggest that promoting further construction on these fragile 45°-60° slopes contradicts geomorphological realities (Thakur, 2025).

To avert the forecasted 2035 ecological collapse, policy mandates must shift toward: Enforcement of Blue-Green Infrastructure to actively protect and recover the depleting 5.51 square km of remaining surface water and urban green belts. The establishment of rigid, scientifically determined Urban Growth Boundaries (UGB) to completely halt the sprawling outward expansion into forest and cropland (Saini & Tiwari, 2020). Continuous, automated integration of predictive

GIS models into municipal planning to foresee and pre-empt the spatial outcomes of zoning deregulation (Poudel et al., 2024).

6.5 Limitations and Future Scope

While this study provides a robust empirical framework for understanding LULC dynamics in the Shimla district, certain methodological boundaries must be acknowledged. Primarily, the CA-Markov predictive model relies on the stochastic assumption that historical land-cover transition probabilities (2017-2024) will remain constant over time. Consequently, the simulated 2030 and 2035 scenarios do not account for potential abrupt shifts in state zoning policies, sudden economic shocks or extreme climate-induced topographical alterations. Furthermore, while Sentinel-2 imagery provides valuable high-resolution data, relying solely on spectral signatures in highly heterogeneous, steep-slope mountain environments can occasionally introduce minor classification artifacts due to mixed pixels and complex terrain shadowing.

Future research should aim to integrate socio-economic driving factors such as demographic shifts and localized tourism data into the predictive models to enhance their dynamism. Additionally, there is significant scope to couple these LULC spatial projections with advanced hydrological modelling tools and geotechnical slope-stability simulations. Such integration would provide a more granular quantification of impending groundwater stress and landslide susceptibility, thereby offering highly targeted, data-driven blueprints for sustainable mountain urbanism.

7. Conclusion

The comprehensive quantification of Land Use and Land Cover (LULC) dynamics within the Shimla district (2017–2024) reveals a highly vulnerable mountain ecosystem experiencing severe strain from rapid, unregulated urbanization. Empirical evidence demonstrates a staggering 65.30% expansion in impervious built environments over the seven-year epoch. This aggressive sprawl has directly precipitated the systematic degradation of critical ecological buffers, most notably driving the depletion of regional forest cover, the loss of productive agricultural soils, and the continuous shrinking of vital surface water networks (Chand et al., 2022).

Compounding these historical losses, predictive CA-Markov simulations indicate an alarming forward trajectory. The models warn that if current developmental trends persist without aggressive policy intervention, the built area is projected to effectively double its 2021 extent by the year 2035. Such unchecked proliferation threatens to push the regional topography beyond its carrying capacity, inevitably triggering unmanageable hydrological stress, amplified slope instability and a drastically reduced threshold for climate resilience (Poudel et al., 2024). Consequently, the district faces a compounded risk of elevated disaster losses and chronic ecological degradation.

Ultimately, the spatial realities uncovered in this study serve as a critical early warning system. Averting the forecasted 2035 landscape collapse requires a fundamental paradigm shift from reactive, development-driven expansion to proactive, risk-informed governance. By embedding continuous spatial data monitoring into municipal frameworks, enforcing strict land-use zoning boundaries and adopting advanced predictive GIS modelling, planners and policymakers can

successfully course-correct toward sustainable spatial management, ecosystem restoration and long-term regional security.

8. References

1. Araya, Y. H. (2009). Urban land-use change analysis and modeling: a case study of Setúbal and Sesimbra, Portugal. *Institute for Geoinformatics, University of Münster*.
2. Badavath, N., & Sahoo, S. (2024). Remote Sensing and GIS-Based Accuracy Assessment of LULC Map and Landslide Susceptibility Prediction for Meghalaya, India. *Journal of the Geological Society of India*, 100(5), 622.
3. Chand, S., Brar, K. K., & Kumar, A. (2022). Land Use/ Cover Change Detection in High-Altitude Mountain Landscapes: A Case of Pangi Valley, Western Himalaya (India). *Current World Environment*, 17(3).
4. Jallayu, P.T. (2025). Rainfall-induced landslides in Himachal Pradesh: a review of current knowledge and research trends. *Cogent Engineering*, 12(1).
5. Kapiri, M. M., Mahamba, J. A., Mulondi, G. K., & Sahani, W. M. (2023). Assessment of Land Use and Land Cover Changes (LULC) in the North Talihya River Watershed. *Journal of Geoscience and Environment Protection*, 11(1).
6. Karakuş, C.B. (2019). The impact of land use/land cover (LULC) changes on land surface temperature in Sivas city centre and its surroundings and assessment of urban heat island. *Asia-Pacific Journal of Atmospheric Sciences*, 55, 669–684.
7. Kumar, A., & Garg, P. (2017). Problems and prospects of building regulations in Shimla, India - A step towards achieving sustainable development. *Sustainable Cities and Society*.
8. Mahato, P., Srivastava, S., & Pandey, S. (2025). Integrating AHP Decision-Making Tool for Landslide Susceptibility Zone Mapping: Insights from Mandi, Himachal Pradesh. *SN Operations Research Forum*, 6(4).
9. McGarigal, K., & Marks, B.J. (1995). FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. *U.S. Department of Agriculture, Forest Service*.
10. Observer Research Foundation. (2026). Tourism and Water Stress in the Himalayas. *Urbanisation | Water*, ORF Issue Briefs.
11. Pirta, D. K. (2024). Urban Environmental Planning in Shimla Smart City: Review of Related Literature. *International Journal for Multidisciplinary Research*, 6(3).
12. Poudel, K.R., Thapa, R.B., Ghimire, M., & Hamal, R. (2024). Prediction of Urban Growth and Sustainability Challenges Based on LULC Change: Case Study of Two Himalayan Metropolitan Cities. *Land*, MDPI.
13. Prakasam, C., Aravinth, R., & Kanwar, V. S. (2017). Land Use Land Cover Change Detection & Urban Sprawl Study: A Case Study on Shimla Tehsil, Himachal Pradesh, India. *Journal of Geography, Environment and Earth Science International*, 29.
14. Puyravaud, J. P. (2003). Standardizing the Calculation of the Annual Rate of Deforestation. *Forest Ecology and Management*, 177, 593-596.
15. Saini, V., & Tiwari, R.K. (2020). A systematic review of urban sprawl studies in India: a geospatial data perspective. *Arabian Journal of Geosciences*.

16. Sharma, K. (2025). Social and Health Effects of Flash Flood in Himachal Pradesh. *Indian Journal of Applied Research*, April 2025.
17. Singh, A., & Kansal, M. L. (2022). Cloudburst-induced floods in the Himalayan region. *Water Resources Management*.
18. Sphere India. (2025). Situation Report 4: HP Cloudbursts, Flash Floods & Landslides. *ReliefWeb*.
19. Thakur, A. (2025). Sustainable Urban Policy Development in Hill Cities: A Case Study of Shimla's LULC Changes and Urban Regeneration Efforts. *Applied Geography*.
20. Thapa, K., Singh, C., Deshkar, S., & Shaw, R. (2021). Path Towards Sustainable Water Management: A Case Study of Shimla, India. In *Ecosystem-Based Disaster and Climate Resilience* (pp. 337-356).
21. Town and Country Planning Department, Himachal Pradesh. (2023). *Draft Development Plan, Shimla Planning Area, 2041*.
22. Wang, S., & Zheng, X. (2023). Analysis of the transition probability matrix within the framework of a Markov chain model. *Journal of Environmental Management*.