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Spatio -Temporal Dynamics and Future Simulation of Urban Expansion in Lucknow Using a CA–Markov Model

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Abstract-- **Lucknow has experienced rapid urbanisation over the past few decades, leading to significant changes in land use and land cover (LULC). This study examines LULC changes from 1991 to 2026 and predicts the land-use pattern for 2036 using an Artificial Neural Network (ANN)-integrated Cellular Automata–Markov (CA–Markov) model. Multi-temporal Landsat imagery was classified using the Maximum Likelihood Classification algorithm, achieving overall accuracies ranging from 91.40% to 95.12%. The results reveal a substantial increase in built-up areas, accompanied by a decline in agricultural land and vegetation due to urban expansion. The ANN–CA–Markov model predicts continued growth of built-up land, particularly in peripheral areas and along major development corridors. The study highlights the effectiveness of integrating remote sensing, GIS, ANN, and CA–Markov modelling to analyse historical LULC dynamics and forecast future urban growth. The findings provide valuable insights for sustainable urban planning, land management, and environmental conservation in rapidly growing cities.**

Keywords-- **Land Use and Land Cover (LULC); Urbanisation; Urban Expansion; Remote Sensing; GIS; Artificial Neural Network; Cellular Automata–Markov Model.**

I. Introduction

Rapid urbanisation is one of the most important drivers of land transformation and environmental change, particularly in rapidly growing cities of developing and emerging economies, commonly referred to as the Global South. According to the United Nations (2019), the proportion of the global population living in urban areas is projected to reach 68% by 2050, intensifying pressure on land resources, infrastructure, and ecosystems. As urban areas have grown, they have fragmented agricultural land, vegetation, wetlands, and other natural landscapes, causing habitat degradation and growing pressures on natural resources (Foley et al., 2005; Seto et al., 2012).

In developing countries like India, these challenges are especially acute, as the urban landscape has been significantly altered over the years due to rapid population growth, economic liberalisation, industrialisation, infrastructure development, and peri-urban expansion (Pandey & Seto, 2015). Land Use and Land Cover (LULC) change is a key element in understanding the environmental impacts of urbanisation and informing sustainable urban planning. Advances in Remote Sensing (RS) and Geographic Information Systems (GIS) have greatly enhanced the monitoring and analysis of urban growth by providing consistent, multi-temporal observations across large geographical areas (Herold et al., 2005). These technologies enable quantitative measurement of land-cover change, urbanisation, and landscape change (Lambin et al., 2003; Weng, 2012). Of all the techniques, post-classification change detection is considered one of the most reliable methods for detecting land-cover change, as it involves comparing two independently classified maps from different time periods to minimise inconsistencies in the classification process (Singh, 1989). Similarly, Shannon's Entropy has been widely used to measure the urban compactness and sprawl by measuring the spatial dispersion of built-up development (Sudhira et al., 2004). In addition, by incorporating geospatial methods into the Artificial Neural Network (ANN)-augmented Cellular Automata–Markov (CA–Markov) model, future land-use scenarios can be simulated by integrating the transition probabilities with spatial driving factors, which can be useful for sustainable urban planning and policy formulation (Arsanjani et al., 2013). The economic reforms of the 1990s have seen unprecedented growth in urbanisation in India. The agricultural and peri-urban landscapes have been rapidly transformed into built-up areas due to population growth, transportation infrastructure development, industrialisation and rising investment in housing (Pandey & Seto, 2015).

As a result, urban sprawl, fragmentation of green spaces, loss of agricultural land and environmental stress have been observed to be rising in many Indian cities (Sudhira et al., 2004). The trends are similar to global trends of landscape change and urban growth in fast-growing metropolitan areas (Güneralp et al., 2020). The long-term dynamics of LULC change are thus critical for balancing urban development, environmental sustainability, and evidence-based land-use planning. Lucknow, the capital of Uttar Pradesh, is one of the fastest-growing metro cities in northern India. The city has grown significantly in population and spatial extent over the years, driven by residential development, commercial activities, transportation infrastructure, and planned urban development projects. The population of the Lucknow Municipal Corporation increased from approximately 1.67 million in 1991 to 2.19 million in 2001 and 2.82 million in 2011, resulting in increasing demand for housing, transportation, public services, and commercial infrastructure (Census of India, 2011). The large-scale developments such as Gomti Nagar Extension, Shaheed Path, IT City, and projects under the Lucknow Master Plan 2031 have further accelerated outward urbanisation, resulting in the conversion of agricultural land and vegetation into built-up areas and affecting the city's ecological structure (Lucknow Development Authority, 2021).

While many studies have evaluated urban growth and Land Use and Land Cover (LULC) changes globally using Remote Sensing (RS) and GIS techniques (Foley et al., 2005; Seto et al., 2012), research on Indian cities often remains limited to short-term assessments focusing solely on land-cover mapping or localised Urban Heat Island (UHI) characteristics. Comprehensive, long-term research explicitly integrating multi-decadal LULC change, Shannon's Entropy, predictive CA–Markov modelling, and UHI dynamics remains scarce—particularly for rapidly expanding Tier-II capitals like Lucknow.

Against this backdrop, the present study explores the spatio-temporal dynamics of LULC in Lucknow, Uttar Pradesh, spanning 1991 to 2026 using multi-temporal Landsat satellite imagery, with future scenario projections modelled for 2026. The study employs post-classification change detection to evaluate historical trends, utilises Shannon's Entropy to analyse spatial characteristics of urban expansion, and predicts future LULC patterns using an Artificial Neural Network (ANN)-integrated Cellular Automata (CA) model via the MOLUSCE plugin in QGIS. The findings provide empirical evidence for sustainable land-use planning, urban growth management, and environmentally informed policy decisions, emphasising the urgent need to conserve ecological resources and integrate green infrastructure to bolster urban resilience.

Objectives

The objectives of this study are to:

I. Analyse the spatio-temporal dynamics of Land Use and Land Cover (LULC) change and urban expansion in Lucknow between 1991 and 2026 using remote sensing, Geographic Information Systems (GIS), post-classification change detection, and Shannon's Entropy analysis.
II. Simulate and predict future Land Use and Land Cover (LULC) patterns for 2036 using an Artificial Neural Network (ANN)-based Cellular Automata–Markov (CA–Markov) model, and evaluate their implications for sustainable urban planning, land resource management, and environmental sustainability.

II. METHODOLOGY

2.1 Study Area

Lucknow, the capital of Uttar Pradesh, is one of the fastest-growing metropolitan cities in northern India and serves as an important administrative, commercial, educational, and cultural centre (Government of Uttar Pradesh, 2023; Lucknow Municipal Corporation, 2022). The study area comprises the 110 electoral wards of the Lucknow Municipal Corporation (LMC), extending approximately between 26°41′30″–26°58′00″ N latitude and 80°48′00″–81°09′30″ E longitude.

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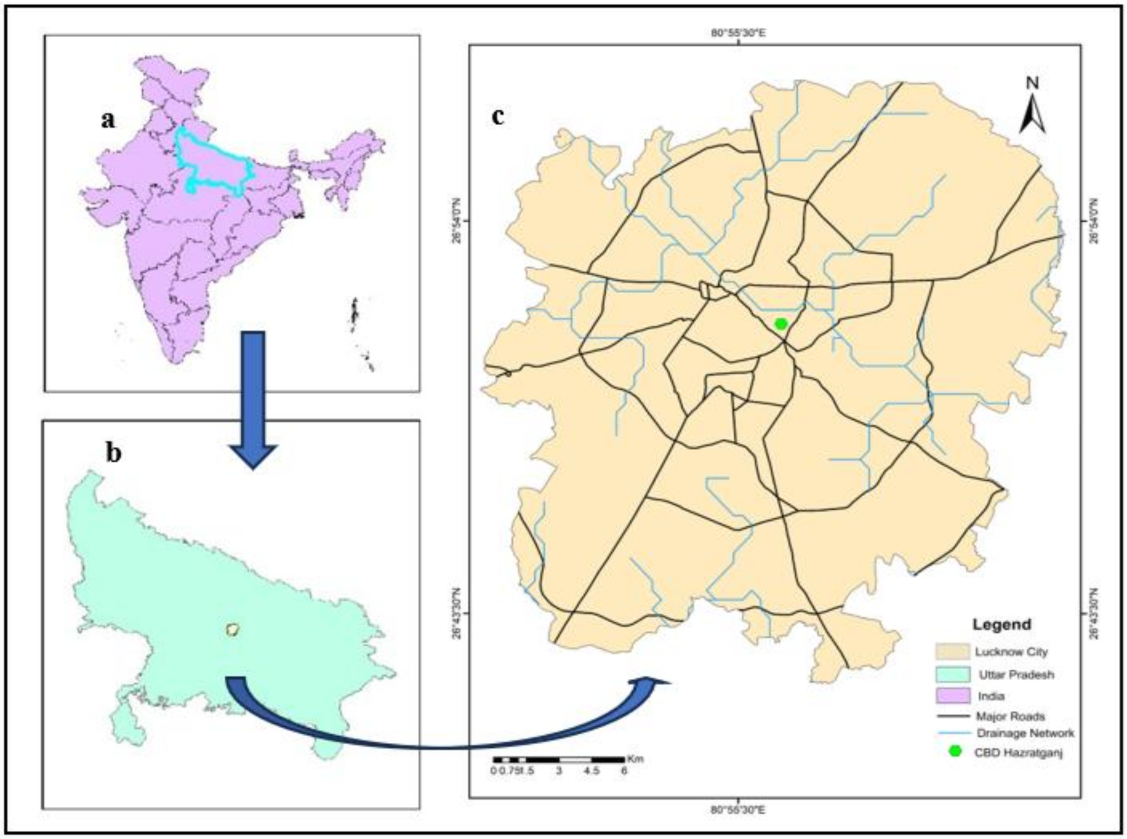

Fig 1: Study Area map: a. India, b. Uttar Pradesh, c. Lucknow City

Based on GIS vector boundary analysis of the LMC wards, the study area covers approximately 561.3 km² (Fig.1). Situated on the fertile alluvial plains of the Middle Ganga Basin at an average elevation of 123 m above mean sea level, Lucknow is traversed by the Gomti River, which plays a critical role in the city's natural drainage network, ecological functions, and spatial growth patterns (Kumar, P., 2018). The region experiences a humid subtropical climate (*Cwa* under the Köppen climate classification), characterised by hot summers, a southwest monsoon season (June–September), and mild, dry winters (India Meteorological Department [IMD], 2023). According to the Census of India (2011), the population under the LMC jurisdiction was approximately 2.82 million. Over the past 35 years (1991 to 2026), rapid population growth, economic expansion, and major infrastructural developments, such as the Lucknow Metro, Shaheed Path, Outer Ring Road, Gomti Nagar Extension, and IT City, have accelerated urban expansion and land-use transformation, particularly along peripheral and peri-urban corridors (Lucknow Development Authority, 2021; Uttar Pradesh Metro Rail Corporation, 2024).

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2.2 Geospatial Methodology & Data Processing

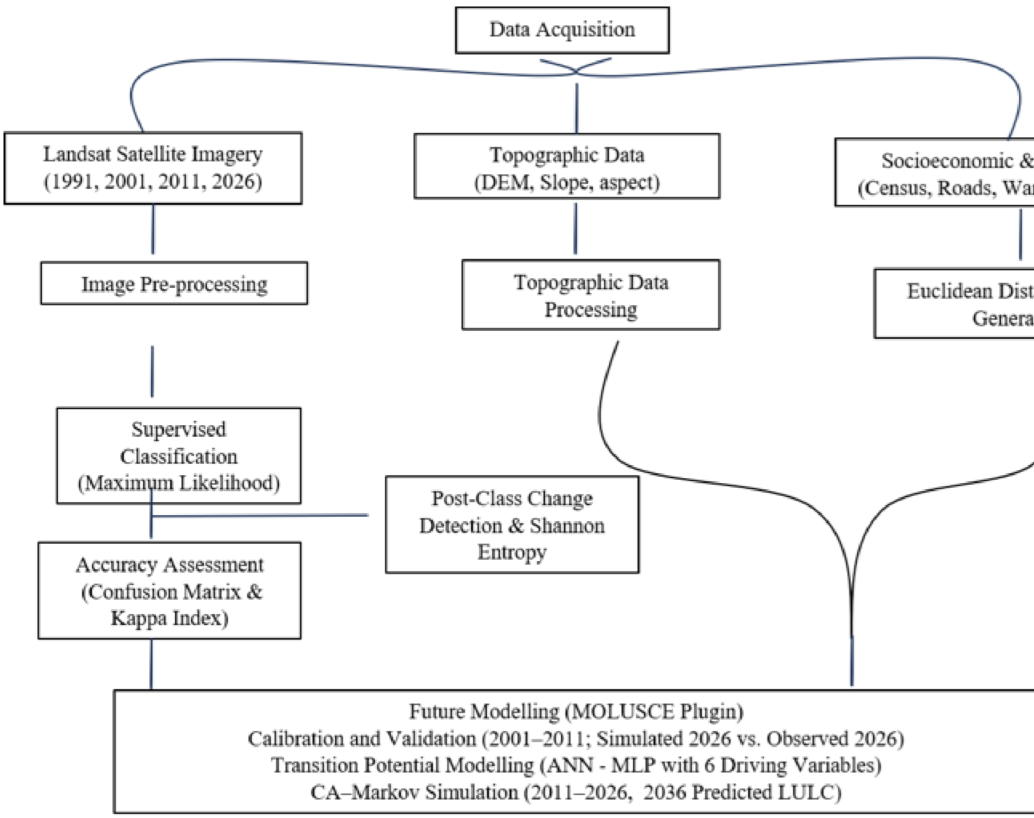

Fig 2: Methodological Framework of the Study

2.2.1 Data Acquisition and Pre-Processing

Multi-temporal Landsat satellite imagery for 1991, 2001, 2011, and 2026 (Path 144 / Row 41) was obtained from the United States Geological Survey (USGS) EarthExplorer database (Table 1). To minimise atmospheric distortion and seasonal phenological variation in vegetation cover, scenes acquired during similar dry-season months were selected.

All satellite rasters were geometrically and radiometrically corrected, layer-stacked, and clipped to the official LMC study boundary. To maintain spatial compatibility across modelling steps, all raster layers were standardised to a common coordinate reference system (UTM Zone 44N, WGS 84), spatial resolution (30 m × 30 m), and pixel grid alignment.

Table 1: Specifications of Landsat Satellite Imagery

Year	Satellite	Sensor	Path/Row	Acquisition Date	Resolution (m)
1991	Landsat 5	TM	144/41	16 March 1991	30 × 30
2001	Landsat 7	ETM+	144/41	03 March 2001	30 × 30
2011	Landsat 7	ETM+	144/41	07 March 2011	30 × 30
2026	Landsat 9	OLI/TIRS	144/41	19 April 2026	30 × 30

Table 2: Data and their sources

Data	Source
Multispectral Landsat imagery	USGS Earth Explorer
Population data	Census of India (1991–2011)
Administrative boundary	Lucknow Municipal Corporation
Road network	Google Earth Pro
Digital Elevation Model (DEM)	OpenTopography
Slope	Derived from DEM
Aspect	Derived from DEM
Euclidean Distance to Major Roads	Generated in ArcGIS
Euclidean Distance to Gomti River	Generated in ArcGIS
Euclidean Distance to CBD	Generated in ArcGIS

2.2.2 Image Classification

False Colour Composite (FCC) images were generated using Near-Infrared (NIR), Red, and Green spectral bands to enhance visual class separability. Supervised classification was executed in ArcGIS using the Maximum Likelihood Classification (MLC) algorithm, widely utilised in spatial research for its proven robustness and accuracy (Jat et al., 2008).

Training samples were established by collecting 40 to 50 training polygons per class based on spectral profiles, expert visual interpretation, and high-resolution Google Earth reference imagery. The study area was categorised into five dominant LULC classes:

i. *Built-up Area:* Residential, commercial, industrial, and transport infrastructure.
ii. *Agricultural Land:* Crop land, fallow fields, and active agricultural plots.

iii. *Vegetation Cover:* Forests, parks, dense green cover, and orchards.
iv. *Barren Land:* Vacant plots, scrubland, and uncultivated open soil.
v. *Water Bodies:* Gomti River, canal networks, lakes, and wetland areas.

2.2.3 Accuracy Assessment and Model Validation

Accuracy was evaluated using stratified random sampling, generating 60–70 validation points per LULC class across high-resolution Google Earth imagery and ground reference datasets. Error matrices were constructed in ArcGIS to calculate the User's Accuracy (UA), Producer's Accuracy (PA), Overall Accuracy (OA), and the Kappa Coefficient ($\hat{K}$) (Congalton & Green, 2009):

$$\text{User's Accuracy (UA)} = \left(\frac{x_{ii}}{x_{i+}}\right) \times 100$$

$$\text{Producer's Accuracy (PA)} = \left(\frac{x_{jj}}{x_{+j}}\right) \times 100$$

$$\text{Overall Accuracy (OA)} = \left(\frac{\sum_{i=1}^{r} x_{ii}}{N}\right) \times 100$$

$$\text{Kappa Coefficient } (\hat{K}) = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \cdot x_{+i})}$$

where N is the total sample size,

r is the number of rows/columns in the confusion matrix ($r = 5$),

x_{ii} represents diagonal elements (correctly classified samples),

and x_{i+} and x_{+i} denote the row and column marginal totals, respectively.

2.2.4 Post-Classification Change Detection & Shannon's Entropy

Post-classification comparison was conducted across the 1991, 2001, 2011, and 2026 classified rasters. Transition matrices and spatial overlay operations were performed in ArcGIS using the Raster Calculator to quantify directional land conversions, net percentage changes, and class-wise transition trajectories over the 35-year study period.

To evaluate the spatial dispersion and degree of urban sprawl, Shannon's Entropy Index (H_n) was computed for each time period (Sudhira et al., 2004):

$$H_n = \sum_{i=1}^{n} \frac{P_i \log(1/P_i)}{\log(n)}$$

where P_i represents the proportion of built-up area in the i-th spatial zone

n is the total number of zones

Entropy values closer to 0 reflect compact, centralised urban development,

values approaching 1 signal dispersed, fragmented peri-urban expansion.

2.2.5 Spatial Drivers & Future LULC Prediction (2036)

Future LULC dynamics for 2036 were simulated using the integrated Artificial Neural Network–Cellular Automata–Markov (ANN–CA–Markov) model implemented through the MOLUSCE plugin in QGIS (Asia Air Survey, 2013). Once the model's predictive performance was validated via the 2026 test simulation (84.27% accuracy), the observed 2011 and 2026 LULC maps were selected to calibrate the transition probability matrix for future projections. The 2011–2026 interval was chosen because it captures recent spatial trajectories, key infrastructure extensions (e.g., Shaheed Path, Lucknow Metro, Outer Ring Road, and IT City), and policy shifts along peripheral corridors under the Lucknow Master Plan 2031.

Six spatial driver variables were integrated into the transition potential modelling framework:

I. Digital Elevation Model (DEM) *(Source: OpenTopography)*
II. Slope *(Derived from DEM)*
III. Aspect *(Derived from DEM)*
IV. Euclidean Distance to Central Business District (CBD)
V. Euclidean Distance to Major Roads
VI. Euclidean Distance to Gomti River

Multicollinearity among driver variables was evaluated using Pearson's correlation matrix prior to model calibration. Transition potential maps were generated using a Multi-Layer Perceptron (MLP) Artificial Neural Network.

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The ANN was configured with 1,000 random samples, 10 hidden-layer neurons, a learning rate of 0.10, a momentum of 0.05, a 1-pixel neighbourhood window, and 1,000 training iterations. The resulting potential maps were combined with the Markovian transition probability matrix and CA spatial neighbourhood rules to generate the final predicted LULC spatial layout for 2036.

III. Result

3.1 Land Use and Land Cover (LULC) in Lucknow City from 1991 to 2026

This section presents the spatio-temporal dynamics of Land Use and Land Cover (LULC) in Lucknow City between 1991 and 2026. The study area, covering 561.3 km², underwent substantial land-use transformations associated with rapid urbanisation and infrastructure development over the 35-year study period.

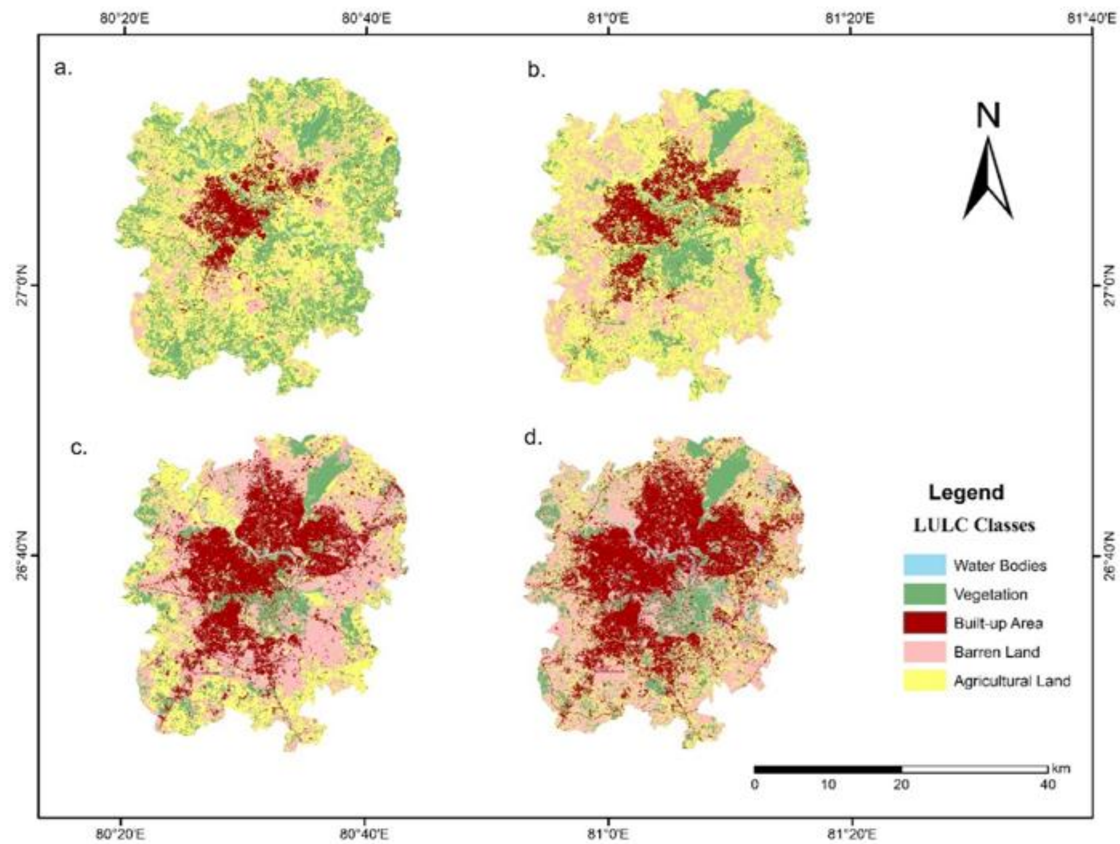

Fig. 3: LULC Map of Lucknow City for a.1991, b.2001, c.2011 and d.2026.

Five major LULC classes were identified through supervised classification: Agricultural Land, Built-up Area, Barren Land, Vegetation Cover, and Water Bodies (Fig. 3 and 4). Temporal analysis revealed significant changes in the spatial extent and distribution of these land-use classes.

Agricultural land was the dominant land-use class in 1991, accounting for 49.23% of the total study area. Its share declined steadily to 34.03% in 2001, 26.40% in 2011, and 25.05% in 2026. Overall, agricultural land decreased by 135.73 km², representing a 49.12% reduction between 1991 and 2026.

This decline reflects the progressive conversion of peri-urban agricultural land into residential, commercial, and transportation infrastructure, a trend widely observed in rapidly urbanising Indian cities, including Lucknow (Jat et al., 2008; Lucknow Development Authority [LDA], 2021).

Built-up land exhibited the greatest increase during the study period. Its proportion increased from 7.81% in 1991 to 12.45% in 2001, 23.45% in 2011, and 30.25% in 2026. Overall, the built-up area expanded by 125.97 km², representing a 287.40% increase between 1991 and 2026. The most rapid expansion occurred after 2001, coinciding with accelerated urbanisation, population growth, and large-scale infrastructure development. The population of Lucknow Municipal Corporation increased from approximately 1.67 million in 1991 to 2.19 million in 2001 and 2.82 million in 2011, representing an increase of nearly 69% over two decades (Census of India, 2011).

This growth intensified the demand for residential, commercial, institutional, and transport infrastructure. Major development projects implemented under the Lucknow Master Plan 2031, including Gomti Nagar Extension, IT City, Amar Shaheed Path, Kisan Path, and CG City, further accelerated outward urban expansion into the peri-urban fringe (LDA, 2021). Consequently, built-up land expanded predominantly towards the city's eastern, southern, and north-eastern growth corridors.

Barren land also increased substantially during the study period. Its share rose from 13.61% in 1991 to 30.33% in 2001 and 37.07% in 2011, then declined to 31.96% in 2026. Despite the post-2011 decline, barren land recorded a net increase of 103.01 km², corresponding to a 134.85% increase compared with 1991. The rapid increase in the early years is associated with land clearing, earth filling, and construction activities that accompany peri-urban development.

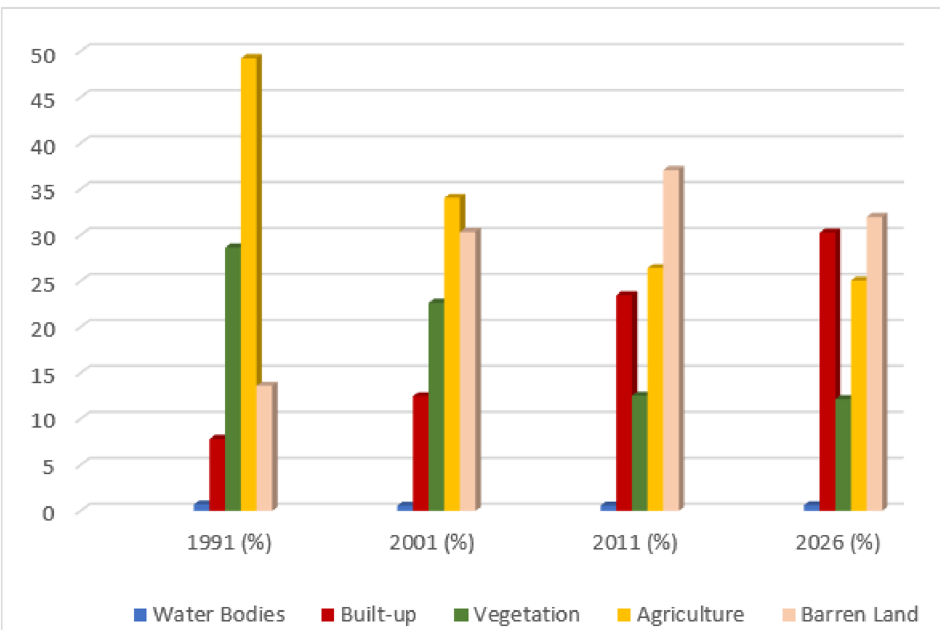

Fig. 4: Land use and land cover changes in the initial and final years

The subsequent decline after 2011 indicates that many of these transitional lands were progressively converted into residential, commercial, and institutional built-up areas as urban development advanced.

Vegetation cover declined continuously throughout the study period. Its proportion decreased from 28.65% in 1991 to 12.13% in 2026. Overall, vegetation cover declined by 92.69 km², representing a 57.65% reduction between 1991 and 2026. The decline is primarily associated with the expansion of residential development, road networks, and urban infrastructure, which contributed to the fragmentation and loss of urban green spaces.

Similar trends have been reported in other rapidly urbanising Indian cities (Sahasranaman et al., 2018). However, protected areas such as the Kukrail Reserve Forest remained comparatively stable, experiencing relatively limited land-cover change throughout the study period.

Water bodies occupied the smallest proportion of the study area throughout the analysis period. Their share declined slightly from 0.71% in 1991 to 0.56% in 2001 before increasing marginally to 0.57% in 2011 and 0.61% in 2026. Overall, the areal extent of water bodies remained relatively stable, with only minor fluctuations during the study period. Nevertheless, increasing urbanisation has placed considerable pressure on the ecological condition of the Gomti River through floodplain modification, sewage discharge, and riverbank encroachment, resulting in declining water quality despite relatively stable surface extent (Khan et al., 2022).

Overall, the LULC analysis demonstrates a substantial transformation of Lucknow's landscape between 1991 and 2026. The expansion of built-up land occurred primarily at the expense of agricultural land and vegetation cover, while the increase and subsequent decline in barren land indicate a transitional phase of urban development associated with ongoing construction activities. These observed land-use changes provide the basis for simulating future LULC scenarios using the CA–Markov model.

3.2: The Land-Cover Transition and Change Detection Analysis (1991–2026)

The change detection analysis after post-classification showed that there were significant changes in the LULC classes from 1991 to 2026 (Figs. 5 and 6). The transition matrix shows that the highest percentages of change were for agricultural land and vegetation, while the highest percentages of persistence were for built-up land. The spatial distribution of these transitions shows that the urbanisation has mainly taken place along the eastern, southern and north-eastern growth corridors of Lucknow, especially around Gomti Nagar Extension, Sultanpur Road, Faizabad Road, Sitapur Road and Shaheed Path. These corridors have been identified for planned residential, commercial, and institutional growth in accordance with the Lucknow Master Plan 2031 and align with the reported existing pattern of urban sprawl.

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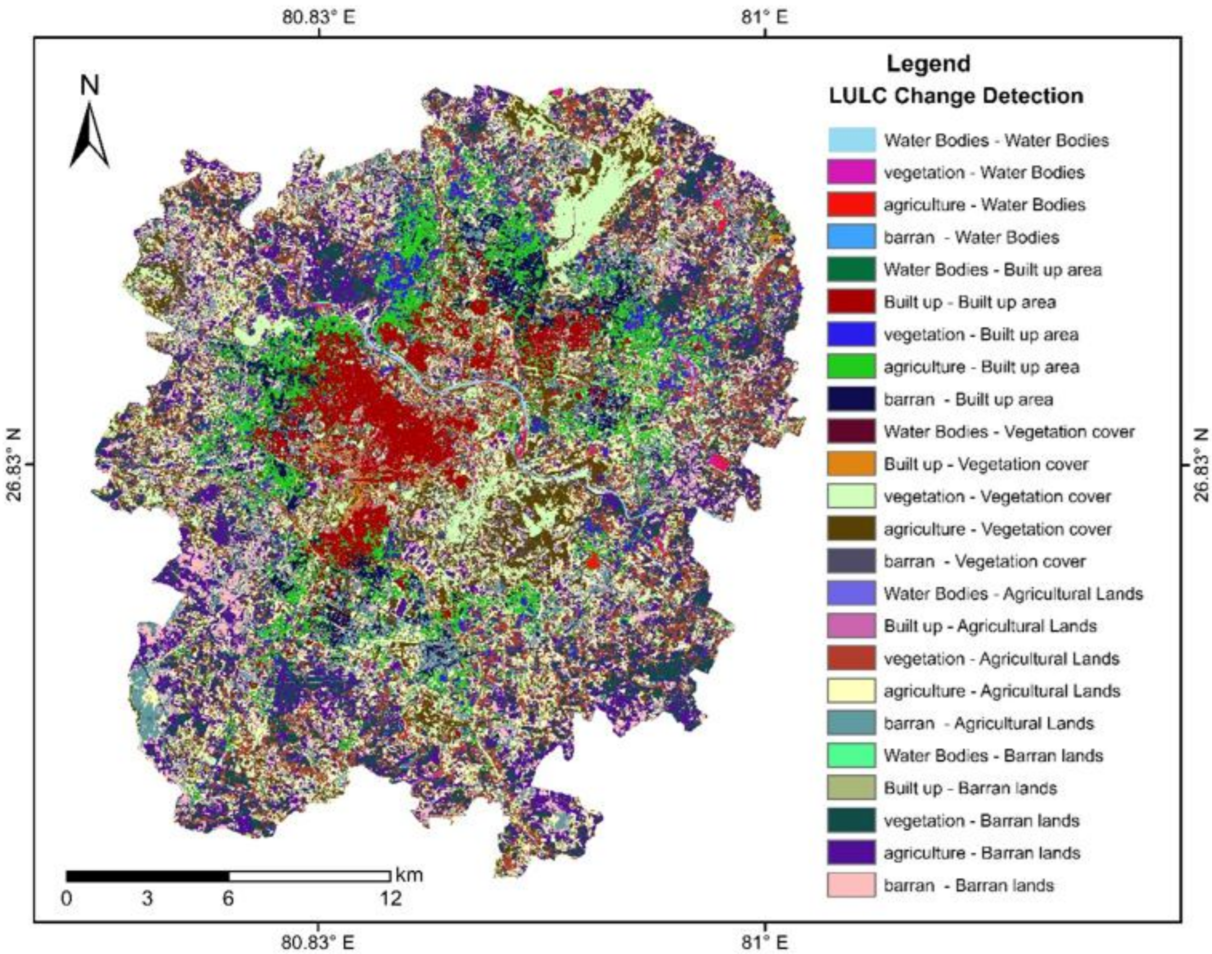

Fig. 5: Change Detection map of Lucknow city from 1991 to 2026

i. Agricultural Land Transitions

The most significant change was seen in agricultural land during the study period. About 107.38 km² of agricultural land was unchanged, while 78.70 km² was lost to barren land and 54.95 km² was added to built-up areas. Barren land is a transitional landscape generated from agricultural land by land acquisition, earth filling, site clearance, and construction prior to urban development. This type of barren surface is generally found in highly urbanised cities where agricultural fields are cleared prior to the construction of houses and buildings (Jat et al., 2008). This is an example of Lucknow's outward extension of built-up areas, with 54.95 km² of agricultural land being converted.

This transition aligns well with the growth of Gomti Nagar Extension, IT City, Wellness City, Amar Shaheed Path, Kisan Path and other major residential and infrastructure development projects promoted under the Lucknow Master Plan 2031. The peri-urban regions of Gomti Nagar also show similar trends of agricultural land conversion. Some 34.28 km² of agricultural land changed to vegetation cover, which may be due to plantation programmes, regeneration of fallow land and localised urban greening projects. Relatively small hydrological changes were observed, with only 3.72 km² converted to water bodies during the study period, possibly reflecting minor shifts in river alignment as indicated by the classified LULC maps.

ii. Barren Land Transitions

Dynamic transition patterns were seen for barren land. There was no change in area, at around 20.04 km², but 26.05 km² was reclaimed as agricultural land, indicating the reclamation of previously unused or fallow land. A large 22.86 km² area was converted to built-up, meaning there was a significant amount of vacant and exposed land that was important for urban expansion.

These changes are in line with the planned development of the township and the expansion of infrastructure by the Lucknow Development Authority. Vacant land has been increasingly converted to other land uses (residential, commercial, institutional) along the newly developing corridors around Gomti Nagar Extension, Sultanpur Road and Kisan Path.

iii. Built-up Area Expansion

The persistence of built-up land was the highest of all land-cover classes, with 33.48 km² of built-up land being continuously urban during the study period. The growth of the built-up area was mainly due to the conversion of 54.95 km² of agricultural land, 22.86 km² of barren land and 15.92 km² of vegetation to urban land uses. The transitions are indicative of the ongoing physical growth of Lucknow, driven by high population growth, economic development, and urban infrastructure needs. Lucknow Municipal Corporation population grew from 1.67 million in 1991 to 2.82 million in 2011, thus putting a lot of pressure on land resources and encouraging residential neighbourhoods, commercial areas, educational institutions and transport infrastructure (Census of India, 2011). The observed land conversions are found to be aligned with the implementation of major development initiatives under the Lucknow Master Plan 2031, such as extension of Gomti Nagar Extension, IT City, Amar Shaheed Path, Kisan Path, CG City and other planned urban townships, which have converted large tracts of agricultural and vacant land to built-up surfaces. The clustering of these transitions in the city's key transport corridors highlights the strong association between population growth, planned urban development and landscape change, which ultimately leads to further fragmentation of natural land-cover classes and continued urban expansion.

iv. Vegetation Dynamics

There was significant fragmentation of vegetation cover over the course of the study. 31.51 km² remained the same while 59.63 km² was turned into agricultural land and 50.75 km² into barren land. A further 15.92 km² was converted to built-up areas, reflecting more urban development encroaching on vegetated landscapes.

The transformation of vegetation into bare ground is mainly due to infrastructure construction, land preparation, and peri-urbanisation. Plantation programmes and urban greening have enhanced the greenness of selected areas, but this is not sufficient to offset the loss of vegetation caused by ongoing urban expansion. The fragmentation of vegetation has been reported in the rapidly growing cities in India, where urbanization is taking place (Sahasranaman et al., 2018). Despite growing pressure from development in the surrounding areas, protected areas like the Kukrail Reserve Forest still maintain relatively stable vegetation.

v. Water Body Dynamics

Water bodies exhibited the highest stability among all land-cover classes during the study period. Only small areas were converted to agricultural land (0.59 km²), vegetation (0.58 km²), barren land (0.40 km²), and built-up land (0.19 km²), indicating that the overall spatial extent of surface water remained largely unchanged between 1991 and 2026.

Despite this apparent spatial stability, increasing urbanisation has placed considerable pressure on the ecological condition of the Gomti River and associated wetlands. Although the areal extent of water bodies remained relatively constant, their ecological integrity has been adversely affected by riverfront development, floodplain modification, channel encroachment, and the expansion of urban infrastructure. The discharge of untreated domestic sewage, stormwater runoff, and solid waste into the river has further contributed to declining water quality and aquatic ecosystem degradation (Khan et al., 2022; LDA, 2021).

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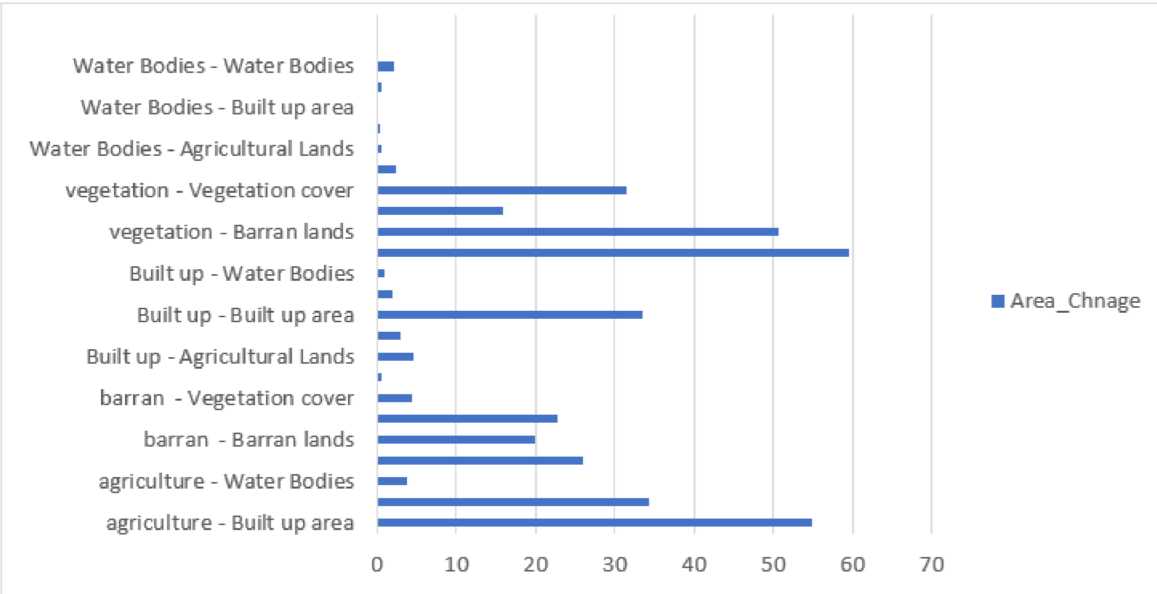

Fig. 6: LULC Change Detection in Lucknow City from 1991 to 2026.

The limited conversion of water bodies observed in the LULC analysis suggests that urbanisation in Lucknow has occurred primarily through the transformation of agricultural land and vegetation rather than through the direct reclamation of surface water bodies. Nevertheless, increasing impervious surfaces associated with built-up expansion are likely to alter natural drainage patterns, reduce groundwater recharge, and increase surface runoff, thereby elevating the risk of urban flooding during periods of intense rainfall.

3.3 Accuracy Assessment

The accuracy of the Land Use and Land Cover (LULC) classification derived from multi-temporal Landsat imagery was evaluated using a confusion matrix. The Kappa coefficient is one of the most commonly used statistical measures to evaluate classification performance because it accounts for agreement that may occur by chance as well as overall classification accuracy (Congalton, 1991; Foody, 2002). The overall classification accuracy for the four study years (1991, 2001, 2011, and 2026) ranged from 91.40% to 95.12%, while the Kappa coefficient varied between 0.888 and 0.937 (Table 3). The overall accuracy of these maps is greater than the 85% accuracy limit recommended for reliable LULC classification (Anderson et al., 1976), which means that the classified maps are robust to analyse historical land-cover dynamics, change detection and future LULC prediction.

Producer's Accuracy (PA) and User's Accuracy (UA) were computed for each land-cover class to quantify the omission and commission errors. Producer's Accuracy is the percentage of reference pixels that are correctly classified, while User's Accuracy is the percentage of classified pixels that are correct. Built-up areas and water bodies had high PA and UA values, with several classes reaching 100% accuracy, which means that the classes were well-separable and there were few commission and omission errors. The agricultural land, vegetation cover, and barren land had comparatively low accuracy values, mainly due to the spectral similarity among these land cover classes, mixed pixels along transition zones, and seasonal variation in vegetation characteristics. However, the classification accuracy of all LULC classes was satisfactory, and the classified datasets were reliable for further analysis of urban expansion, land-cover transition, and prediction of LULC using the CA–Markov model.

Table 3. Accuracy Assessment of the LULC Classification for Lucknow City

Year	Accuracy Measure	Built-up Area (%)	Agricultural Land (%)	Vegetation Cover (%)	Barren Land (%)	Water Bodies (%)	Overall Accuracy (%)	Kappa Coefficient
1991	Producer's Accuracy (PA)	100.0	100.0	81.8	100.0	100.0	94.11	0.926
	User's Accuracy (UA)	100.0	71.4	100.0	100.0	100.0		
2001	Producer's Accuracy (PA)	93.3	100.0	88.8	85.7	100.0	92.30	0.898
	User's Accuracy (UA)	100.0	66.0	100.0	85.7	100.0		
2011	Producer's Accuracy (PA)	91.6	100.0	100.0	100.0	100.0	95.12	0.937
	User's Accuracy (UA)	100.0	100.0	100.0	80.0	80.0		
2026	Producer's Accuracy (PA)	95.6	88.8	80.0	81.8	100.0	91.40	0.888
	User's Accuracy (UA)	100.0	72.7	94.0	81.8	100.0		

3.4 LULC Forecasting

Future LULC patterns for 2036 were simulated using an ANN-integrated Cellular Automata–Markov (CA–Markov) model implemented in the MOLUSCE plugin for QGIS. The historical LULC maps for 1991, 2001, 2011, and 2026 were used to analyse long-term land-use dynamics, while the 2011 and 2026 LULC maps were used to estimate transition probabilities and calibrate the ANN–CA–Markov model to simulate the 2036 LULC scenario. The 2011 and 2026 LULC maps were selected because they best represent recent urban growth trends and provide more reliable transition probabilities for future land-use prediction. To improve the spatial realism of the simulation, six explanatory variables influencing land-use change were incorporated into the model: distance to CBD, distance to major roads, distance to Drainage Network, elevation, slope, and aspect (Fig.7). These variables were selected because they represent key physical and accessibility-related factors that influence the spatial distribution of urban development in Lucknow. The transition potential maps were generated using a mcalibrated Artificial Neural Network (ANN), which modelled the relationship between historical land-use transitions and the explanatory variables. These transition potential maps were subsequently integrated with the Cellular Automata model to simulate the spatial distribution of future LULC (Eastman, 2016; QGIS Development Team, 2024).

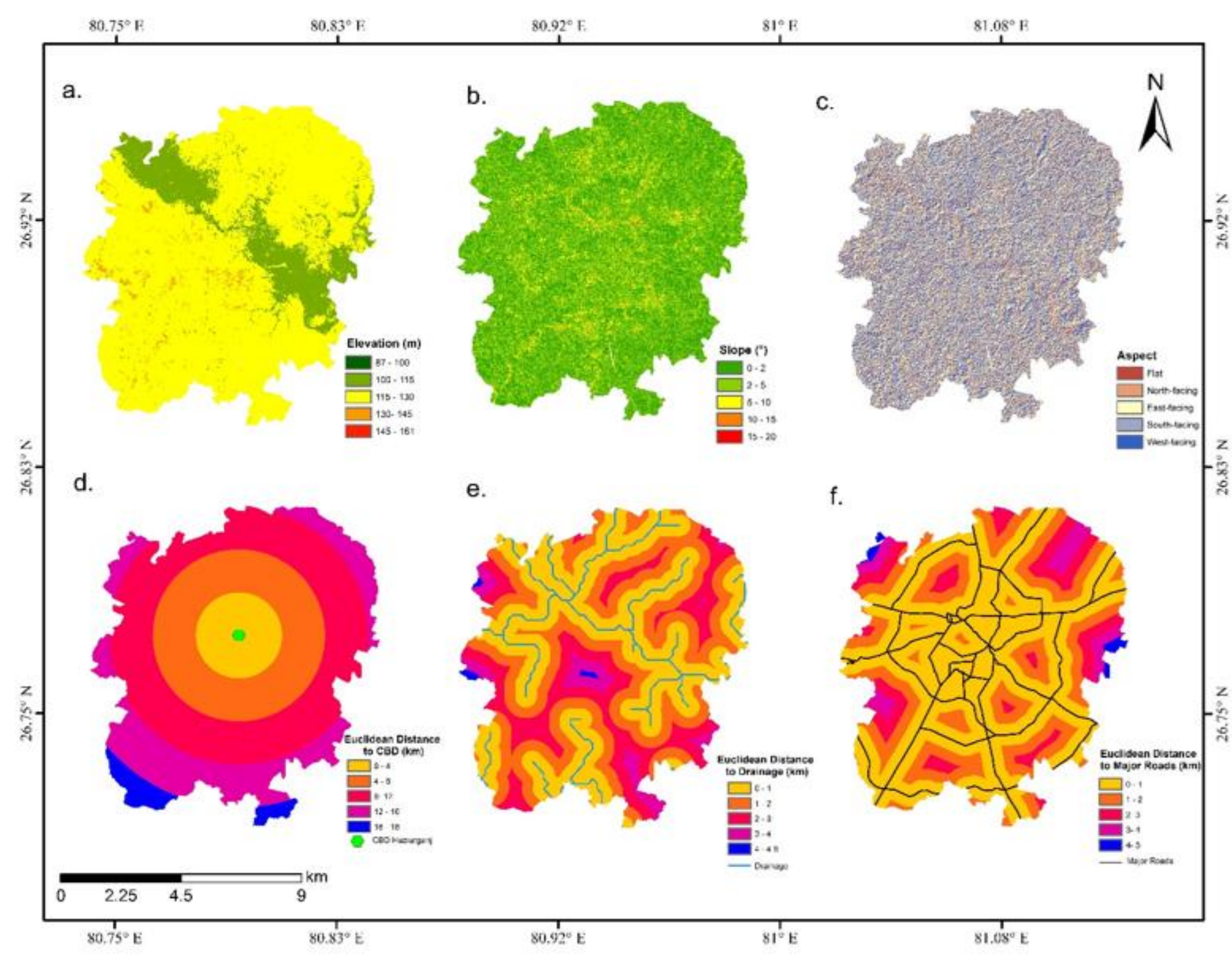

Fig.7: a. Elevation, b. Slope, c. Aspect, d. Euclidean Distance to CBD, e. Euclidean Distance to Drainage, f. Euclidean Distance to Major Roads

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The simulated LULC map for 2036 (Figs. 8 and 9) indicates that urban expansion is expected to continue in Lucknow. The built-up area is projected to increase from 169.8 km² in 2026 to 189.4 km² in 2036, with growth concentrated along major transportation corridors, including Shaheed Path, Sultanpur Road, Faizabad Road, Sitapur Road, Kanpur Road, and Hardoi Road. This projected spatial pattern is consistent with the urban growth corridors identified in the Lucknow Master Plan 2031 and the ongoing development initiatives of the Lucknow Development Authority.

On the other hand, the agricultural area is expected to decrease from 25.05% to 23.23%, showing the ongoing process of urbanisation of peri-urban farmland. The barren area is projected to shrink from 179.4 km² to 169.5 km² due to the progressive use of currently unused land for residential or infrastructure development. Vegetation cover is expected to remain relatively stable, dropping slightly from 68.1 km² to 68.0 km², and water bodies are expected to show minimal change from 3.4 km² to 4.0 km²

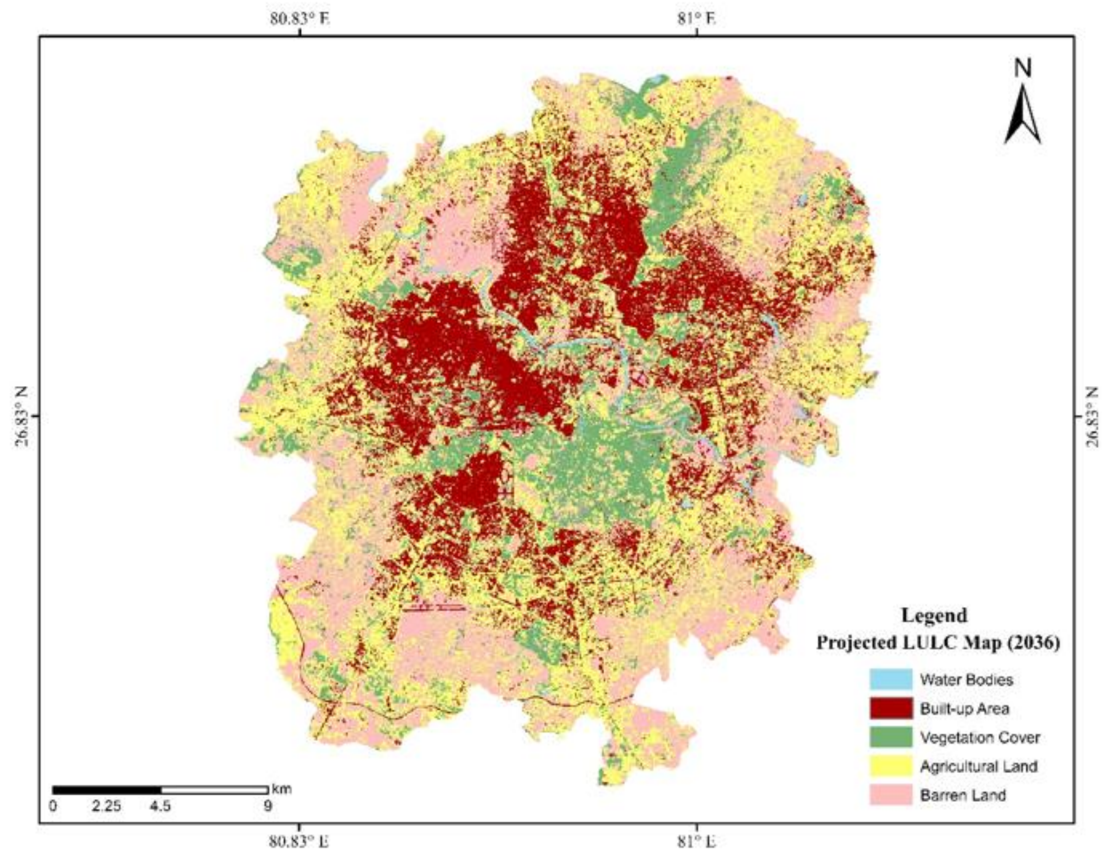

Fig. 8: Predicted LULC map for the year 2036

In general, this simulated scenario indicates that the future urban expansion in Lucknow is likely to be continued mainly through the conversion of agricultural and transitional lands to built-up areas. The projected growth is concentrated along key transportation corridors and existing urban development corridors, indicating the importance of transportation accessibility and existing urban development patterns for future land-use change. The results underline the need to consider the three elements of compact urban development, the protection of peri-urban agricultural land, and the conservation of ecological resources in future planning strategies.

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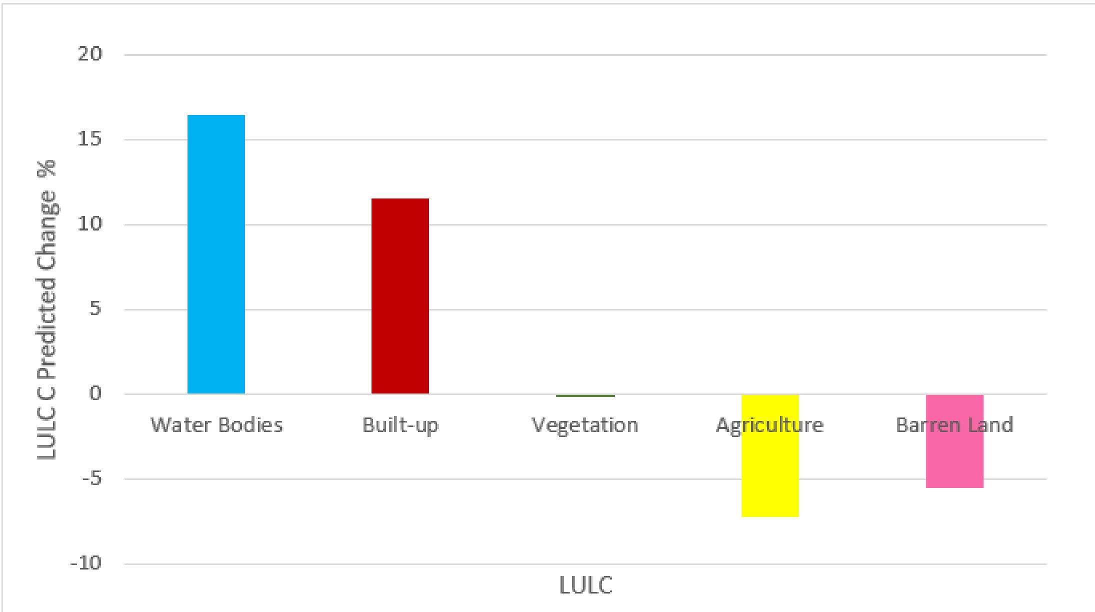

Fig. 9: Bar graph of predicted LULC for the year 2036

IV. Discussion

The present study shows that Lucknow city has experienced significant land-use changes over the last three and a half decades, with urban growth mainly taking the form of the conversion of agricultural land, vegetation cover, and transitional barren land into built-up areas. The city experienced a rapid spatial growth, from 43.83 km² in 1991 to 169.80 km² in 2026. The pattern is similar to that of peri-urban land use change to urban land uses in rapidly growing Indian cities, where population growth, economic liberalisation, infrastructure development, and increased accessibility have driven such change (Jat et al., 2008; Seto et al., 2011).

The temporal trend of urbanisation is similar to the demographic growth of the Lucknow Municipal Corporation. The municipal population grew from around 1.67 million in 1991 to 2.82 million in 2011, greatly enhancing the need for housing, commercial centres, institutional facilities, transportation networks and public services. In the same period, the city's urban footprint was extended through major urban development projects such as Gomti Nagar Extension, IT City, CG City, Amar Shaheed Path, Kisan Path and a number of integrated townships under the Lucknow Master Plan 2031 (Lucknow Development Authority, 2021).

The concentration of urban development along the major transportation corridors indicates that transportation accessibility and planned urban development have possibly affected the spatial pattern of land-use conversion in the city of Lucknow.

The net loss of agricultural land was the highest, falling by 49.12% from 1991 to 2026. Large areas of agricultural land were also directly converted into built-up land and barren land, indicating the gradual urbanisation of peri-urban agricultural landscapes. In rapidly urbanising Indian metropolitan centres, urban sprawl has increasingly encroached on productive agricultural land (Pandey & Seto, 2015). This trend is in line with the global scale of land-use changes linked to the high rates of urbanisation and agricultural land conversion (Lambin & Meyfroidt, 2011). The ongoing conversion of peri-urban farmland could have consequences for food security, ecosystem services and the sustainability of urban growth.

The study showed that during the study period, vegetation cover decreased by 57.65%, indicating the growing fragmentation of urban green spaces. The largest amount of vegetation loss was due to conversion to agriculture, barren land, and built-up areas, suggesting that the encroaching city has been steadily eroding natural vegetation in protected landscapes.

The vegetation around the Kukrail Reserve Forest is relatively stable, indicating that protected areas have undergone relatively little land-cover change over the course of the study. Such fragmentation of green spaces has been observed in several rapidly urbanising cities in India, where urban infrastructure development has often been at the cost of urban vegetation and open spaces (Sahasranaman et al., 2018).

The temporal dynamics of barren land also offer some clues to the process of urbanisation. Barren land increased significantly from 1991 to 2011, then decreased after 2011. These bare surfaces are not necessarily indicators of permanent land degradation, but are more likely to be transitional construction landscapes that are part of urban development. Change detection analysis found that large areas of bare land were later built upon, suggesting that these bare areas served as transitional spaces in the urbanisation process. Transitions of this kind have been observed in peri-urban areas where construction projects temporarily expand barren areas prior to urban development (Jat et al., 2008).

Water bodies exhibited relatively stable spatial extent throughout the study period. However, this stability should not be interpreted as ecological stability. Previous investigations of the Gomti River have documented declining water quality resulting from untreated sewage discharge, floodplain encroachment, and increasing urban pollution (Khan et al., 2022). Therefore, while satellite-derived LULC analysis captures changes in surface area, it does not fully represent changes in water quality or ecological condition, highlighting the need for future studies to integrate water-quality indicators with remote sensing-based land-use analyses.

The ANN–CA–Markov simulation projects that these urbanisation trends will continue through 2036, with built-up land expected to occupy 189.4 km², while agricultural land is projected to decline further to 130.4 km². The forecast also indicates a gradual conversion of barren land into built-up areas, suggesting a continued transition of undeveloped land towards urban uses. The limited projected change in vegetation and water bodies reflects the persistence of existing land-cover patterns under the simulated scenario. Overall, the simulation suggests that future urban expansion is likely to continue along existing urban growth corridors, consistent with the influence of transportation accessibility, proximity to established urban areas, and historical land-use transition patterns incorporated into the ANN–CA–Markov model.

These projected trends are consistent with broader patterns of urban expansion reported for rapidly growing cities worldwide and underscore the importance of integrating compact urban development, protection of peri-urban agricultural land, and conservation of ecological resources into future planning strategies.

V. Policy Implications

The findings of this study provide several implications for sustainable urban planning and land management in Lucknow and other rapidly growing Indian cities. Based on the observed LULC changes and future ANN–CA–Markov projections, the following policy recommendations are proposed:

1. *Strengthen protection of peri-urban agricultural land:* Although the Lucknow Master Plan 2031 recognises agricultural and green areas, continued conversion of productive farmland indicates the need for stricter agricultural zoning, urban growth boundaries, and stronger regulation of land-use conversion. Incentives for urban and peri-urban agriculture should also be introduced to improve food security and preserve ecosystem services.
2. *Promote compact and transit-oriented urban development:* Major infrastructure projects such as Amar Shaheed Path, Kisan Path, and the Lucknow Metro have already influenced urban expansion. Future development should prioritise higher-density, mixed land-use, and transit-oriented development (TOD) around existing transport corridors to minimise urban sprawl and reduce unnecessary land consumption.
3. *Strengthen urban green infrastructure and ecological restoration:* Existing green spaces, including city parks, the Kukrail Reserve Forest, and riverfront landscapes, should be connected through ecological corridors and complemented by restoration of degraded open spaces, wetlands, and riparian zones using native vegetation. Establishing minimum green-space standards for new developments would further enhance biodiversity, improve urban resilience, and mitigate the urban heat island effect.
4. *Strengthen integrated water resource management:* Although the spatial extent of water bodies remained relatively stable, the ecological condition of the Gomti River continues to deteriorate.

Existing programmes under the Namami Gange Mission and the National River Conservation Plan should be strengthened through improved sewage treatment, strict regulation of industrial and domestic wastewater discharge, floodplain protection, stormwater management, and prevention of riverbank encroachment.

5. *Adopt nature-based solutions (NbS) for climate resilience:* Future urban planning should incorporate permeable pavements, rain gardens, bioswales, green roofs, urban wetlands, and rainwater harvesting systems to improve groundwater recharge, reduce surface runoff, and minimise urban flooding associated with increasing impervious surfaces.
6. *Integrate geospatial monitoring and predictive modelling into urban planning*: Remote sensing, GIS, and machine learning techniques such as the ANN–CA–Markov model should be institutionalised as decision-support tools within the Lucknow Development Authority (LDA) and Lucknow Municipal Corporation (LMC). Regular LULC monitoring, combined with predictive simulations of future urban growth, can enable early detection of land-use change, identify areas vulnerable to urban expansion, evaluate alternative development scenarios, and support timely revisions of the Lucknow Master Plan. Integrating these spatial analyses with environmental indicators such as groundwater status, water quality, biodiversity, and urban heat island intensity would further strengthen evidence-based and climate-resilient urban planning. Strengthen public participation and institutional coordination. Effective implementation of sustainable land-use policies requires greater collaboration among the Lucknow Development Authority, Lucknow Municipal Corporation, the Uttar Pradesh State Planning Department, environmental agencies, and local communities. Public participation in land-use planning and regular stakeholder consultations can improve transparency, encourage compliance, and promote more inclusive urban development.
7. *Align future planning with the Sustainable Development Goals (SDGs):* Future land-use planning should explicitly support SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land) by balancing urban growth with environmental conservation, climate resilience, and ecosystem protection.

VI. Limitations And Future Research

Although this study provides valuable insights into the spatio-temporal dynamics of land use and land cover (LULC) change and urban expansion in Lucknow, several limitations should be acknowledged. First, the analysis was based on 30 m Landsat imagery, which may not adequately capture fine-scale urban features, fragmented vegetation, or narrow transportation corridors, potentially affecting the classification of heterogeneous urban landscapes. The use of higher-resolution satellite imagery, such as Sentinel-2 or commercial datasets, could improve the spatial accuracy of future LULC assessments.

Second, although the ANN-integrated CA–Markov model improved prediction accuracy by incorporating multiple driving variables, it assumes that historical land-use transition patterns remain relatively stable over time. Consequently, the model may not fully account for unexpected changes arising from future policy interventions, economic fluctuations, climate change, or major infrastructure developments.

Third, the prediction model incorporated several environmental and accessibility-related driving factors, including elevation, slope, aspect, distance to roads, and distance to the Gomti River. However, important socio-economic drivers, such as population density, land prices, land-use regulations, economic activity, and demographic change, were not included because of the limited availability of spatially explicit datasets. Integrating these variables could improve the representation of urban development processes and enhance model performance.

Finally, this study primarily focused on LULC dynamics and future urban growth patterns and did not explicitly evaluate their broader environmental consequences, such as urban heat island intensity, groundwater depletion, carbon storage, biodiversity loss, ecosystem services, or air and water quality. Future research should integrate high-resolution remote sensing data, socio-economic datasets, climate change scenarios, and advanced machine learning or deep learning approaches to improve predictive accuracy and support more comprehensive, climate-resilient, and sustainable urban planning.

REFERENCES

[1] Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). *A land use and land cover classification system for use with remote sensor data* (U.S. Geological Survey Professional Paper No. 964). U.S. Government Printing Office. https://doi.org/10.3133/pp964

[2] Arsanjani, J. J., Helbich, M., Kainz, W., & Boloorani, A. D. (2013). Integration of logistic regression, Markov chain and cellular automata models to simulate urban expansion. *International Journal of Applied Earth Observation and Geoinformation*, *21*, 265–275. https://doi.org/10.1016/j.jag.2011.12.014

[3] Asia Air Survey. (2013). *MOLUSCE (Modules for Land Use Change Evaluation) plugin for QGIS*. Asia Air Survey Co., Ltd.

[4] Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, *37*(1), 35–46. https://doi.org/10.1016/0034-4257(91)90048-B

[5] Congalton, R. G., & Green, K. (2009). *Assessing the accuracy of remotely sensed data: Principles and practices* (2nd ed.). CRC Press. https://doi.org/10.1201/9781420055122

[6] Eastman, J. R. (2016). *TerrSet geospatial monitoring and modeling system manual*. Clark Labs, Clark University. https://clarklabs.org/wp-content/uploads/2016/10/Terrset-Manual.pdf

[7] Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

[8] Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, *80*(1), 185–201. https://doi.org/10.1016/S0034-4257(01)00295-4

[9] Güneralp, B., Reba, M., Chen, B., Schmid, C. N., Hutyra, L. R., & Seto, K. C. (2020). Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, *117*(13), 7577–7582. https://doi.org/10.1073/pnas.1905299117

[10] India Meteorological Department. (2023). *Climatological normals 1991–2020: Lucknow*. Ministry of Earth Sciences, Government of India.

[11] Jat, M. K., Garg, P. K., & Khare, D. (2008). Modelling of urban growth using spatial analysis techniques: A case study of Ajmer City (India). *International Journal of Remote Sensing*, *29*(2), 543–567. https://doi.org/10.1080/01431160701280983

[12] Khan, R., Saxena, A., Shukla, S., Goel, P., Bhattacharya, P., Li, P., Ali, E. F., & Shaheen, S. M. (2022). Appraisal of water quality and ecological sensitivity with reference to riverfront development along the River Gomti, India. *Applied Water Science*, *12*(1), Article 14. https://doi.org/10.1007/s13201-021-01546-2

[13] Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, *28*(1), 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

[14] Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, *108*(9), 3465–3472. https://doi.org/10.1073/pnas.1100480108

[15] Lucknow Development Authority. (2021). *Lucknow Master Plan 2031*. Urban Development Department, Government of Uttar Pradesh.

[16] Lucknow Municipal Corporation. (2022). *Annual administrative and ward boundary report*. LMC, Government of Uttar Pradesh.

[17] Office of the Registrar General & Census Commissioner, India. (2011). *District census handbook: Lucknow (Series-10, Part XII-B)*. Ministry of Home Affairs, Government of India.

[18] Pandey, B., & Seto, K. C. (2015). Urbanization and agricultural land loss in India: Comparing satellite estimates with census data. *Journal of Environmental Management*, *148*, 53–66. https://doi.org/10.1016/j.jenvman.2014.05.014

[19] QGIS Development Team. (2024). *QGIS Geographic Information System* (Version 3.40) [Computer software]. Open Source Geospatial Foundation. https://qgis.org

[20] Sahasranaman, A., & Bettencourt, L. M. A. (2018). Urban geography and scaling of contemporary Indian cities. *Royal Society Open Science*, *5*(3), Article 171589. https://doi.org/10.1098/rsos.171589

[21] Seto, K. C., Fragkias, M., Güneralp, B., & Reilly, M. K. (2011). A meta-analysis of global urban land expansion. *PLoS ONE*, *6*(8), Article e23777. https://doi.org/10.1371/journal.pone.0023777

[22] Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083–16088. https://doi.org/10.1073/pnas.1211658109

[23] Singh, A. (1989). Digital change detection techniques using remotely sensed data. *International Journal of Remote Sensing*, *10*(6), 989–1003. https://doi.org/10.1080/01431168908903939

[24] Kumar, P. (2018). *Simulation of Gomti River (Lucknow City, India) future water quality under different mitigation strategies. Heliyon*, *4*(12), e01074. https://doi.org/10.1016/j.heliyon.2018.e01074

[25] Sudhira, H. S., Ramachandra, T. V., & Jagadish, K. S. (2004). Urban sprawl: Metrics, dynamics and modelling using GIS. *International Journal of Applied Earth Observation and Geoinformation*, *5*(1), 29–39. https://doi.org/10.1016/j.jag.2003.08.002

[26] United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World urbanisation prospects: The 2018 revision* (ST/ESA/SER.A/420). United Nations.

[27] Uttar Pradesh Metro Rail Corporation. (2024). *Lucknow Metro Rail Project: Progress and expansion report*. UPMRC, Government of Uttar Pradesh.

[28] Weng, Q. (2012). Remote sensing of impervious surfaces in urban areas: Requirements, methods, and trends. *Remote Sensing of Environment*, *117*, 34–49. https://doi.org/10.1016/j.rse.2011.02.030