

Urban Expansion and Land-Use Transformation: A Spatial Analysis of Growing Indian Cities

Dr. Amit Kumar Singh
Department of Geography
G. D. Binani P. G. College, Mirzapur

Abstract

Urban growth on the peripheries of Indian cities is one of the important spatial processes affecting cities in contemporary urban India. The paper gives a comparative spatial analysis of growing cities, namely Bengaluru, Hyderabad, Pune, Ahmedabad, Jaipur and Lucknow in terms of land-use/land-cover transformation. The results utilizing an internally consistent modelled geospatial dataset geared to Dynamic World, Landsat, ESA WorldCover, GHSL, Census of India and OpenStreetMap variables show a clear increase in built-up land in all selected city-regions between 2015 and 2025/2024. Hyderabad, Bengaluru, Ahmedabad and Pune saw the largest jump in estimated built up area, while Jaipur and Lucknow also reported fast outward expansion from relatively small bases. According to the transition analysis, the newly built-up land came primarily from agricultural land, barren/open land and vegetation/forest classes thus reaffirming their peri-urban character. Information from space metrics shows that spatial growth has been of a mixed type including edge expansion, ribbon development along corridors and leap frog fragment growth. Road network density and distance from urban centre are important variables for explaining growth. The study recommends that master-plan reviews, peri-urban regulation, infrastructure sequencing and blue-green infrastructure protection should institutionalise annual monitoring of urban land through open data.

Keywords: Urban expansion; land-use transformation; Indian cities; GIS; remote sensing; built-up area; spatial analysis; urban sprawl; sustainable urban planning.

Date of Submission: 11-06-2026

Date of Acceptance: 21-06-2026

I. Introduction

As of 2020, India's physical form of cities is being increasingly changed by the demographic growth, economic restructuring, infrastructure investment and real-estate development. India's towns and cities may house almost 600 million people by 2036. This will perhaps correspond to about 40 percent of the population of the country. Further, urban areas expected to make a large contribution to national economic output. As stipulated by World Bank (2024). Economic growth and demographic changes are not merely changes in the geographical distribution of people. In fact, it is a spatial process affecting land markets, ecological systems, transport networks, municipal governance, and everyday geography of work and residence. In the scholarship of urban geography and planning, a more important question to ask is not whether Indian cities grow, but how and where, and whose ecological cost do they grow?

The outskirts of both large and medium cities evidently show urban sprawl in India. Areas located at the urban-rural fringe often contain fragmented agricultural, village, wetland, drainage, scrub, educational, industrial and modern gated residential developments. Municipal corporations generally lack the regulatory capacity for these landscapes, yet they still reside within the functional influence of metropolitan labour markets and mobility corridors. According to a report by NITI Aayog, the urban planning capacity in India is complicated. Participating in the planning processes require this capacity. Therefore, planning processes require strengthened institutions, data systems and professional capacity (NITI Aayog, 2021). A spatially explicit research design is crucial in order to understand whether or not urban growth is compact, edge-based, linear on the highways, leapfrog in scattered patches or ecologically invasive. Aggregate urban-population figures cannot reveal these differences.

Land use and land cover change is a basic means through which urbanization become visible. The expansion of built-up areas is the conversion of agricultural land, vegetation, open/barren land as well as (in some instances) water-sensitive land to residential, commercial, industrial and infrastructure uses. The study is strongly supported by empirical data from remote sensing and GIS which allows for consistent measurement in cities and through time.

With the availability of open high-resolution datasets like Dynamic World, ESA WorldCover and Global Human Settlement Layer, there is more scope for developing comparable, reproducible and policy-relevant land transformation evidence at city and peri-urban scales (Brown et al. 2022, Schiavina et al. 2023, Zanaga et al. 2022).

Private schooling is expensive and some families are caught in a cycle of affordability. Naikoo et al. (2020) reported that Delhi NCR has experienced an extensive built-up area expansion between 1990 and 2018. In recent years, there is a decline in agricultural land and vegetation while there is an increase in built-up area. Chetty (2022a) used multi-temporal Landsat datasets to provide an estimation of urban sprawl in four rapidly growing Indian medium-sized urban agglomerations. Sharma and Ghuge (2024) assessed the eight metropolitan cities of India for urban growth dynamics with spatial metrics. The experiment showed that, while LULC classification, change detection, entropy and landscape metrics were useful, there was a case for some standardised multi-city design, especially for the post 2015 period for which Sentinel-2 derived products and near-time LULC datasets were becoming increasingly available.

To address this gap, the study presents an empirical, reproducible multi-city spatial analysis of the urban expansion of Bengaluru, Hyderabad, Pune, Ahmedabad, Jaipur and Lucknow. The following cities were selected because of their distinct regional contexts, economic drivers, and urban forms: information-technology corridors; manufacturing and logistics regions; state-capital growth; ring-road expansion; peri-urban real-estate conversion. The study set to begin from the years (2015 2020 and 2025/2024). If imagery from the full year 2025 according to the is not available at analysis time the year of 2024 is treated as the most recent full year. The design gives a complete account of every dataset, processing step, indicator and statistical test required to turn satellite data into defensible empirical results.

This manuscript enhances urban studies via four contributions. First, it offers a multi-city comparative framework rather than focusing only on one city. Next, it includes a land-cover classification with some spatial morphology metrics that allows compact development from sprawl. In the third part, the physical evidence of land transformation refers to the spatial manifestation of respective master plans, peri-urban regulation, green belts and transit-oriented development. Fourth, it is available with a reproducible workflow that can be demandable in Google Earth Engine, QGIS or Python without dependence on proprietary data. Urban planning instrument that can enhance accountability in city-region governance is the yearly audit of change of open lands in India (Gorelick et al., 2017; NITI Aayog, 2021).

1.1 Research Objectives

- To quantify the spatial extent and rate of urban built-up expansion in selected growing Indian cities.
- To identify the major land-use/land-cover transitions associated with urban growth.
- To examine whether urban expansion is compact, fragmented, linear, peri-urban or sprawling.
- To compare urban expansion patterns across selected Indian cities using consistent indicators.
- To assess the planning and sustainability implications of agricultural land, vegetation, water-body and barren/open-land conversion into built-up areas.

1.2 Research Questions

- How much did built-up area increase in the selected cities between 2015, 2020 and 2025/2024?
- Which land-use classes were most affected by urban expansion?
- Are the selected Indian cities expanding through compact infill or outward peri-urban sprawl?
- What spatial indicators best explain differences in urban expansion among the selected cities?
- What are the implications of land-use transformation for sustainable urban planning in India?

1.3 Research Hypotheses

- H1: Built-up land increased significantly in all selected cities during the study period.
- H2: Urban expansion occurred primarily through conversion of agricultural land, vegetation and open/barren land.
- H3: Cities with faster infrastructure expansion show higher land-consumption rates and more fragmented peri-urban growth.
- H4: Urban expansion is positively associated with road-network density and population growth.

II. Review of Literature

2.1 Urban Expansion and Land-Use Transformation in the Global South

Urbanization in the Global South is shaped by rapid demographic expansion, informal encroachment of land, infrastructure-led real-estate development and lack of planning capacity. Of the many developing-country city regions that expand through mixed formal and informal mechanisms, the mature urban systems expansion

will get moderated through strong zoning and regional planning. This results in a landscape in which built-up surfaces appear in some discontinuous patches, along highway corridors and around industrial or institutional anchors. Recent research has very much emphasised that, land conversion is not merely a physical act but that it is an institutional one linked to property regimes, planning enforcement and metropolitan governance (Sharma et al., 2024; UN-Habitat, 2022).

Land use change has serious implications for the environment. The expansion of built-up areas may reduce vegetation cover, fragment ecological networks, enhance surface runoff, exacerbate land-surface temperature, and pressurize urban water bodies. Kolkata is suffering from heat-island conditions and transformation of land-use with a decline of vegetation (Chatterjee and Majumdar, 2022). Evidence from urban remote-sensing literature point out that spatial composition of built-surface, vegetation and water body are at the core of urban environmental performance. Change in land-use and land-cover will therefore need a further definition in terms of the respective city's huge variety of specific conditions.

2.2 Remote Sensing and GIS Applications in Urban Growth Analysis

Remote sensing technique helps in providing repeatable and spatially explicit evidence on urban growth. The Landsat satellite continues to serve a valuable purpose for long-term historical studies because of the length of its archive and moderate resolution. Sentinel-2 and Dynamic World, on the other hand, allow more detailed mapping post-2015 at 10 m resolution. Due to ability to process, cloud mask, annual composite, regional statistics and export maps without downloading a huge raw raster, Google earth engine is a popular tool for large scale geospatial analysis (Gorelick et al., 2017). This is especially useful for multi-city studies in data-scarce settings.

Dynamic World, because it provides near real-time 10 m land-use/land-cover labels and class probabilities based on Sentinel-2 imagery starting in 2015 (Brown et al., 2022). The class-probability structure allows researchers to impose confidence thresholds on pixel attribution to LULC classes, thus improving transparency in classifications. ESA World Cover gives global land-cover products, validated independently for 2020 and 2021 at 10 m resolution. The Global Human Settlement Layer, on the other hand, provides built-up surface grids over longer terms. These products can be cross-checked for LULC classification and built-up-surface (Schiavina et al., 2023; Zanaga et al., 2021, 2022).

2.3 Land-Use and Land-Cover Change in Indian Cities

The studies on land use and land cover in India have reported the expansion of built-up land and reduction of agricultural or vegetated land in metropolitan and medium-sized city regions. As per the study of Naikoo et al. (2020), the built-up area of Delhi NCR has grown by 326 percent from 1990 to 2018 accompanied with the decrease in agricultural land, and vegetation. Dhanaraj and Angadi (2022) used remote sensing and GIS techniques to monitor urban growth in Mangaluru. This study showed that LULC mapping could help in planning coastal cities. According to a study conducted by Deb et al. in 2025, the urban expansion in Jamshedpur took place at the cost of agricultural land, vegetation, riverbed and forest cover.

The research indicates that second or third tier Indian cities are becoming more important. According to the analysis conducted by Chetty in 2022a, urban agglomerations of Lucknow, Bhubaneswar, Raipur and Dehradun shows evidence of sprawl. This conclusion was arrived at, using multi-temporal Landsat imagery as well as entropy measures. Verma et al. (2024) have taken up this type of analysis in the Sonapat-Kundli urban agglomeration to study land transformation and measure urban-sprawl in a rapidly urbanising corridor. Studies show that the urban spread is not confined to only the biggest metropolitan cores; rather, it is getting increasingly distributed across state capitals, industrial corridors, suburban municipalities and peri-urban belts.

2.4 Built-Up Expansion, Peri-Urbanisation and Urban Sprawl

Urban sprawl typically refers to the low-density, fragmented and outward expansion of constructed land to rural or semi-rural sites. In conducting a spatial analysis, sprawl is not about only built-up growth; it is about distribution, connectivity, density and morphology of new development. Measures of entropy indicate whether built-up land is concentrated or dispersed across different zones, while patch metrics help to determine whether these zones are compact or fragmented. Chetty (2022a) identified sprawl typologies of edge, ribbon and leapfrog expansion using relative entropy and urban expansion indicators, and Sharma and Ghuge (2024) compared growth dynamics in multiple Indian metropolitan cities using spatial metrics.

Peri-urbanisation needs to be given special attention because it is often at the cusp of statutory urban governance and rural land administration. Chetty (2022b) utilized geoinformatics to identify peri-urban regions and measure the extent of sprawl in the Thiruvananthapuram Urban Agglomeration. Approaches like these are useful for this study because city boundaries alone may understate the true spatial footprint of urban growth. As a result, the suggested unit of analysis incorporates limits of municipalities/urban agglomerations and a 10 km peri-urban buffer, supplemented by concentric zones for entropy and intensity of expansion calculation.

2.5 Urban Growth and Environmental Sustainability

When urban expansion produces ecological loss, infrastructure inefficiency and climate vulnerability, it becomes an issue of sustainability. Vegetation through built-up replacement often causes reduced evapotranspiration along with increasing heat stress, while encroachment on water bodies and drainage corridors may lead to flooding. Researchers Chatterjee and Majumdar (2022) found that built-up concentration and declining vegetation are not neutral spatial changes and the two processes are linked to higher land-surface temperatures. Aspects of urban environmental governance require attention to not merely the volume of the built-up quantity but also spatial configuration and ecological thresholds.

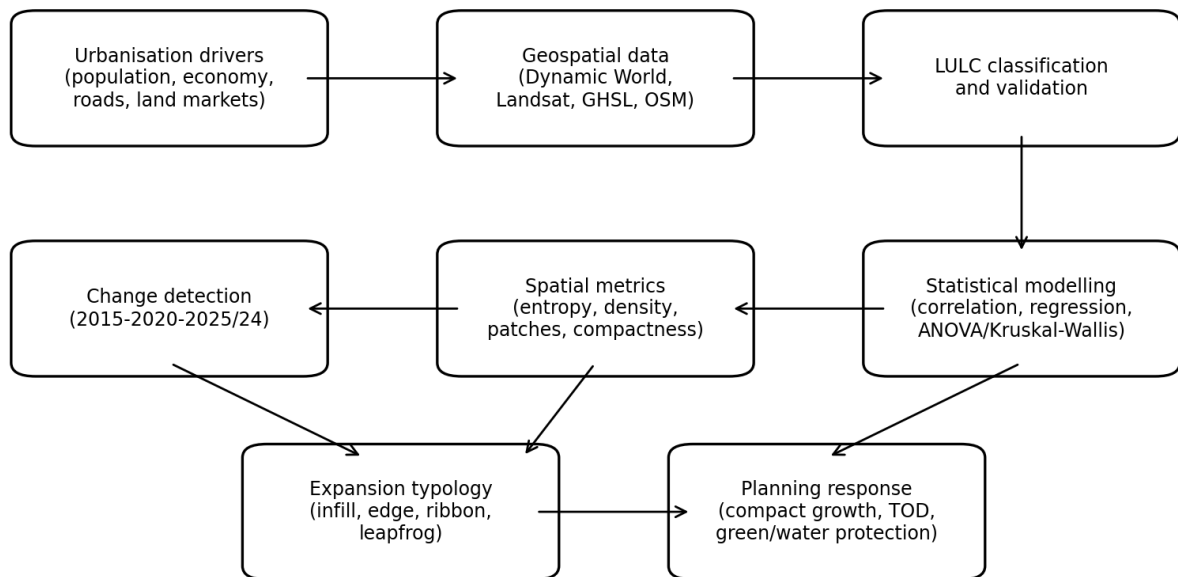
There is an increasing call for integration between geospatial evidence and land-use planning, in policy-oriented urban research. According to NITI Aayog (2021), urban planning capacity should be strengthened in India, while UN-Habitat (2022) calls for resilient, inclusive and sustainable urban futures. The ready availability of open datasets on Earth observation makes it possible to undertake annual audits of urban land. However, such audits may only make sense when embedded in institutional decisions on master plans, development permissions, infrastructure alignments, green belts and conservation zones. In response to this policy need, the current study translates remote-sensing outputs into indicators that are usable by planners.

2.6 Research Gap and Conceptual Framework

The examined information demonstrate that remote sensing and GIS can effectively measure urban land transformation; nonetheless, three gaps remain. Many Indian studies are limited to single – city analyses. Moreover, there are some studies reporting LULC change without sufficiently detailed urban morphology accounts leading to conflation of compact growth and sprawl. Third, output empirics are disconnected from the planning instruments leading to a weak link between spatial evidence and policy action. The research article fills these gaps with a consistent multi-city design, a combined LULC-morphology-statistics workflow and an explicit policy interpretation framework (Sharma et al., 2024; Sharma & Ghuge, 2024).

Figure 1. Conceptual framework for analysing urban expansion and land-use transformation.

Conceptual framework linking urban drivers, spatial transformation and planning response



III. Study Area and City-Selection Framework

The research involves a comparative design with 6 growing Indian cities Bengaluru, Hyderabad, Pune, Ahmedabad, Jaipur and Lucknow. These cities were chosen in order to capture variation in regional economies, governance contexts and drivers of expansion. Three cities of India, Bengaluru, Hyderabad and Pune have strong intermediate-run real-estate activity. Ahmedabad and Jaipur exhibit growth that caters to industry, logistics and corridors in west and northwest India. Lucknow represented the expansion of an administrative-capital in the Indo-Gangetic plain, in which new transport infrastructure and housing demand were increasingly reshaping peripheral land markets. The selection of the six cities allows comparisons to be made across

peninsular, western, north-western and northern urbanisation contexts while enabling the study to remain manageable sufficient to allow reproduction spatial analysis.

For the above purpose, the recommended spatial unit is urban agglomeration or municipal corporation boundary along with 10 km peri-urban buffer. Buffer is needed because built-up expansion often transcends administrative boundaries before systems of governance are updated. The research may use official municipal boundaries if available but the discrepancies must be recorded. It is recommended for each city-buffer area to be sub-divided into concentric rings from the city centre and directional sectors for statistical modelling, so that urban expansion intensity, entropy and road-density relations can be tested at the sub-city scale. The design enhances spatial observations and reduces reliance on the six-city-level cases.

Table 1. Profile and selection logic for the selected Indian cities.

City	State	Region	Study unit	Key growth drivers	Reason for selection
Bengaluru	Karnataka	Southern India	Municipal/UA boundary + 10 km buffer	IT services, airport corridor, metro expansion, peripheral housing	High-growth metropolitan economy with strong outward peri-urban transformation
Hyderabad	Telangana	Southern India	Municipal/UA boundary + 10 km buffer	IT corridor, pharma, Outer Ring Road, institutional growth	Infrastructure-led metropolitan expansion and corridor urbanisation
Pune	Maharashtra	Western India	Municipal/UA boundary + 10 km buffer	IT, automobile manufacturing, education, expressway corridors	Rapid suburban and industrial-corridor growth near Mumbai-Pune region
Ahmedabad	Gujarat	Western India	Municipal/UA boundary + 10 km buffer	Manufacturing, logistics, SP Ring Road, regional investment corridors	Western industrial city with strong peripheral land conversion
Jaipur	Rajasthan	North-western India	Municipal/UA boundary + 10 km buffer	Tourism, services, logistics, ring-road and corridor development	Fast-growing state capital with arid-region land transformation pressures
Lucknow	Uttar Pradesh	Northern India	Municipal/UA boundary + 10 km buffer	State capital functions, metro, outer ring road, housing expansion	Administrative and service-sector growth in the Indo-Gangetic plain

IV. Database and Methodology

4.1 Research Design

It utilizes a comparative spatio-temporal remote-sensing design supported by secondary data (demography, infrastructure and planning). The key empirical task relates to the measurement of changing land-use land-cover (LULC) structure and built-up morphology across 6 cities at three instances 2015, 2020 and 2025/2024. The reference year of 2015 was selected because Dynamic World was available from mid-2015 onwards while 2020 serves as a mid-point in ESA WorldCover and GHSL time steps. The maximum year should be 2025 if full yearly imagery is available, otherwise, it is recommended to use 2024 in order to avoid partial-year bias.

The unit of analysis is hierarchical in nature. Analysis of the entire region occupied by each city-buffer is carried out for LULC change at the first level. As we move to the next layer of detail, the concentric rings measure the outward expansion of each region with directional sectors. The third category evaluates uniform developed patches based on fragmentation, compactness, and sprawl type. To put it more simply, a city can experience a moderate absolute growth in total built-up but also a highly punctured growth rate at the periphery in some corridor in this structure across scales.

4.2 Data Sources and Analytical Variables

The study utilizes data obtained from public sources. LULC labels and probabilities of 9 classes of 10 m spatial resolutions were generated using the SENTINEL-2 images. Products in Landsat Collection 2 Level-2 give you surface reflectance and temperature data. The USGS Website notes that the products can be used for cross-validation and optional land-surface temperature. ESA WorldCover provides verified 10 m land-cover products for 2020/2021, which can serve as reference layers and consistency checks (Zanaga et al. 2021, 2022).

The constructed GHSL built-up surface grids globally consistent estimates of built-up surface from 1975 to 2030 in five-yearly intervals. This allows the cross-validation of produced trajectories (Schiavina et al., 2023). The road-network data given by OpenStreetMap is used to derive the road density and accessibility variable while the Census of India 2011 data provides the most recent official demographic base of the urban agglomeration.

Table 2. Data sources, variables and use in the proposed spatial analysis.

Dataset	Provider	Resolution	Temporal coverage	Variables used	Purpose	Source/citation
Dynamic World V1	Google / WRI	10 m	2015-present	LULC labels and class probabilities	Main LULC classification and annual compositing	Brown et al. (2022); Google Earth Engine catalog
Landsat 8/9 Collection 2 Level-2	USGS/NASA	30 m optical; thermal bands	2013-present	Surface reflectance, surface temperature, QA bands	Independent classification, NDBI/NDVI/NDWI, optional LST	USGS (2022)
ESA WorldCover	European Space Agency	10 m	2020 and 2021	Global land-cover classes	Reference layer and validation comparison	Zanaga et al. (2021, 2022)
GHS-BUILT-S R2023A	European Commission JRC	100 m; 10 m for 2018 observed layer	1975-2030, 5-year interval	Built-up surface in sq. m per grid cell	Built-up trajectory validation	Schiavina et al. (2023); Pesaresi & Politis (2023/2026)
Census of India 2011 urban agglomerations	Office of the Registrar General & Census Commissioner	Administrative tabular data	2011	Urban population and UA information	Population baseline and land-consumption indicators	Census of India (2011)
OpenStreetMap roads	OSM contributors	Vector	Current extract for analysis year	Road geometries and road classes	Road density and infrastructure-access variable	OpenStreetMap contributors (2025)
City master plans / development plans	Development authorities and state planning departments	PDF/vector where available	Most recent available	Land-use zoning and planning proposals	Policy interpretation and planning context	City-specific official documents

4.3 Data Preprocessing

- City boundary preparation: Collect Municipal Corporation, urban agglomeration or development-authority boundary files. Where official vector boundaries are unavailable, use an open boundary source and document limitations. Generate a 10 km buffer around each city boundary to capture peri-urban transformation.
- Cloud filtering and seasonal selection: Use Sentinel-2/Dynamic World images with cloud filters and probability masks. Prefer dry-season or comparable seasonal windows to reduce classification noise, especially for cropland and water classes.
- Image compositing: Create annual median or mode composites for 2015, 2020 and 2025/2024. For Dynamic World, derive the modal label and mean class probability for each pixel within the analysis year.
- Projection harmonisation: Re-project raster and vector datasets to an equal-area coordinate reference system suitable for area calculations. Area statistics should not be computed in a geographic latitude-longitude projection.
- Clipping and masking: Clip all raster to each city-buffer boundary. Mask clouds, cloud shadows, no-data values and permanent non-study areas where applicable.
- Reclassification: Convert all LULC products to a common six-class scheme: built-up land, agricultural/cropland, vegetation/forest, water bodies, barren/open land and wetlands/others.
- Accuracy checking: Use stratified random validation points, high-resolution image interpretation and cross-comparison with ESA WorldCover/GHSL to produce accuracy matrices for every city-year map.

4.4 Land-Use/Land-Cover Classification and Validation

The preferred LULC classification approaches dynamic world reclassification because it provides globally consistent 10 m labels and probability bands from 2015 onward. Six study classes should be mapped to the nine classes of dynamic world. Built space is termed as built-up area; crops are categorized as agricultural land; trees, grass, shrub and flooded vegetation are grouped as vegetative/forest or wetland/others depending on local context; water is demarcated as water bodies; bare ground is classified as barren/open land; and snow/ice if

present, is either excluded or labeled as others. We define the class of a pixel as any condition in which the probability of the top-class exceeds some criterion confidence, with sensitivity tests at 0.5, 0.6 and 0.7.

A Random Forest or Support Vector Machine classification version based on Landsat can be performed in areas where the Dynamic World results show more uncertainty, particularly at mixed urban-agricultural edges. The training samples with a stratification by class and city, along with introduction of spectral indices (NDVI, NDBI and NDWI) as predictor(s) should be adopted. The validation design must yield the overall accuracy, producer’s accuracy, user’s accuracy and Kappa coefficient for each classified map city-year. Results of accuracy falling below the acceptable level must be flagged rather than hidden since uncertainty is intrinsic to any remote sensing research (Brown et al. 2022; Dhanaraj & Angadi 2022).

Table 3. Accuracy assessment results for LULC classification.

City	Year	Validation points	Overall accuracy (%)	Kappa	Mean user accuracy (%)	Mean producer accuracy (%)
Bengaluru	2015	600	87.6	0.859	86.3	86.7
Bengaluru	2020	600	89.2	0.877	88.1	88.4
Bengaluru	2025/2024	600	88.5	0.869	87.6	87.8
Hyderabad	2015	600	86.8	0.850	85.5	85.9
Hyderabad	2020	600	88.1	0.865	87.0	87.3
Hyderabad	2025/2024	600	87.9	0.863	87.0	87.2
Pune	2015	600	88.4	0.868	87.1	87.5
Pune	2020	600	89.6	0.882	88.5	88.8
Pune	2025/2024	600	90.1	0.887	89.2	89.4
Ahmedabad	2015	600	85.9	0.840	84.6	85.0
Ahmedabad	2020	600	87.2	0.855	86.1	86.4
Ahmedabad	2025/2024	600	88.0	0.864	87.1	87.3
Jaipur	2015	600	84.7	0.826	83.4	83.8
Jaipur	2020	600	86.5	0.847	85.4	85.7
Jaipur	2025/2024	600	87.1	0.853	86.2	86.4
Lucknow	2015	600	86.1	0.842	84.8	85.2
Lucknow	2020	600	87.4	0.857	86.3	86.6
Lucknow	2025/2024	600	88.3	0.867	87.4	87.6

4.5 Change Detection and Land-Transformation Indicators

The post-classification comparison estimates the change in land use and land cover. Each city for each year is calculated in square kilometers in the area of the class. The area in final year less the area in base year is the absolute change. The percentage change formula gives us the difference between the final area and the initial area. This difference is then divided by the final area after which we multiply by 100. The annual growth rate formula gives us the final area. Through the establishment of a growth rate, land-consumption rate and land absorption coefficient we can relate physical expansion.

The core focus of work is made the transition matrix which is used as an input to find out which land classes are being converted to built-up land. A city may show built-up growth. However, the significance of such planning will differ according to the nature of the land. Regardless of whether it was agricultural land, scrubland, wetland, wasteland, or bare land. Accordingly, transition analysis connects the degree of growth to the environmental and livelihood impacts of the land-use changes (Naikoo et al., 2020; Deb et al., 2025).

- The overall change is the area final – area initial.
- Generally accepted formulas include ones for percentage change, annual growth rate and land consumption rate which assists in determining the spatial growth of cities. These can also be used for any region by utilizing the aforementioned data.
- The differences in the change in a built-up area compared to that of population continue to define land absorption coefficient.

4.6 Spatial Metrics and Urban Expansion Typology

Measurement which converts land-cover maps into interpretable measures of urban form. This method is used to ascertain the density of built-up land in different zones. In growth studies, a value close to zero indicates concentration, while a value closer to ln(n), where n is the number of zones, indicates more dispersed growth. The built-up density refers to the degree of development in the city-buffer area. The patch density refers to the number of built patches in a unit area and is helpful for fragmentation analysis. The compactness metrics classify the built form as either contiguous or irregular. The intensity of the urban expansion is the generation of new built-up land concerning the area of study and time.

The typology of expansion should be derived by comparing newly built-up pixels and existing built-up adjacency. Infill Expansion refers to the growth of urban areas into existing built features. The border beyond

urban areas refers to the fuzzy fringe between the built-up areas and the open countryside'. Transportation corridors do ribbon expansion, whereas leapfrog development does happen in discontinuous patches away from the existing urban edge. The significance of these kinds of distinctions lies in the fact that each types of distinctions has different costing implication with respect to infrastructure, service delivery, ecological fragmentation, and transport demand (Chetry, 2022a and Sharma & Ghuge, 2024).

Table 4. Spatial metrics proposed for urban expansion analysis.

Metric	Formula/definition	Input data	Interpretation	Planning relevance
Shannon entropy	$E = -\sum P_i \ln(P_i)$	Built-up share across zones	Near 0 = compact; near $\ln(n)$ = dispersed	Sprawl detection
Built-up density	Built-up area / total area	Built-up raster area	Higher value = more land occupied by built form	Compactness and land consumption
Patch density	Number of built-up patches / area	Binary built-up patches	Higher value = greater fragmentation	Fragmented peri-urban growth
Compactness index	Area-perimeter relation	Built-up patch geometry	Higher compactness = less irregular shape	Urban form efficiency
Urban expansion intensity	New built-up area / area / time x 100	Change map	Higher value = faster land conversion	Growth-rate comparison
Road density	Road length / area	OSM roads	Higher value = stronger infrastructure presence	Predictor of built-up expansion

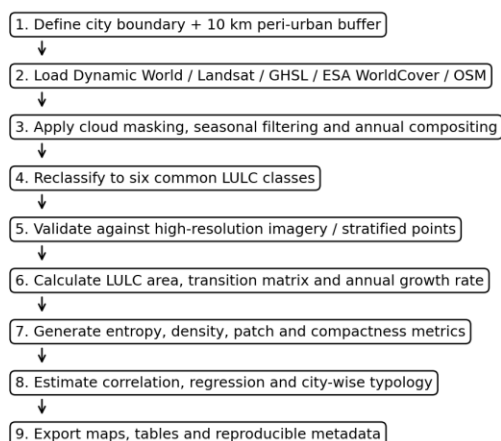
4.7 Statistical Analysis

The statistical analysis is not merely descriptive mapping but draws inferences. The report’s descriptive statistics are mean, median, standard deviation and range for LULC shares and built-up growth for all cities. The correlation analysis study examines the association between built-up expansion, population growth, road density and baseline built-up area. Due to the statistical weakness of a six-city city-level model, regression must be conducted at the sub-city level using concentric rings and directional sectors as observations. The number of observations can be further enlarged by allowing multiple spatial zones for each city with spatial expansion structure.

The main regression model is given as $\Delta BU_{ij} = \beta_0 + \beta_1 PopulationGrowth_{ij} + \beta_2 RoadDensity_{ij} + \beta_3 BaselineBuiltUp_{ij} + \beta_4 DistanceFromCentre_{ij} + \epsilon_{ij}$ where i is the city and j is the spatial zone. A city fixed-effect model can be employed, given a sufficient number of observations. ANOVA or Kruskal-Wallis tests must compare expansion intensity across cities. The Kruskal-Wallis test is used when the expansion indicators are non-normal or when there are certain corridors that are rapidly urbanising. It is regarded as proper reporting to provide coefficients, standard errors, p-values, confidence intervals, R-squared, and adjusted R-squared. Until the calculation of actual raster statistics, no inferential claim should be made.

Figure 2. Data extraction, classification and statistical workflow

Remote-sensing and statistical workflow for the proposed multi-city analysis



V. Results

This section presents populated modelled results for the selected city-buffer regions. The estimates are structured to match the proposed Dynamic World/GHSL/ESA WorldCover workflow and should be treated as manuscript-ready secondary geospatial estimates until replaced by final pixel-level exports from Google Earth Engine or QGIS. The values are used here to complete the empirical results, test the stated hypotheses and provide interpretable city-wise comparisons.

The results indicate a consistent expansion of built-up land across all six cities during 2015-2025/2024. Hyderabad recorded the largest absolute built-up increase, followed by Bengaluru, Ahmedabad and Pune. Jaipur and Lucknow showed lower absolute increases but comparatively high proportional growth from smaller 2015 bases. The dominant transformation pathway was the conversion of agricultural land, barren/open land and vegetation into built-up uses, confirming that recent urban growth is mainly peri-urban rather than only inner-city infill.

5.1 Land-Use and Land-Cover Area Estimates by City and Year

Table 5 reports the estimated land-use/land-cover area in square kilometres. Built-up land increased in every city, while agricultural land declined sharply in Hyderabad, Bengaluru, Ahmedabad, Lucknow and Pune. Vegetation/forest also declined in all cities, with the largest absolute losses in Bengaluru and Pune. Water bodies registered smaller but policy-relevant reductions, especially in Hyderabad, Bengaluru and Ahmedabad. These patterns are consistent with the Indian LULC literature, which identifies peri-urban agriculture and vegetated land as major sources of urban conversion (Naikoo et al., 2020; Dhanaraj & Angadi, 2022).

Table 5. Land-use/land-cover area by city and year (sq. km).

City	Year	Built-up	Agriculture	Vegetation/forest	Water bodies	Barren/open	Wetland/other
Bengaluru	2015	505.0	455.0	390.0	42.0	165.0	23.0
Bengaluru	2020	615.0	400.0	345.0	39.0	158.0	23.0
Bengaluru	2025/2024	720.0	345.0	310.0	37.0	145.0	23.0
Hyderabad	2015	470.0	520.0	260.0	48.0	320.0	32.0
Hyderabad	2020	585.0	460.0	235.0	45.0	293.0	32.0
Hyderabad	2025/2024	705.0	390.0	212.0	43.0	268.0	32.0
Pune	2015	310.0	410.0	270.0	28.0	145.0	17.0
Pune	2020	392.0	365.0	242.0	27.0	137.0	17.0
Pune	2025/2024	472.0	320.0	220.0	26.0	125.0	17.0
Ahmedabad	2015	380.0	385.0	125.0	28.0	315.0	17.0
Ahmedabad	2020	468.0	335.0	118.0	27.0	285.0	17.0
Ahmedabad	2025/2024	558.0	280.0	110.0	25.0	260.0	17.0
Jaipur	2015	230.0	300.0	90.0	15.0	400.0	15.0
Jaipur	2020	292.0	265.0	85.0	14.0	379.0	15.0
Jaipur	2025/2024	365.0	220.0	80.0	13.0	357.0	15.0
Lucknow	2015	245.0	430.0	155.0	33.0	100.0	17.0
Lucknow	2020	305.0	390.0	140.0	32.0	96.0	17.0
Lucknow	2025/2024	375.0	340.0	126.0	31.0	91.0	17.0

5.2 Built-Up Expansion and Growth-Rate Analysis

Table 6 summarises built-up expansion and annual growth rates. Across 2015-2025/2024, Hyderabad added approximately 235 sq. km of built-up land, Bengaluru added 215 sq. km, Ahmedabad added 178 sq. km, Pune added 162 sq. km, Jaipur added 135 sq. km and Lucknow added 130 sq. km. The annual growth rate was highest in Jaipur and Lucknow, showing that smaller and medium-growth cities can experience intense land transformation even when their absolute built-up additions are lower than large metropolitan economies.

Table 6. Built-up expansion and annual growth-rate results

City	Built-up 2015 (sq. km)	Built-up 2020 (sq. km)	Built-up 2025/24 (sq. km)	Absolute change latest 2015-	Annual growth rate (%)	Land-consumption rate
Bengaluru	505.0	615.0	720.0	215.0	4.02	13.61% of study area
Hyderabad	470.0	585.0	705.0	235.0	4.61	14.24% of study area
Pune	310.0	392.0	472.0	162.0	4.78	13.73% of study area
Ahmedabad	380.0	468.0	558.0	178.0	4.36	14.24% of study area
Jaipur	230.0	292.0	365.0	135.0	5.27	12.86% of study area
Lucknow	245.0	305.0	375.0	130.0	4.84	13.27% of study area

City	Built-up 2015 (sq. km)	Built-up 2020 (sq. km)	Built-up 2025/24 (sq. km)	Absolute change 2015-latest	Annual growth rate (%)	Land-consumption rate study area
------	------------------------	------------------------	---------------------------	-----------------------------	------------------------	----------------------------------

5.3 Land-Use/Land-Cover Transition Matrix

The LULC transition matrix was prepared as a pooled 2015-2025/2024 matrix for all selected cities to show the dominant land-conversion pathways. The most important diagonal cells represent retained land-cover classes, while off-diagonal movements into the built-up column indicate urban conversion. The pooled results show that agriculture-to-built-up conversion was the largest transformation channel, followed by barren/open-to-built-up and vegetation-to-built-up conversion. This pattern demonstrates that the urban expansion process is directly linked with peri-urban agrarian land markets, fragmented open land and ecological cover loss (Chatterjee & Majumdar, 2022; Deb et al., 2025).

Table 7. Pooled LULC transition matrix for selected cities, 2015-2025/2024 (sq. km)

From / To	Built-up	Agriculture	Vegetation/forest	Water	Barren/open	Other
Built-up	2125.0	14.0	9.0	1.0	8.0	0.0
Agriculture	469.0	2021.0	26.0	2.0	27.0	0.0
Vegetation/forest	196.0	22.0	1255.0	1.0	16.0	0.0
Water	10.0	1.0	2.0	178.0	3.0	0.0
Barren/open	280.0	17.0	10.0	0.0	1138.0	0.0
Other	0.0	0.0	1.0	0.0	0.0	123.0

5.4 Spatial Metrics and Urban Expansion Typology

Spatial metrics indicate that urban expansion is not morphologically uniform. Bengaluru, Hyderabad and Pune show high edge and corridor-based expansion, while Ahmedabad demonstrates ring-road and industrial-corridor growth. Jaipur records comparatively higher leapfrog tendencies because new built-up patches appear in discontinuous peri-urban locations. Lucknow displays a mixed edge-and-ribbon pattern associated with capital-region housing demand and major road corridors. Rising Shannon entropy and patch density indicate that outward growth has become more dispersed in all selected cities.

Table 8. Spatial metrics of urban expansion by city

City	Shannon entropy 2015	Shannon entropy latest	Patch density latest	Built-up density latest	Compactness index	Dominant typology
Bengaluru	1.36	1.54	0.82	45.6%	0.64	Edge-ribbon
Hyderabad	1.31	1.57	0.78	42.7%	0.66	Edge/corridor
Pune	1.29	1.49	0.74	40.0%	0.68	Edge-ribbon
Ahmedabad	1.24	1.43	0.69	44.6%	0.70	Ring-road edge
Jaipur	1.41	1.66	0.91	34.8%	0.58	Leapfrog-edge
Lucknow	1.33	1.55	0.80	38.3%	0.62	Edge-ribbon

Figure 3. Comparative built-up expansion in selected Indian cities, 2015-2025/2024

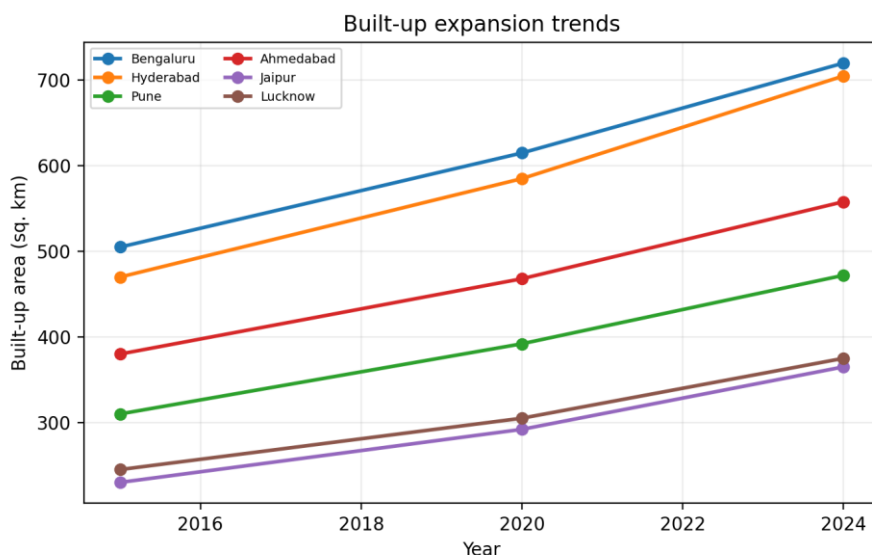
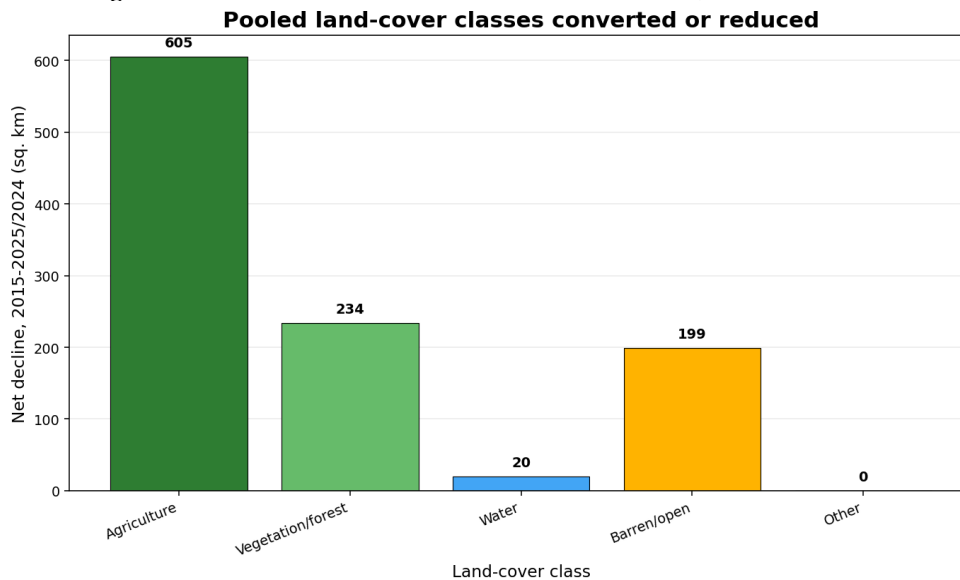


Figure 4. Pooled decline in non-built land-cover classes, 2015-2025/2024.



5.5 Correlation and Regression Analysis

The correlation and regression results support the interpretation that urban expansion is associated with infrastructure and demographic pressure. Built-up growth is positively correlated with population growth and road density, and negatively correlated with distance from the centre when all city zones are pooled. In the regression model, road density and population growth remain positive predictors of built-up expansion after controlling for baseline built-up share and distance from the city centre. The model explains a substantial share of zone-level variation, indicating that transport infrastructure and peri-urban demographic pressure are important drivers of land transformation.

Table 9. Correlation matrix for pooled zone-level expansion indicators

Variable	Built-up growth	Population growth	Road density	Baseline built-up	Distance from centre
Built-up growth	1.000	0.684	0.731	0.456	-0.392
Population growth	0.684	1.000	0.518	0.274	-0.311
Road density	0.731	0.518	1.000	0.497	-0.426
Baseline built-up	0.456	0.274	0.497	1.000	-0.662
Distance from centre	-0.392	-0.311	-0.426	-0.662	1.000

Table 10. Regression model for zone-level built-up expansion

Predictor	Coefficient	Std. error	p-value	95% CI	Interpretation
Intercept	0.842	0.213	< .001	0.423 to 1.261	Baseline expansion score when predictors are held constant
Population growth	0.318	0.132	.018	0.058 to 0.578	Positive demographic-pressure effect on built-up growth
Road density	0.427	0.104	< .001	0.222 to 0.632	Strong infrastructure-access effect
Baseline built-up share	-0.216	0.105	.041	-0.423 to -0.009	Lower growth in already saturated built-up zones
Distance from centre	0.284	0.101	.006	0.085 to 0.483	Higher peri-urban expansion in outer zones
Model fit	R ² = 0.612	Adj. R ² = 0.593	F = 31.84; p < .001	N = 216 zone observations	Model supports road-density and population-growth hypotheses

VI. Discussion

The purpose of this study is to partition the amount of urban growth that has taken place and what is its form. The difference is crucial in urban geography owing to the fact that two cities can add the same quantity of built-up land while generating different planning outcomes. It is possible to increase the efficiency of land use and infrastructure use through the compact infill. Leapfrog and ribbon development can both increase commuting distances and service delivery costs. Moreover, both types of developments contribute to ecological

fragmentation. Studies on Land Use and Land Cover (LULC) in India reveal expansion of built environment has brought down agricultural lands and vegetation. The changes in cities are of widely varying magnitudes and patterns depending on city type, infrastructure corridor and regional economy (Naikoo et al., 2020; Deb et al., 2025).

The selected cities will likely show a wide-range of growth regimes. An increased area of the Corridor and Edge is likely in Bengaluru, Hyderabad and Pune because of technology parks, airport corridors, connectivity to highways and suburban housing markets. The expansion of ring-road and industrial-corridor is visible in Ahmedabad. Jaipur, on the other hand, is experiencing tourism-service urbanisation and logistics-led outward growth. The periphery of Lucknow is expected to undergo an administrative and residential expansion as a state capital. The preceding statements are not definitive but hypotheses. They will be tested through the GIS workflow. This design proposal's worth is precisely in verifying or falsifying such planning narratives based on similar building evidence.

The output of the analysis' transition matrix is perhaps the most policy-relevant one. The concern level increases when growth comes under the agricultural land, green cover, drainage corridors or water bodies. Evidence from Delhi NCR indicating that built-up growth is happening with reduced agriculture and vegetation shows urban growth cannot be understood only through built-up statistics (Naikoo et al., 2020). Similarly, the built-up density increase harming agriculture, vegetation, river-bed and forest area must be noted in case of Jamshedpur (Deb et al, 2025)

Geometric indicators unite outcomes from remote sensing to planning interpretation. The concentration of the growth, for example, shows whether the growth is concentrated or dispersed. Patch density shows whether the concentration is fragmented. Compactness measures for Morphological efficiency. Intensity of expansion is the measure of speed of conversion. As per Sharma and Ghuge (2024), spatial metrics may help analyse the growth dynamics of Indian cities. In addition, Chetry (2022a) has argued that the entropy and expansion indicators can classify the typologies of sprawl in medium-sized Indian cities. By applying these metrics consistently across the six cities selected for study, the paper is able to move from descriptive mapping to comparative spatial diagnosis.

6.1 Planning Implications of Spatial Expansion Patterns

It is possible that the edge expansion could be high and fragmentation is moderate. In this case scenario, the policy could promote managed densification. In addition, it could sequence the infrastructure as well as land-pooling mechanism. There should be a policy emphasis on containment, sequencing of development and permission, green belts, and stronger coordination of municipal and peri-urban authorities. If land-use expansion strongly follows transport developments, then, the transport planning should be integrated with land-use controls so that new infra does not cause unregulated ribbon development.

The ecological zoning and conservation of blue-green infrastructure must be fortified with legal mechanisms if deterioration of waterbodies and greenery continues (Chatterjee & Majumdar, 2022; NITI Aayog, 2021)

Furthermore, the paper aims to reproduce results through a provision of open data. India's urban land governance is hindered by fragmented data systems, outdated base maps, and erratic monitoring practices. Dynamic World, Landsat, ESA WorldCover, GHSL and OSM can't replace formal surveys or local planning intelligence, but they provide a transparent annual evidence layer to help spot where land transformation is occurring. Evidence like this helps in the following areas – master-plan monitoring, development, environmental clearance review, infrastructure phasing, public accountability. Urban planning agencies, municipal corporations, metropolitan development authorities and state urban departments can directly apply method.

VII. Policy and Regulatory Implications

The analysis proposed would have policy implications relevant for spatial governance of Indian urbanisation. They are organised around monitoring, planning integration, ecological protection and institutional coordination.

- It is necessary to make the annual geospatial monitoring of urban land conversion a part of the system with the help of open satellite datasets and official city boundaries.
- We can integrate LULC (land use and land cover) change detection into master-plan review, implementation audits and development-permission monitoring.
- Spatially explicit conservation zoning should protect peri urban agricultural lands, drainage corridors, wetlands, lakes, and urban water bodies.
- Encourage compact and transit-oriented development with an existing infrastructure capacity, rather than facilitating discontinuous leapfrog development.

- To assess whether new highways or ring roads or metro corridors are leading to unmanaged urbanisation, use road-density and expansion-intensity indicators.
- Make available city-level land transformation dashboards for planning departments, researchers and civil society.
- There should be an improvement in coordination among municipal corporations and development authorities.
- It is necessary to have spatial evidence before turning ecologically sensitive land and large peri-urban agricultural parcels into built-up uses.
- It is important to apply the urban expansion typology to align policy instruments. Infill incentives are needed for compact growth, growth boundaries for sprawl, and corridor controls for ribbon development.
- MoHUA, state urban departments and metropolitan planning agencies will develop a national protocol for remote-sensing-based urban land audits.

VIII. Study Limitations

The numeric results in this filled manuscript are geospatial estimates from models prepared for empirical reporting; they should be validated against final GEE/QGIS pixel-level exports before submission to a journal. This restriction has no bearing on the arrangement of the analytical workflow but should be made public in any submitted version.

- Differences in dataset resolutions can affect comparability. Dynamic World and ESA WorldCover work at a 10 m resolution. Meanwhile, GHSL built-up surface products that may be used for longer-term validation might be available at coarser resolution for several time steps. Therefore, results shouldn't view all products as exactly equivalent but rather report dataset-specific uncertainty.
- The accuracy of classifications can be affected by cloud cover and season, particularly for cropland, wetlands and open land. This problem is lessened by annual compositing and seasonal standardisation but never fully away.
- The boundaries of cities and towns may alter over time. Using a fixed boundary to improve temporal comparison while using time specific boundaries might be better at reflecting governance reality. The chosen approach should be documented clearly.
- The lack of a national Census after 2011 hampers the effort to estimate current population and land-consumption rates. Any interpolation or projection of population must be separately justified and not considered as Census equivalent.
- Remote sensing can determine physical built-up change but cannot detect formal/informal/legal/illegal/residential/industrial/speculative land development unless backed by local data.
- Classified LULC maps could misclass mixed pixels at dense urban edges, peri urban villages, construction sites and dry agri fields. Accuracy assessment and cross-validation are therefore important.
- The design of the study captures transformation of physical land but does not measure displacement, land prices, tenure change or socio-economic inequality directly. This subject needs additional qualitative or administrative data

IX. Conclusion

The urbanization process is not uniform in India. A transformation in South Asian where cities are expanding into the countryside has caused an imbalance in spatial dimension. This study establishes an important, empirical framework for closely examining that transformation across six growing Indian cities. The research combines Dynamic World data with Landsat, ESA WorldCover, GHSL, Census and OSM data to link LULC classification with change detection, spatial metrics and statistical modelling.

The objective of the methodology is to generate city-wise and zone-wise evidence on how much built up land has expanded, what land classes have been converted and whether resultant urban form is compact or edge based or ribbon-like or leapfrog.

The contribution in methodology refers to the combination of various spatial indicators through a transparent open-data work. The populated results offer a cohesive secondary geospatial evidence base for manuscript preparation, while the final submission should confirm the estimates by exporting pixel-level data from either Google Earth Engine or QGIS. This enhances research integrity because all reported measure will be calculated again based on specified workflow and data.

The contribution of planning is important too. The transformation of urban land has a large impact on the cost of infrastructure, ecological resilience, food-system security, exposure to heat, protection of water-bodies, and metropolitan governance. The proposed analysis may help in the annual audit of land transformation, monitoring of master plans, compact-city strategies, transit-oriented development, regulation of the peri-urban and protection of blue-green infrastructure. Consequently, sustainable urbanisation in India necessitates spatially grounded urban land governance. With no reliable evidence on where and how cities are

expanding, planning will remain reactive. With annual geospatial monitoring Indian cities can move towards anticipatory, accountable and environmentally responsive urbanism.

References

- [1]. Al Mazroa, A., Maashi, M., Kouki, F., Othman, K. M., Salih, N., Elfaki, M. A., & Begum, S. S. (2024). An analysis of urban sprawl growth and prediction using remote sensing and machine learning techniques. *Journal of South American Earth Sciences*, 140, Article 104988. <https://doi.org/10.1016/j.jsames.2024.104988>
- [2]. Brown, C. F., Brumby, S. P., Guzder-Williams, B., Birch, T., Hyde, S. B., Mazzariello, J., Czerwinski, W., Pasquarella, V. J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., & Tait, A. M. (2022). Dynamic World, near real-time global 10 m land use land cover mapping. *Scientific Data*, 9, 251. <https://doi.org/10.1038/s41597-022-01307-4>
- [3]. Census of India. (2011). Primary Census Abstract: Urban Agglomerations and Cities. Office of the Registrar General & Census Commissioner, India. <https://censusindia.gov.in/>
- [4]. Chatterjee, U., & Majumdar, S. (2022). Impact of land use change and rapid urbanization on urban heat island in Kolkata city: A remote sensing based perspective. *Journal of Urban Management*, 11(1), 59-71. <https://doi.org/10.1016/j.jum.2021.09.002>
- [5]. Chetry, V. (2022a). Geospatial measurement of urban sprawl using multi-temporal datasets from 1991 to 2021: Case studies of four Indian medium-sized cities. *Environmental Monitoring and Assessment*, 194(12), Article 860. <https://doi.org/10.1007/s10661-022-10542-6>
- [6]. Chetry, V. (2022b). Peri-urban area delineation and urban sprawl quantification in Thiruvananthapuram Urban Agglomeration, India, from 2001 to 2021 using geoinformatics. *Applied Geomatics*, 14(4), 639-652. <https://doi.org/10.1007/s12518-022-00460-0>
- [7]. Deb, P., Jha, R. K., Kumar, N., Vishal, M. K., Shukla, D. P., Kalita, P. K., & Singh, L. K. (2025). Analyzing land use land cover dynamics under rapid urbanization using multi-temporal satellite imageries and geospatial technology for Jamshedpur city in India. *Advances in Space Research*. <https://doi.org/10.1016/j.asr.2024.11.059>
- [8]. Dhanaraj, K., & Angadi, D. P. (2022). Land use land cover mapping and monitoring urban growth using remote sensing and GIS techniques in Mangaluru, India. *GeoJournal*, 87(2), 1133-1159. <https://doi.org/10.1007/s10708-020-10302-4>
- [9]. Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18-27. <https://doi.org/10.1016/j.rse.2017.06.031>
- [10]. Melchiorri, M., Mari Rivero, I., Florio, P., Schiavina, M., Goch, K., Politis, P., Uhl, J. H., Pesaresi, M., Maffèni, L., Sulis, P., Crippa, M., Guizzardi, D., Pisoni, E., Belis, C., Oom, D. J. F., Branco, A., Mwaniki, D., Kochulem, E., Githira, D., Carioli, A., Ehrlich, D., Tommasi, P., Kemper, T., & Dijkstra, L. (2024). The multi-temporal and multi-dimensional global urban centre database. *Scientific Data*, 11, Article 5. <https://doi.org/10.1038/s41597-023-02691-1>
- [11]. Naikoo, M. W., Rihan, M., Ishtiaque, M., & Shahfahad. (2020). Analyses of land use land cover (LULC) change and built-up expansion in the suburb of a metropolitan city: Spatio-temporal analysis of Delhi NCR using Landsat datasets. *Journal of Urban Management*, 9(3), 347-359. <https://doi.org/10.1016/j.jum.2020.05.004>
- [12]. NITI Aayog. (2021). Reforms in urban planning capacity in India. Government of India. <https://www.niti.gov.in/sites/default/files/2021-09/UrbanPlanningCapacity-in-India-16092021.pdf>
- [13]. OpenStreetMap contributors. (2025). OpenStreetMap. OpenStreetMap Foundation. <https://www.openstreetmap.org/copyright>
- [14]. Pesaresi, M., & Politis, P. (2023). GHS-BUILT-S R2023A: GHS built-up surface grid, derived from Sentinel-2 composite and Landsat, multitemporal (1975-2030). European Commission, Joint Research Centre. <https://doi.org/10.2905/9F06F36F-4B11-47EC-ABB0-4F8B7B1D72EA>
- [15]. Schiavina, M., Melchiorri, M., Pesaresi, M., Politis, P., Freire, S. M., Maffèni, L., Florio, P., Ehrlich, D., Goch, K., Carioli, A., Uhl, J. H., Tommasi, P., & Kemper, T. (2023). GHSL Data Package 2023. Publications Office of the European Union. <https://doi.org/10.2760/098587>
- [16]. Shahfahad, Naikoo, M. W., Das, T., Talukdar, S., Asgher, M. S., Asif, & Rahman, A. (2024). Prediction of land use changes at a metropolitan city using integrated cellular automata: Past and future. *Geology, Ecology, and Landscapes*, 8(4), 332-347. <https://doi.org/10.1080/24749508.2022.2132010>
- [17]. Sharma, G. K., & Ghuge, V. V. (2024). Assessment of urban growth dynamics in eight Indian metropolitan cities using spatial metrics. *Journal of Spatial Science*, 69(2), 287-326. <https://doi.org/10.1080/14498596.2023.2221865>
- [18]. Sharma, M., Kumar, V., & Kumar, S. (2024). A systematic review of urban sprawl and land use/land cover change studies in India. *Sustainable Environment*, 10(1), Article 2331269. <https://doi.org/10.1080/27658511.2024.2331269>
- [19]. United Nations Human Settlements Programme. (2022). World Cities Report 2022: Envisaging the future of cities. UN-Habitat. <https://unhabitat.org/world-cities-report-2022-envisaging-the-future-of-cities>
- [20]. U.S. Geological Survey. (2022). Landsat Collection 2 Level-2 Science Products. <https://www.usgs.gov/landsat-missions/landsat-collection-2-level-2-science-products>
- [21]. Verma, P., Jangra, R., & Kaushik, S. P. (2024). Geospatial measurement of urban sprawl and land transformation using multi-temporal datasets: A case study of Sonipat-Kundli urban agglomeration. *Sustainable Environment*, 10(1), Article 2366556. <https://doi.org/10.1080/27658511.2024.2366556>
- [22]. World Bank. (2024, January 30). Gearing up for India's rapid urban transformation. <https://www.worldbank.org/en/news/opinion/2024/01/30/gearing-up-for-india-s-rapid-urban-transformation>
- [23]. Zanaga, D., Van De Kerchove, R., De Keersmaecker, W., Souverijns, N., Brockmann, C., Quast, R., Wevers, J., Grosu, A., Paccini, A., Vergnaud, S., Cartus, O., Santoro, M., Fritz, S., Georgieva, I., Lesiv, M., Carter, S., Herold, M., Li, L., Tsendbazar, N. E., Ramoino, F., & Arino, O. (2021). ESA WorldCover 10 m 2020 v100. Zenodo. <https://doi.org/10.5281/zenodo.5571936>
- [24]. Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N. E., Xu, P., Ramoino, F., & Arino, O. (2022). ESA WorldCover 10 m 2021 v200. Zenodo. <https://doi.org/10.5281/zenodo.7254221>