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Spatiotemporal Assessment of Urban Expansion Using Multi-Resolution Remote Sensing: Evidence from Tier-I Urban Growth Centres and the Hyderabad region

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Abstract

Urban expansion in India has accelerated significantly over the past two decades, leading to widespread changes in land use and land cover patterns. This study examines the spatiotemporal dynamics of urban expansion and land cover changes from 2001 to 2022 using a dual-resolution geospatial framework. MODIS MCD12Q1 (500 m) data were used for national-scale assessment across twenty Tier-I urban growth centres, while GLC_FCS30D (30 m) data supported high-resolution assessment in the Hyderabad metropolitan region. At the national level, the study revealed a steady increase in built-up areas, often exceeding 30–80% growth across key urban growth centres. Croplands were identified as the primary land category converted into urban use, followed by losses in grasslands and shrublands. The Hyderabad case study demonstrated the limitations of coarse-resolution datasets in detecting fragmented growth and peri-urban development. In contrast, the high-resolution GLC_FCS30D data enabled more detailed mapping of edge expansion, spatial fragmentation, and heterogeneous growth morphology. Unlike prior studies limited to either national or local focus, this work develops a unified, dual-resolution LULC analysis framework with pixel-level transition tracking enables cross-scale insights into urban expansion patterns in India. The integration of both datasets facilitated a comprehensive understanding of urban land changes, combining long-term trend detection with local-level spatial clarity. This approach underscores the importance of resolution–aware methods in urban monitoring and supports evidence–based decision–making in sustainable urban planning, infrastructure development, and land governance. The findings highlight the need for scalable geospatial strategies to address the challenge of rapid urbanization in India, particularly in developing countries undergoing intense land transformation.

1. Introduction

Urbanization is among the most transformative land-use processes of the 21st century, reshaping ecosystems, altering biogeochemical cycles, and generating socio-spatial inequalities (Seto et al., 2012; Angel et al., 2011). In India, rapid urban expansion particularly in Tier-I metropolitan regions has triggered widespread conversion of croplands, shrublands, and semi-natural landscapes into impervious built-up surfaces (Ramachandra et al., 2014; Jat et al., 2017). While this transformation signifies economic progress, it simultaneously threatens ecological resilience, food security, and sustainable development. Effective monitoring of such land transformations requires high-quality spatiotemporal data capable of capturing both national-level trends and localized dynamics. Remote sensing has long served as a core methodology for land use and land cover (LULC) mapping. Coarse-resolution products like MODIS MCD12Q1 (500m) offer consistent, annual global coverage and are widely used for long-term trend detection (Friedl et al., 2010; Schneider et al., 2010). However, their limited spatial granularity often obscures the heterogeneity of urban growth, especially in fragmented peri-urban areas (Herold et al., 2005).

Recent advances in high-resolution global products; such as the 30m GLC_FCS30D dataset derived from Landsat and Sentinel imagery enable more precise urban diagnostics, capturing edge expansion, ecological degradation, and land use fluxes at a finer scale (Zhang et al., 2021; Gong et al., 2019). Despite the availability of both resolutions, few studies have attempted to systematically integrate them into a unified analytical framework, resulting in a persistent gap between macro-scale monitoring and micro-scale land governance (Verburg et al., 2015; Liu et al., 2020). This study addresses that gap by employing a dual-resolution geospatial framework to assess LULC transitions across India from 2001 to 2022. At the national level, Tier-I urban agglomerations were extracted from MODIS 2022 built-up masks and compared with 2001 data to detect temporal change. To validate and augment these results, a high-resolution case study of the Hyderabad metropolitan region was conducted using both MODIS and GLC_FCS30D data. This allowed for pixel-level transition analysis and resolution-based comparisons of land transformation patterns. By bridging national and regional scales through resolution-aware analysis, this study presents a replicable dual-resolution LULC framework that enables pixel-level transition mapping, improves urban diagnostics, and supports sustainable planning in rapidly urbanizing geographies.

2. Study Area and Datasets

Our study adopts a two-tiered spatial framework to examine urban expansion patterns in India over a nearly 2 decadal period from 2001 to 2022. This approach enables both synoptic long-term trend analysis and localized spatial interpretation.

2.1. National-Level: Urban Clusters Across India

The identification and analysis of urban expansion at national level with coarser scale datasets was followed by regional analysis with finer scale datasets. The Hyderabad metropolitan region in Telangana state is characterized by high urban growth rate and spatial fragmentation over the past two decades, with both planned expansion and informal peri-urban sprawl. The study area is geographically defined by a bounding box between 78°–79°E longitude and 17°–18°N latitude, extending beyond the administrative boundaries of the city to include peripheral zones, municipalities, and development corridors.

2.2. MODIS MCD12Q1 LULC Data

The MODIS MCD12Q1 product provides global annual land cover classification at 500 m resolution using input reflectance, NDVI, and phenological variables (Friedl et al., 2010). The dataset follows the International Geosphere–Biosphere Programme (IGBP) classification scheme with 17 land cover types. The MODIS dataset is particularly well-suited for large-scale temporal monitoring due to its consistency, availability, and processing stability, though its spatial resolution limits detection of small-scale fragmentation and edge growth (Sulla-Menashe & Friedl, 2018). MODIS MCD12Q1 v6.1 reports a global overall accuracy (OA) of 74–80%, with class-specific accuracies for cropland and built-up areas typically exceeding 85% (Friedl et al., 2010; Sulla-Menashe et al., 2019). In this study, MODIS LULC data from 2001 to 2022 were utilized to identify and examine LULC changes over major urban centres across India.

2.3 GLC_FCS30D LULC Data

The GLC_FCS30D dataset provides global land cover classification at 30 m resolution, produced by Tsinghua University using multi-source Landsat and Sentinel imagery processed through deep learning algorithms (Zhang et al., 2021). The product adheres to the FAO's LCCS classification standard and includes nine land cover categories. GLC_FCS30D dataset, reports an OA of 85–88% globally, with built-up and cropland classes often achieving over 90% accuracy (Zhang et al., 2021). The GLC_FCS30D dataset for 2022 was utilized to capture finer spatial detail, map non-contiguous built-up growth, and quantify urban fragmentation over Hyderabad metropolitan region.

3. Methodology

Urban clusters were delineated using the MODIS MCD12Q1 dataset for the year 2022, specifically extracting the built-up pixels. Using raster connectivity algorithms within ArcGIS Pro, spatially contiguous pixels were grouped into discrete urban clusters. Each cluster was converted into a polygon and its area was computed. A total of 1,516 urban clusters were identified and stratified into three tiers based on percentile-based thresholds for areal extent:

- Tier I: > 218.4 km^2 (>98.7^{th} percentile) – 20 clusters
- Tier II: 18.97 km^2 (75^{th} percentile) to 218.4 km^2
- Tier III: < 18.97 km^2

For each of these Tier-I clusters, LULC area statistics were computed using MODIS rasters for the years 2001 and 2022. The 2022 cluster boundaries were used to spatially clip both rasters, allowing temporal comparison within consistent spatial extents. Zonal statistics were applied to compute the total area of each land cover category; cropland, forest, shrubland, grassland, barren, and built-up. These measurements enabled assessment of dominant land cover transitions and quantified the spatial extent of urban expansion over two decades.

To investigate pixel-level transitions between land cover classes, a transition matrix was generated using the "Combine" tool in ArcGIS Pro. The MODIS rasters for 2001 and 2022 were merged into a single raster, recording each pixel's original and final land cover class. Transition counts were tallied and converted to area-based metrics, producing a matrix of all land cover class changes. These matrices were then aggregated across all Tier-I clusters to reveal dominant transformation pathways such as cropland-to-built-up or shrubland-to-urban. The transition data were visualized using summary charts and spatial overlays to enhance interpretability.

3.1 Reclassification of LULC Datasets

To enable a consistent cross-dataset comparison, the GLC_FCS30D land cover classes were reclassified (Table 1) to match the MODIS MCD12Q1 IGBP scheme. This reclassification was essential to avoid classification mismatches and ensure that the land cover change metrics derived from MODIS and GLC_FCS30D were directly comparable. The same analytical procedures zonal statistics, reclassification, and transition matrix generation were applied across both datasets to enable a comparative assessment.

Table 1: Reclassification of GLC_FCS30D classes into MODIS MCD12Q1 IGBP categories

MODIS LULC Classes		GLC_FCS30 LULC Classes	
Code	**Name**	**Code**	**Name**
0	Water Bodies	210	Water bodies
1	Evergreen Needleleaf Forest	71, 72	Mixed forest (mainly evergreen), Mixed Forest (mainly deciduous)
2	Evergreen Broadleaf Forest	51, 52	Evergreen needleleaf forest, Evergreen broadleaf forest
3	Deciduous Needleleaf Forest	61	Shrubland
4	Deciduous Broadleaf Forest	62	Deciduous needleleaf forest, Deciduous broadleaf forest
5	Mixed Forest	91	Herbaceous vegetation
7	Open Shrublands	81,120, 12,	Sparse vegetation, Sparse herbaceous vegetation
10	Grasslands	130	Grassland
11	Permanent Wetlands	181, 182, 183	Permanent wetland, Inland marsh, Coastal marsh
12	Croplands	10, 11, 12, 20	Cropland rainfed, Cropland irrigated, Paddy field, Mosaic cropland-natural vegetation
13	Built-Up	190	Built-up
16	Barren or Sparsely	140, 150, 200	Bare soil, Rocky land, Snow and ice

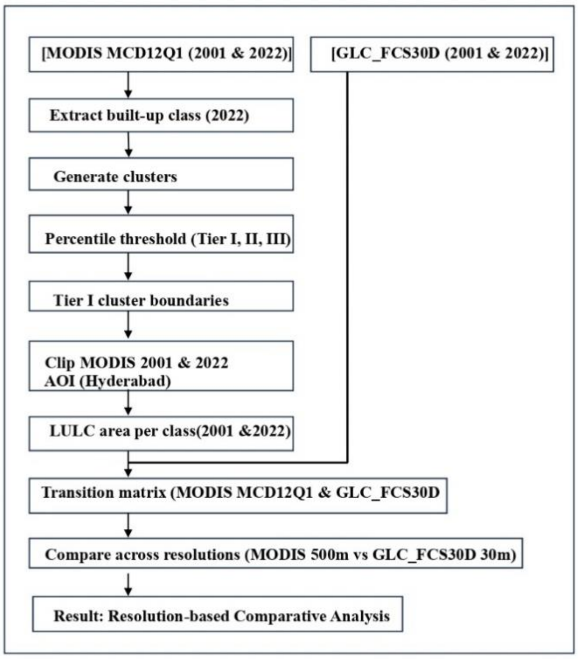

Figure 1: Methodological workflow for multi-resolution analysis of urban expansion (2001–2022)

All spatial analyses were performed in ArcGIS Pro Visualization and charting of results including land cover area change plots, transition diagrams, and urban expansion maps were conducted using Python's Matplotlib library and Microsoft Excel.

4. Results and Discussion

4.1 LULC Transitions in Tier-I Cities: 2001 to 2022

In 2001, the MODIS-derived LULC classification revealed that India's Tier-I urban clusters encompassed a mix of consolidated urban cores and peripheral agricultural or semi-natural landscapes. Built-up land dominated in cities like New Delhi (1,512 km²), Mumbai (547.7 km²), Hyderabad (639.8 km²), Chennai (497.3 km²), and Bengaluru (494.6 km²), reflecting early stages of infrastructural consolidation. However, cropland occupied substantial areas even within these urban extents. Surat (175.6 km²), Hyderabad (149.4 km²), and Ahmedabad-Gandhinagar (58.2 km²) recorded high cropland coverage, suggesting vast peri-urban reserves poised for conversion. Shrublands, savannas, and open vegetated classes persisted in clusters such as Ahmedabad, Coimbatore, and Asansol, indicating transitional landscapes undergoing piecemeal development (Table 2).

By 2022, significant transformation in land cover patterns was observed across all clusters. Built-up areas had expanded markedly Delhi (1,753.3 km²), Hyderabad (744.8 km²), Mumbai (672.5 km²), and Bengaluru (594.3 km²). Smaller clusters such as Coimbatore and Surat exhibited high relative increases, indicating intense peri-urban growth. Cropland declined sharply across all clusters, underscoring its role as the primary land donor for urban expansion (Table 3).

Pixel-wise transition analysis shows that cropland was the largest contributor to newly built-up areas, accounting for 1,141 km² or 63.6% of total urban expansion. Grasslands (342 km², 19.1%) and savannas (216.75 km², 12.1%) followed, reflecting large-scale transformation of ecologically functional lands.

Interestingly, 60.1% of newly mapped cropland emerged from former built-up land, indicating temporary land use reversals or misclassifications common in peri-urban contexts.

Grasslands and savannas also appeared on previously cultivated lands, reflecting fallow cycles and low-density transitions. These transition matrices for built-up, cropland, savanna, and grassland are illustrated in (Figure 2).

The cumulative built-up area across the 20 Tier-I clusters increased from 7,591.6 km² in 2001 to 8,866.8 km² in 2022, marking a net gain of approximately 1,275.2 km². New Delhi accounted for the highest absolute increase (+241.1 km²), followed by Mumbai (+124.8 km²), Hyderabad (+105.0 km²), and Bengaluru (+99.7 km²). In percentage terms, the fastest-growing clusters were Coimbatore (+27.8%) and Dhanbad (+25.5%), highlighting latent urbanization pressures in mid-tier cities with large peri-urban footprints.

Table 2: LULC Distribution by Class (km²) for Tier I urban growth centres: MODIS 2001

Tier_I_Clusters	Representative_City	WB	SB	SV	PW	CR	BU	NV	BR	UC	Tot Area
CL_1	Chandigarh	0	0.00	31.21	0.25	23.28	155.06	1.24	0.50	0	215
CL_2	New Delhi	0	0.00	34.15	1.25	390.06	1512.14	5.98	0.00	0	2051
CL_3	Jaipur	0	3.98	0.00	0.25	36.10	297.52	0.00	0.00	0	362.25
CL_4	Lucknow	0	0.00	0.76	0.00	45.72	194.26	0.25	0.00	0	241.75
CL_5	Kanpur	0	0.00	1.00	0.00	74.81	216.46	0.00	1.75	0	301.75
CL_6	Dhanbad	0	0.00	0.00	0.00	60.71	148.26	0.00	0.00	0	217
CL_7	Asansol	0	0.00	0.50	1.00	276.58	346.85	0.00	0.25	8.03	642.75
CL_8	Ahmedabad–GNR	0	26.07	1.75	0.00	58.16	352.99	0.25	0.00	0.50	447.75
CL_9	Kolkata	0	0.00	167.77	5.67	15.54	604.72	39.72	1.48	39.48	885.25
CL_10	Indore	0	0.00	1.01	0.00	76.70	285.44	0.00	0.00	0.00	421.75
CL_11	Vadodara	0	0.25	3.26	0.00	49.19	189.48	1.00	0.00	0.00	259.25
CL_12	Ankleshwar	0.75	0.00	8.52	0.00	31.32	143.83	0.00	0.00	6.01	217.5
CL_13	Surat	1.74	0.00	150.09	3.97	175.65	345.09	5.95	1.74	8.19	713.75
CL_14	Nagpur	0.00	0.00	0.49	0.49	56.20	165.38	0.00	0.25	0.00	227.25
CL_15	Mumbai	12.65	0.00	3.72	26.54	183.57	547.73	0.00	0.00	22.82	834.5
CL_16	Pune	0.00	0.50	6.51	0.00	58.57	279.36	0.00	0.00	0.00	391.5
CL_17	Hyderabad	0.00	0.00	0.00	0.00	149.40	639.76	0.25	2.00	0.25	857.5
CL_18	Chennai	15.17	0.00	6.47	1.99	101.99	497.25	0.00	0.50	7.96	697.5
CL_19	Bengaluru	0.00	1.00	0.00	2.50	147.47	494.55	0.00	0.00	0	653
CL_20	Coimbatore	0.00	0.00	2.76	0.25	41.91	175.42	1.25	0.00	0	261

Abbreviations: WB – Water Bodies; SB – shrublands; SV – Savannas; PW – Permanent Wetlands; CR – Croplands; Built-Up; NV – Natural Vegetation; BU –BR – Barren; UC – Unclassified; Tot – Total area in km²(2001).

Table 3: LULC Distribution by Class (km²) for Tier I urban growth centres: MODIS 2022

Abbreviations: WB – Water Bodies; SV – Savannas; GL – Grasslands; PW – Permanent Wetlands; CR – Croplands; Built-Up; NV – Natural Vegetation; BU –BR – Barren; UC – Unclassified; Tot – Total area(km²).

Tier I Clusters	Representative City	WB	SV	GL	PW	CR	BU	NV	BR	UC	Tot Area
CL_1	Chandigarh	0	25.5	0.5	0.75	6.5	181.75	0	0	0	215
CL_2	New Delhi	0	56.75	37	1.75	202	1753.3	0.25	0	0	2051
CL_3	Jaipur	0	0	1.5	0	30.75	330	0	0	0	362.25
CL_4	Lucknow	0	1.25	2.5	0	19	219	0	0	0	241.75
CL_5	Kanpur	0	1.25	8.75	0	46.25	245.25	0	0.25	0	301.75
CL_6	Dhanbad	0	0	9.75	0	21.25	186	0	0	0	217
CL_7	Asansol	0	4	14	1	207.5	410.25	0	0	6	642.75
CL_8	Ahmedabad–GNR	0	0	1	0	59.25	387.25	0	0	0.25	447.75
CL_9	Kolkata	0	124.8	3.25	0.75	9.25	680.5	27.25	1	38.5	885.25
CL_10	Indore	0	4.5	2.25	0	92.75	322.25	0	0	0	421.75
CL_11	Vadodara	0	2.25	0.75	0	44.5	211	0.75	0	0	259.25
CL_12	Ankleshwar	0	7.75	3.75	0	42	163	0	0	1	217.5
CL_13	Surat	0.5	142	16	3.75	122	422.25	1.25	0.25	5.75	713.75
CL_14	Nagpur	0	1.25	5.5	0.75	25.5	194.25	0	0	0	227.25
CL_15	Mumbai	4.25	16	55	9.25	58.25	672.5	0	0	19.25	834.5
CL_16	Pune	0	7.75	11.25	0	34.5	338	0	0	0	391.5
CL_17	Hyderabad	0	0	11	2	98.5	744.75	0	0.5	0.75	857.5
CL_18	Chennai	0	15.75	28.5	0.5	61.5	587	0	1	3.25	697.5
CL_19	Bengaluru	0	0.75	5	0	52.75	594.25	0.25	0	0	653
CL_20	Coimbatore	0	10.75	6	0	19.25	224.25	0.75	0	0	261

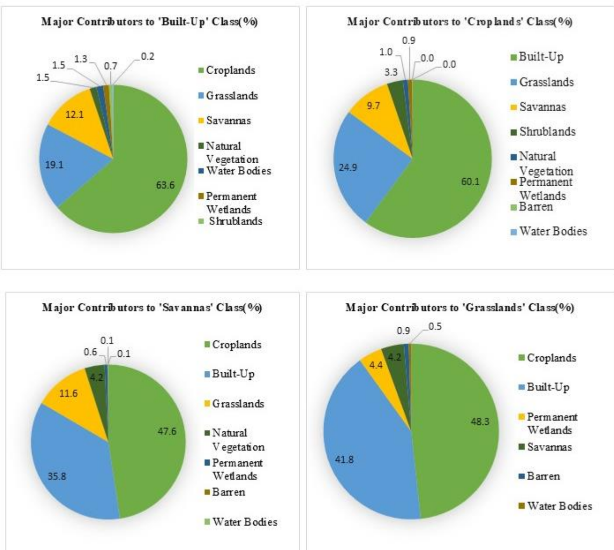

Figure 2: Illustrating transition matrices for built-up, cropland, savanna, and grassland

4.2 Regional Case Study: LULC Changes over Hyderabad

4.2.1 LULC Changes from MODIS MCD12Q1

MODIS analysis revealed an increase in built-up area from 747.3 km² in 2001 to 838.6 km² in 2022, a 12.2% growth. While this reflects gradual urbanization, the coarse resolution may underrepresent fragmented peri-urban growth. Most expansion occurred at the expense of natural vegetation classes, especially grasslands (−114.4 km²) and savannas (−3.75 km²), indicating progressive urban encroachment into ecological buffers. Unexpectedly, deciduous vegetation increased from 0.5 km² to 7.75 km² potentially due to spectral misclassification or

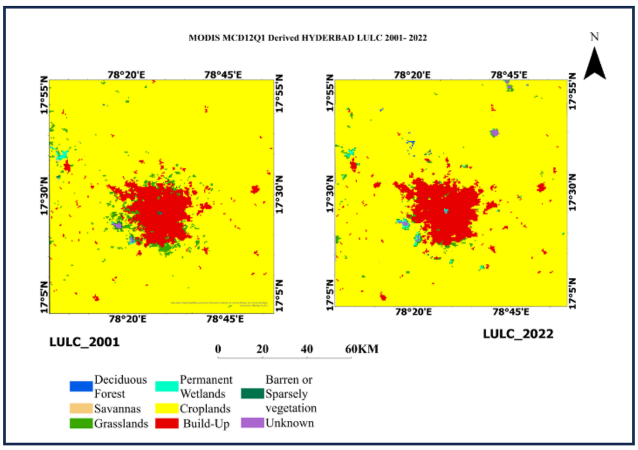

Figure 3: MODIS MCD12Q1 derived land use/land cover classification maps for the study region in 2001 and 2022

vegetation regrowth in transitional zones. Wetlands expanded from 18.0 to 31.24 km², likely reflecting water accumulation in low-lying urban areas rather than natural wetland restoration. Meanwhile, barren land declined from 8.7 to 3.0 km², and unclassified pixels more than doubled, possibly due to spectral heterogeneity at urban edges (Table 4).

Table 4: . LULC transition matrix for the Hyderabad region (2001–2022) from MODIS MCD12Q1 (500 m resolution). Values are in km²

Abbreviations: BR – Barren; CR – Croplands; DF – Deciduous Forest; EF – Evergreen Forest; GL – Grasslands; PW – Permanent Wetlands; SV – Savannas; UC –Unclassified; BU – Built-Up; TOT – Total area (km²).

From Class	BR	CR	DF	GL	PW	SV	UC	BU	Total From class 2001
BR	0.5	1.25	0	1.25	4.75	0	0.75	0.25	8.75
CR	2.5	10192.5	7.5	68	9.75	2.75	15.25	95	10393.2
DF	0	0.5	0	0	0	0	0	0	0.5
GL	0	156.5	0.25	26	4.75	0.25	0	30.75	218.5
PW	0	3	0	6.5	8	0	0.5	0	18
SV	0	6	0	0.5	0.25	0.25	0	0	7
UC	0	0.25	0	0	2.75	0	7.25	0	10.25
BU	0	32	0	1.75	1	0	0	712.75	747.5
Total To class 2022	3	10392	7.75	104	31.25	3.25	23.75	838.75	11403.75

4.2.2 LULU Changes from GLC_FCS30D

The GLC_FCS30D dataset reveals a substantial built-up increase from 660.1 km² to 1035.8 km² (+57%). This dramatic expansion, particularly along the western and southern corridors of Hyderabad, provides clearer evidence of sprawling development missed by MODIS. In contrast to the modest cropland decline seen in MODIS, high-resolution GLC data confirms a 912.4 km² loss in cropland, emphasizing its primacy as a source for new urban land.

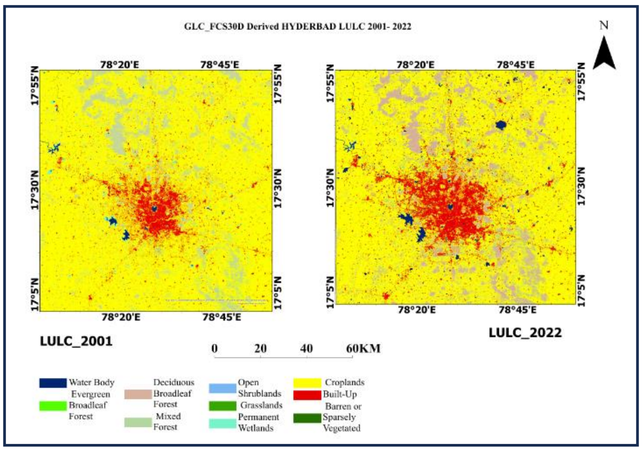

Figure 4: GLC_FCS30D derived land use/land cover classification maps for the study region in 2001 and 2022

Deciduous forest and mixed forest increased by 175 km² and 169.7 km², respectively likely representing plantation efforts or classification shifts due to regrowth. However, wetlands declined sharply (−60.2 km²), highlighting the degradation of hydrologically sensitive zones. The spatial fragmentation of cropland and loss of vegetative buffers reinforce concerns about the ecological costs of unchecked urban sprawl (Table 5).

Table 5: LULC transition matrix for the Hyderabad region (2001–2022) from GLC_FCS30D (30 m resolution). Values are in km²

Abbreviations: BR – Barren; BU – Built-Up; CR – Croplands; DF – Deciduous Forest; EF – Evergreen Forest; GL – Grasslands; MF – Mixed Forest; WL – Wetlands; SB – Shrublands; WB – Water Bodies; TOT – Total area (km²).

From Class	BR	BU	CR	DF	EF	GL	MF	WL	SB	WB	Total From class 2001
BR	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7
BU	0.0	593.1	60.5	0.9	0.1	1.2	0.5	0.0	3.0	0.7	660.1
CR	0.6	424.1	8025.3	468.9	33.5	7.7	234.1	2.5	112.1	52.3	9361.0
DF	0.1	16.4	274.0	711.1	9.9	0.6	28.2	0.2	14.8	2.0	1057.3
EF	0.0	0.3	15.7	22.7	8.8	0.0	0.1	0.0	0.5	0.1	48.2
GL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
MF	0.0	0.5	60.2	25.0	0.1	0.0	51.3	0.0	9.3	0.2	146.7
WL	0.0	0.0	2.6	0.0	0.0	0.0	0.1	28.6	0.0	62.3	93.7
SB	0.0	1.4	9.1	3.7	0.3	0.1	2.2	0.0	19.9	0.4	37.0
WB	0.0	0.0	0.9	0.0	0.0	0.0	0.0	2.1	0.0	35.9	38.9
ToT to Class 2022	0.8	1035.8	8448.7	1232.3	52.7	9.7	316.4	33.5	159.5	154.2	11443.7

A comparative transition analysis using MODIS (2001–2022) and GLC_FCS30D (2001–2022) datasets reveals key spatiotemporal patterns of land use transformation in the Hyderabad metropolitan region. MODIS-derived transitions indicate that built-up area increased by 126 km², predominantly sourced from croplands (75.4%) and grasslands (24.4%), illustrating the typical peri-urban expansion pattern of Indian cities (Seto et al., 2012). Simultaneously, cropland exhibited dynamic flux, with 199 km² of new cropland arising mostly from grasslands (78.6%) and even previously built-up zones (16.1%) suggesting informal or opportunistic farming practices in transitional plots (Verburg et al., 2015). Grasslands themselves gained 78 km², primarily from cropland (87.2%), highlighting cycles of agricultural abandonment and vegetative succession (Liu et al., 2020). In contrast, high-resolution GLC_FCS30D data revealed a significantly larger built-up gain of 442.41 km², with a staggering 95.86% sourced from croplands, alongside smaller losses from forests and shrublands (Güneralp & Seto, 2013). Cropland area also increased by 407.31 km², reclaimed largely from deciduous forest (67.27%) and built-up areas (14.85%), reflecting bidirectional land contestation and reversible use patterns. Notably, deciduous forests expanded by 498.54 km²—94% of which came from croplands suggesting localized reforestation, land abandonment, or passive ecological recovery in the absence of cultivation pressure (Schneider et al., 2010). These transitions confirm that cropland serves as both the most stable and the most frequently converted land class in peri-urban landscapes.

The transition matrices derived from both datasets provide deeper insight into the intensity and direction of these changes. MODIS data identified croplands as both the most persistent (10,192.5 km² unchanged) and the primary donor to built-up expansion (95 km²). Meanwhile, GLC_FCS30D matrices showed 424.1 km² of cropland loss to urban growth, and a further 468.9 km² conversion to deciduous forest, signalling dual processes of urban encroachment and ecological transformation. These patterns underscore the complex interplay between rapid urbanization, landscape fragmentation, and sporadic ecological restoration in transitional urban ecologies. Visual tools including land cover maps, Sankey diagrams, pie charts, and temporal overlays were used to communicate these multidirectional flows and spatial transformations effectively, highlighting the diagnostic value of high-resolution geospatial monitoring in urban planning and land governance (Ramachandra et al., 2012; Kumar et al., 2021).

5. Conclusions

This study examines urban land use and cover change across India from 2001 to 2022, integrating MODIS MCD12Q1 (500 m) for national-scale analysis and GLC_FCS30D (30 m) for high-resolution insights in the Hyderabad region. A total of 20 Tier-I urban clusters were analysed, revealing a net built-up increase of over 1,270 km², equivalent to ~18.5% of the total monitored urban footprint, with cropland contributing 63–96% of this expansion depending on resolution. This pervasive cropland-to-urban transformation confirms the long-standing trend of peri-urban agricultural land loss in fast-growing Indian cities.
Comparative results underscore the critical role of spatial resolution: MODIS enabled temporal continuity and macro-scale trend detection but exhibited limitations in capturing spatial heterogeneity, edge fragmentation, and smaller class transitions. In contrast, GLC_FCS30D offered sharper urban boundaries, better delineation of mixed land mosaics, and greater sensitivity to transitional zones, especially evident in Hyderabad, where built-up gains reached 442.4 km², cropland loss exceeded 900 km², and wetlands shrank by more than 60%. These results not only reinforce known patterns of spatial metabolism (Seto et al., 2012) and peri-urban transition theory but also suggest ecotonal landscapes are functioning as hybrid zones of informal cultivation, ecological reversion, and speculative development.
The observed transitions, supported by transition matrices reveal not only irreversible urban encroachment but also signs of land-use contestation and reclassification e.g., grassland emergence from abandoned cropland and temporary cropland reuse from previous built-up zones. From a planning perspective, zones with high cropland conversion and ecological degradation should be prioritized for green infrastructure integration, and regulatory oversight.
The differentiated results between MODIS and GLC_FCS30D highlight the necessity of resolution-aware policy tools, where national planners can rely on coarse-scale consistency while local authorities require fine-scale diagnostics for enforcement and design. The present study quantifies the evolving urban footprint at national level and proposes a replicable, resolution-sensitive framework for landscape change monitoring, encouraging sustainable urbanization.

6. References

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),pp.16083–16088. https://doi.org/10.1073/pnas.1211658109

Ramachandra, T.V., Bharath, H.A., & Durgappa, D.S., 2014. Insights to urban dynamics through landscape spatial pattern analysis. International Journal of Applied Earth Observation and Geoinformation,39,pp.1–10. https://doi.org/10.1016/j.jag.2015.02.001

Jat, M.K., Garg, P.K., & Khare, D., 2017. Monitoring and modelling of urban sprawl using remote sensing and GIS techniques. International Journal of Applied Earth Observation andGeoinformation,10(1),pp.26–43. https://doi.org/10.1016/j.jag.2007.04.002

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., & Huang, X., 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. Remote Sensing of Environment,114(1),pp.168–182. https://doi.org/10.1016/j.rse.2009.08.016

Schneider, A., Friedl, M.A., & Potere, D., 2010. Mapping global urban areas using MODIS 500-m data: New methods and datasets based on ‘urban ecoregions’. Remote Sensing of Environment,114(8),pp.1733–1746. https://doi.org/10.1016/j.rse.2010.03.003

Herold, M., Goldstein, N.C., & Clarke, K.C., 2005. The spatiotemporal form of urban growth: Measurement, analysis and modeling. Remote Sensing of Environment, 86(3), pp.286–302. https://doi.org/10.1016/j.rse.2005.02.003

Gong, P., Wang, J., Yu, L., Zhao, Y., Zhao, Y., Liang, L., Niu, Z., Huang, X., Fu, H., Liu, S. et al., 2019. Development of a global 30m urban extent map using Landsat data. Remote Sensing of Environment, 228, pp.203–211. https://doi.org/10.1016/j.rse.2019.04.020

Zhang, H., Zhao, S., Tan, C., Gong, P., & Fu, B., 2021. Mapping global urban expansion using Landsat and Sentinel data with deep learning. Remote Sensing of Environment, 256, 112318. https://doi.org/10.1016/j.rse.2021.112318

Verburg, P.H., Neumann, K., & Nol, L., 2011. Challenges in using land use and land cover data for global change studies. Global Change Biology,17(2),pp.974–989. https://doi.org/10.1111/j.1365-2486.2010.02307.x

Liu, X., Huang, X., Yang, H., Zhong, T., & Li, X., 2020. Understanding land use change in peri-urban areas of China: The role of transportation and socioeconomic forces. Applied Geography,120,102224. https://doi.org/10.1016/j.apgeog.2020.102224

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

Güneralp, B., & Seto, K. C. (2013). Futures of global urban expansion: uncertainties and implications for biodiversity conservation. Environmental Research Letters, 8(1), 014025. https://doi.org/10.1088/1748-9326/8/1/014025

Verburg, P. H., Erb, K.-H., Mertz, O., & Espindola, G. (2015). Land System Science: Between global challenges and local realities. Current Opinion in Environmental Sustainability, 15, 1–4. https://doi.org/10.1016/j.cosust.2015.08.009

Liu, X., Liang, X., Li, X., Xu, X., Ou, J., Chen, Y., Li, S., & Wang, S. (2020). A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. Landscape and Urban Planning, 154, 1–12. https://doi.org/10.1016/j.landurbplan.2016.01.007

Ramachandra, T. V., Bharath, S., & Sowmyashree, M. V. (2012). Monitoring urbanization and its impact on ecology and society. Journal of Environmental Management, 112, 133–145. https://doi.org/10.1016/j.jenvman.2012.07.004

Kumar, T., & Thakur, J. K. (2021). Geospatial assessment of urban sprawl and land surface temperature in relation to planning strategy in Indian cities: A case study of Hyderabad. Sustainable Cities and Society, 68, 102772. https://doi.org/10.1016/j.scs.2021.102772

Mathan, M., & Krishnaveni, M. (2020). Spatio-temporal dynamics of urban and peri-urban land transitions using ensemble of remote sensing spectral indices—A case study of Chennai Metropolitan Area, India. Environmental Monitoring and Assessment, 192, Article 409. https://doi.org/10.1007/s10661-019-7986-y

Patel, S.K., Verma, P., & Singh, G.S. (2019). Agricultural growth and land use land cover change in peri-urban India.
Environmental Monitoring and Assessment, 191(2), 124. https://doi.org/10.1007/s10661-019-7736-1

Roy, P.S., Behera, M.D., & Srivastava, V.K. (2020). Land Use and Land Cover Change in India: A Remote Sensing & GIS Perspective. Journal of the Indian Society of Remote Sensing, 48(3), 405–422. https://doi.org/10.1007/s12524-020-01117-1

Pal,S.,&Ziaul,S.(2017). Detection of land use and land cover change and land surface temperature in English Bazar urban centre. Egyptian Journal of Remote Sensing and Space Science, 20(1), 125–145. https://doi.org/10.1016/j.ejrs.2016.11.003

The MODIS MCD12Q1 dataset:
https://lpdaac.usgs.gov/products/mcd12q1v061/

GLC_FCS30D dataset:
https://data.ess.tsinghua.edu.cn/form/form/index?lang=en